

HANDBOOK OF RESEARCH ON

Building Information Modeling and Construction Informatics

CONCEPTS AND TECHNOLOGIES



Jason Underwood & Umit Isikdag

Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies

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Section 1 **Introduction**

This first section concentrates on exploring the conceptual aspects of both Building Information Modelling and Building Information Models including examining the purpose of Building Information Models. The concepts of what is actually being modelled and the way in which these can be modelled are discussed. This is complimented with the perspective of Architectural Design being presented.

Chapter 1

Modelling Concepts for BIM	1

Sander van Nederveen, Delft University of Technology, The Netherlands

Reza Beheshti, Delft University of Technology, The Netherlands

Wim Gielingh, Delft University of Technology, The Netherlands

This chapter discusses the modelling concepts of Building Information Modelling by addressing questions such as What is Building Information Modelling ?, What is a Building Information Model ? along with the rationale and objectives of a Building Information Model. In the chapter a clear distinction is presented between (a) what is being modelled such as requirements, function, boundary conditions, building configuration, connectivity, shape, processes lifecycle aspects and discipline views, and (b) how these can be modelled, such as through parametric models, part libraries, nD models, various representations and presentations, including visualizations. Finally, the chapter concludes with a brief discussion of relevant methods and languages for information modelling and recent ontology-based approaches.

Chapter 2

A Review of Building Information Modeling Tools from an Architectural Design Perspective..... 19

Olcay Çetiner, Yıldız Technical University, Turkey

Building Information Modeling (BIM) continues to evolve and grow along with their application in practice. One of the key advantages of BIM is that it facilitates the development of detailed information and analysis much earlier in the construction process to improve decision making and reduce downstream changes. A key area that Building Information Modeling is used is Architectural Design. This chapter provides a review of BIM from an Architectural Design Perspective.

Section 2

Adoption

Adopting a Building Information Modelling approach is not just about the technology but is also highly dependent on other 'non-technical' factors relating to people, process, organisational structure, work environment, etc. The focus of this section is towards exploring the issues associated with the readiness and maturity of organisations in preparing themselves for the successful adoption of BIM.

Chapter 3

Delivering BIM to the UK Market..... 30

Mark Bew, Scott Wilson Group, UK

Jason Underwood, University of Salford, UK

Technology has developed dramatically over the past five and particularly three decades. The way we live our lives has changed and is set to change ever more with the effects this technology has on our planet's environment. Construction is one of the world's oldest industries and has been slow to adapt and change with the arrival of these developing technologies. For example, it has been nearly two decades since Building Information Modelling (BIM) was first mooted and we still await significant adoption. The UK picture is further burdened with a fragmented supply chain, slow consolidation and generally low investment in the industry. However, BIM is not CAD. It is so much more; like the move from old accounting packages to Enterprise Resource Planning (ERP), it includes the formal management of processes on a consistent, repeatable basis. Like ERP, this is a very difficult transition to make. The product vendors have not helped through creating a confused market, with patchy product capability and no process management tools available on a scalable production basis. Furthermore, the construction industry's approach to contracts, training and education also need attention if it is to deliver this operating model. However, the key questions are: does it work and is it worth pursuing in the competitive UK market? The answer to both questions is yes, but it is important to be aware of what is involved, to understand the evolution and to take sensible steps to achieve the reward. The focus of this chapter is to begin exploring the issues towards the delivery of BIM to the UK construction market sector.

Chapter 4

Building Information Modelling Maturity Matrix..... 65

Bilal Succar, ChangeAgents AEC, Australia

This chapter briefly explores the multi-dimensional nature of the BIM domain and then introduces a knowledge tool to assist individuals, organisations and project teams to assess their BIM maturity and improve their performance. The first section introduces BIM Fields and Stages which lay the foundations for measuring maturity. Section 2 introduces BIM Steps -organised in ‘sets’ and ‘types’- which incrementally separate BIM Stages and act as Key Maturity Areas within them. Section 3 introduces an Organisational Hierarchy which identifies granular scales for applying maturity assessments within the industry. Section 4 explores the concepts of ‘capability maturity’ and adopts a five-level BIM-specific maturity index. Finally, Section 5 introduces the BIM Maturity Matrix (BIm³), a knowledge tool that describes the *range of* and *correlation between* BIM Stages, Steps, Maturity Levels and Organisational Scales.

Section 3 Standards

A key element to Building Information Modelling which is firmly fixed in its origin is that of standards. This section is concerned with standards from two particular aspects. The first is that of product modelling within the AEC sector in terms of an extensive historical review, the characteristics of several conceptual approaches together with the implementation of their constructs, and finally future trends through a number of on-going research projects. The second aspect is a recent national standard which has been set up in the US and is examined in relation to the current and future strengths, weaknesses, opportunities, and impact.

Chapter 5

Product Modelling in the Building and Construction Industry: A History and Perspectives 104

Edwin Dado, The Netherlands Defence Academy, The Netherlands

Reza Beheshti, Delft University of Technology, The Netherlands

Martinus van de Ruitenbeek, Delft University of Technology, The Netherlands

This chapter provides an overview of product modelling in the Building and Construction (BC) industry based on authors’ experiences gained from various conducted research projects and also taking into account results of other research projects. This chapter starts with an introduction and background of the subject area in terms of motivation, industrial needs and requirements. This is followed by an extensive review of the historical background of the subject area. After this historical overview, an analysis of the characteristics of interesting conceptual product approaches is presented. Here, the authors discuss the Standardisation, Minimal Model, Core Model, NOT, Vocabulary and Ontology product modelling approaches. This section is followed by an analysis of a number of specific conceptual product models and how the basic product modelling constructs (i.e. semantics, lifecycle modifiers and multiple project views) are implemented. The chapter ends with a discussion about some ongoing projects (COINS, CHEOPS and SWOP) in the context of future trends.

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The US National Building Information Modeling Standard.....	138

Patrick C. Suermann, University of Florida, USA

Raja R.A. Issa, University of Florida, USA

This chapter looks at the strengths, weaknesses, opportunities, and impact of the National BIM Standard (NBIMS) into 2009 and beyond. Specifically, this chapter focuses into some of the strengths of the NBIMS, such as promulgating a standardized approach for documenting information exchanges between stakeholders, and applying the NBIMS Interactive Capability Maturity Model (I-CMM) to evaluate a project or portfolio for BIM maturity. Opportunities exist in the areas of sustainability, modularity, and fabrication, as demonstrated in several industry projects to date. The primary impact of the NBIMS will be felt in terms of current and future projects promoting interoperable information exchange for specific stakeholders. These include multiple applications of interoperable-IFC-based approaches.

Section 4 Applications

This section focuses on various aspects of applications in support of the Building Information Modelling process including, proposed technology developments, new approaches to applications development, and conceptual implementation frameworks.

Chapter 7

A CAD-Based Interface Management System using Building Information Modeling in Construction.....	155

Yu-Cheng Lin, National Taipei University of Technology, Taiwan

Interface management (IM) is the systematic control of all communications that support an operational process. Construction IM affects cost, scheduling, and quality directly and indirectly. This chapter presents a novel practical methodology for tracking and managing interfaces using Building Information Modeling (BIM) approach. The pilot study presented in the chapter utilized BIMs for IM to the construction/mechanical/electrical interfaces in a building project and developed a CAD-based Interface Management (CBIM) system for project participants. The CBIM system is later applied in Taiwan to verify the proposed methodology and demonstrate the effectiveness of IM.

Chapter 8

A Comparative Analysis of 2D Computer-Aided Estimating (CAE) and BIM Estimating Procedures.....	170

Oluwole Alfred Olatunji, University of Newcastle, Australia

William David Sher, University of Newcastle, Australia

Most estimators are using manual and Computer-Aided Design and Drafting (CADD) software and two dimensional (2D) drawings. The spatio-temporal limitations of these designs complicate information

management, estimators' judgments, speed and accuracy. Building Information Modeling (BIM) promises major improvements that overcome the limitations of conventional 2D methods in both design and construction processes. It provides platforms for value integration, robust information sources, simultaneous access to design database, automated quantification, project visualization and simulation, among others capabilities. These capabilities facilitate accuracy, objective risk assessment, comprehensive information management and early integration of cost management principles during design. The uptake of Information Technology (IT) in the construction industry is increasing and this discipline-specific study on BIM highlights its considerable potential for improving professional service delivery. This chapter reviews the impacts of BIM on cost estimating procedures. In order to develop a conceptual framework for underpinning BIM-propelled changes in estimating practice, in this chapter CAE applications are categorized and compared. In addition, some features for producing automated quantities from BIMs are compared with provisions of standard methods of measurements used by estimators. The chapter concludes with recommendations about the capacity of BIM to revolutionize construction procurement and systems.

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Automated Building Process Monitoring 190

Danijel Rebolj, University of Maribor, Slovenia

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Peter Podbreznik, University of Maribor, Slovenia

Monitoring of building process activities is the basis for effective control and management of a building project. In its traditional way it is, however, time consuming, inaccurate and expensive. The chapter describes methods of automating the monitoring process and then concentrates on a solution, which takes into account all three aspects of project management: coordination, control and communication. Activity progress is monitored directly by using a combination of data collection methods, which are based on the Building Information Model (BIM), especially on the 4D model of the building. Finally in the chapter, the resulting system is described, evaluated and discussed.

Chapter 10

Extracting Fire Engineering Simulation Data from the IFC Building Information Model 212

Michael Spearpoint, University of Canterbury, New Zealand

Fire engineering is a distinctive discipline within the construction industry that has its own language, design goals and analytical approaches. This chapter examines what fire engineers would like to achieve and how Building Information Modeling (BIM) fits in with those goals. It discusses the types of fire simulation models that fire engineers use and gives a brief description of two particular fire growth models which use different means to represent a fire scenario. The chapter then considers how the IFC building information model can be used to transfer building geometry and property data to fire simulation models. Finally, the chapter describes some of the challenges involved in sharing building data with fire simulation models and provides recommendations for further work.

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Oluwole Alfred Olatunji, University of Newcastle, Australia

William David Sher, University of Newcastle, Australia

This chapter reviews some of the capabilities of BIM which may revolutionize conventional practices in FM. Specific platforms for this include, integrated analysis and simulation of project variables in virtual environments, effective communication between project stakeholders and project teams and multi-disciplinary collaboration. Others are interoperability, project visualization, value intelligence. The chapter indicates that BIM capabilities such as project visualization, simulation, auto-alert and value intelligence may stimulate major improvements in facilities management processes.

Chapter 12

Developing Context Sensitive BIM Based Applications	254

Timo Hartmann, Twente University, The Netherlands

Current Building Information Model based applications do not integrate well with the varying and frequently changing work processes of Architectural, Engineering, and Construction (AEC) professionals. One cause for this problem is that traditionally software developers apply software design methods that aim to design software that cater to a broad range of different users without accounting for the possibility of changing work processes. This chapter theoretically introduces a different method to design software - context sensitive software development - and theoretically argues that it is poised to enable application developers to adjust BIM based applications to the varying and frequently changing work processes of AEC professionals.

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Towards the Development of a Project Decision Support Framework for Adoption of an Integrated Building Information Model using a Model Server	270

Kerry London, Deakin University, Australia

Vishal Singh, University of Newcastle, Australia

Ning Gu, University of Newcastle, Australia

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Ljiljana Brankovic, University of Newcastle, Australia

This chapter discusses an action research study towards the development of a decision framework to support a fully integrated multi disciplinary Building Information Model using a Model Server. The framework was proposed to facilitate multi disciplinary collaborative BIM adoption through, informed selection of a project specific BIM approach and tools contingent upon project collaborators' readiness, tool capabilities and workflow dependencies. The framework consists of four inter related key elements including a strategic purpose and scoping matrix, work process mapping, technical requirements for BIM tools and Model Servers, and framework implementation guide. Eight case studies informed the development of the framework and a summary of the key findings is presented in this chapter.

Section 5

Green Building

Green issues and sustainability are firmly high on the global agenda. This is a major concern to the AEC industry which has a significant role to play in addressing these issues. This section examines the opportunities for BIM to facilitate the delivery of green and sustainable projects and ultimately leading to a green and sustainable industry.

Chapter 14

The Idealization of an Integrated BIM, Lean, and Green Model (BLG)..... 302

José L. Fernández-Solís, Texas A&M University, USA

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Idealization, “a very high level view”, is defined here as looking at the possibilities of integrating Green socially responsible requirements with Lean principles of construction practices with well-developed Unifying Models, such as Building Information Modeling (BIM). BIM, Lean, and Green (BLG) will allow a rapid prototyping of design and construction, the integration of drawings, specifications, and manufacturing in a Green best practice ambient that employs benchmarked Lean principles. This chapter explains authors’ propositions on Green as a concept that gives direction on what to do right (effectiveness), on Lean that captures how to do it right (efficiently), and on BIM as an enabling platform that will facilitate the implementation of this effort.

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Goh Bee Hua, National University of Singapore, Singapore

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Yonghui Song, University of Salford, UK

Jürgen Bogdahn, HFT Stuttgart – University of Applied Sciences, Germany

Andy Hamilton, University of Salford, UK

Hongxia Wang, University of Salford, UK

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Hongxia Wang, University of Salford, UK

Andy Hamilton, University of Salford, UK

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André Borrmann, Technische Universität München, Germany

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Norbert Paul, Technische Universität München, Germany

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Some urban management tasks such as disaster management, delivery of goods and services, and city-scape visualisation are managed by using Geospatial Information Systems as the current state-of-art, as the tasks in these processes require high level and amount of integrated geospatial information. Several of these tasks such as fire response management require detailed geometrical and semantic information about buildings in the form of geospatial information, while tasks such as visualisation of the urban fabric might require less geometric and semantic information. Today, service-oriented architectures are becoming more popular in terms of, enabling integration and collaboration over distributed environments. In this context, this paper presents a web service pattern enhancement that will help in facilitating information transfer from Building Information Models into the geospatial environment.

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Ning Gu, University of Newcastle, Australia

Vishal Singh, University of Newcastle, Australia

Claudelle Taylor, Nexuspoint Solutions, Australia

Kerry London, Deakin University, Australia

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This chapter presents a comprehensive analysis of the current state of Building Information Modelling (BIM) in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry and a reassessment of its role and potential contribution in the near future, given the apparent slow rate of adoption by the industry. The chapter analyses the readiness of the industry with respect to the (1) tools, (2) processes and (3) people to position BIM adoption in terms of current status and expectations across disciplines.

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Alex Gerrard, University of South Australia, Australia & Rider Levett Bucknall, Australia

Jian Zuo, University of South Australia, Australia

George Zillante, University of South Australia, Australia

Martin Skitmore, Queensland University of Technology, Australia

This chapter reviews the development of BIM, the extent to which BIM has been implemented in Australia, and the factors which have affected the uptake of BIM. More specifically, the objectives of this chapter are to investigate the adoption of BIM in the Australian AEC industry and factors that contribute towards the uptake (or non uptake) of BIM. These objectives are met by a review of the related literature in the first instance, followed by the presentation of the results of a 2007 postal questionnaire survey and telephone interviews of a random sample of professionals in the Australian AEC industry. In the chapter the main barriers impeding the implementation of BIM widely across the Australian AEC industry are also identified.

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James Harty, Copenhagen School of Design and Technology, Denmark

Richard Laing, The Robert Gordon University, UK

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Ali Murat Tanyer, Middle East Technical University, Turkey

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Jay Love, Degenkolb Engineers, USA
Robert Hazleton, The Herrick Corporation, USA

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construction information that is being produced now is making it possible to deliver better quality buildings. By reducing abortive works on site, buildings can be delivered on time and with reduced post construction claims and penalties. This chapter provides an overview to numerous different real-life cases from Hong Kong on the use of Building Information Modeling/Building Lifecycle Information Management.

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Foreword

We are in the early stages of a transformation in the facilities industry that will profoundly change the way humankind views and interacts with their built environment. This change, which is being triggered by building information modeling, will allow people to experience their built environment virtually through simulation prior to its physical manifestation. Building information modeling will allow building occupants to appreciate fully how a space will work prior to its actual construction so that they can be as productive as possible once it is built. When a facility is completed using building information modeling, it will also be optimized in its use of materials and energy, and minimize its negative affect on the environment. The facility will be in harmony with all aspects of its internal and external environment. Yet, today, far less than half of practitioners are even aware that this change is coming and even fewer facility users and owners are aware of the opportunity. We are only just beginning to get our message refined to a point where we are communicating to the practitioner and customer alike as to what is occurring, what is at stake, and the ultimate positive affects building information modeling can have on society.

Most of our effort to date has been involved with development of the massive technical foundation that the building information modeling transformation will require to succeed. The technologies converging to make all this possible are not just in the architecture, engineer, contractor, owner, operator (AECOO) community. They also include the internet; social networking such as email, LinkedIn, Facebook, and Twitter; high-speed computing; cloud computing; service-oriented architectures; vast amounts of inexpensive storage; three-dimensional (3D) graphics; and many other supporting tools and standards. But realistically, most people do not get involved with, or do not want to get involved with, the underlying technology.

At the Congress on the Future of Engineering Software (COFES) two years ago, a presenter held up an Apple iPod® in front of the audience and asked the audience what was inside the iPod®. Being a room full of engineers, the answers included flash memory, microprocessors, touchpad, video screen, etc. The speaker responded, “No! Music is what is inside an iPod®!” To the customer and consumer of the product, there is only music inside. Often we get captivated with how something works and not what the intended function is. I believe that we are in the same situation with building information modeling. While we are focused on collaboration, interoperability, and technology, all that the customer really wants is to have sustainable facilities delivered on time and on budget, that use as little energy as possible, and are easily maintained at a low lifecycle cost because it is less expensive for them. Nevertheless, if the customer is going to realize this dream, someone needs to work out the details, because, as everyone knows, the devil is in the details.

This book represents a step forward in documenting and communicating the business processes we need to implement building information modeling at the technical level. It is targeted at the practitioner

and technocrat who must understand what is needed to deliver the customer's dreams. If this documentation process does not occur, then the body of knowledge will not expand and we will be destined to more duplication of effort and little forward progress. To support this effort on a larger scale, the buildingSMART alliance is working to provide a clearinghouse for all research and development affecting the business transformation of the facilities industry. We are grateful to the authors of this compendium, which represent some of the most notable concepts and technologies from around the world, for doing their part to organize and coordinate a vast chunk of that information.

Sadly, despite this explosion of technology, thus far we are producing some rather poor facilities with a notable decline in sustainability in the past fifty years. We are also using much the same approach that we have used for the past several hundred years. We need to ensure that we do not simply add another layer of technology on an existing process. This is truly an opportunity for change, but it will not be realized if we do not have strong leadership to lift us out of the way we have always done business.

Given the scope of change that we envision, it is no wonder it is taking some time to accomplish. Even small change never comes easily. It is my belief that the true transformation will likely take a several generations to fully be incorporated into the way we do business. First, we have to overcome a lack of knowledge and understanding of the effort, as well as a fear of the unknown; and then allow enough time for interoperable application tools to mature and work together more effectively. Next, we need to educate an entire new generation of practitioners who can work together more cooperatively and collaboratively than the previous generations. I am envisioning a time when information is truly only created once and then re-used throughout the entire facility life cycle.

However, technology is only a manifestation of human creativity to solve problems once they have been identified as being problems. The process of reaching the manifestation of a solution conceived as a computer-based tool typically takes five years or more to accomplish. Therefore, we are currently dealing with new tools to solve old problems that were identified years ago.

The process seems to go something like this. Someone has a vision of how things could be better and documents the idea (Many of those visions are in this book). The vision is presented to someone who thinks that it might have some value. Then a company develops a software tool to deliver the idea or at least their interpretation of the idea. In many cases, the first product may only be a prototype or a concept that needs further research and development. Yet, even if the prototype is innovative, only a few of them are ever typically sold at this stage. There are a few exceptions to this where the initial product takes off and sells millions of copies. However, more often it takes far longer to reach a critical mass, if ever. Some examples of this are found in products like the radio, which took 38 years to sell 50 million items; the television, which took 13 years; Internet, 4 years; iPod, 3 years; and it only took Facebook 2 years to have 50 million users!

We need to learn from experience and converge information from many segments of society so as not to reinvent things. We are certainly learning from the information technology community, but we must also learn improved leadership and management skills, if we are going to succeed. We must have strong leadership in place to make this work.

Sadly, most segments of our industry remain focused on optimizing their own stovepipe, or as I have heard it said, 'creating cylinders of excellence.' Unless we can act as a complete industry then we will fail to take advantage of the opportunity in front of us. Will the leadership come from within or from outside? This is not to say there are not some strong leaders in place, it is just that they are not quite collaborating at the level required to optimize the transformation event. This needs to be one of the primary focus areas of the Alliance. We need to expand the base of leadership as well as develop the product.

In the European community, I recently heard a term, the “Lions Committee.” This is a committee made of the most powerful people in a facet of the industry. We need a “Lions Committee” for all aspects of the facilities community. Currently some users are voicing their frustration with how the facilities community delivers facilities. I believe there are many more silent folks who are just as frustrated with project delays and cost overruns that have not found a forum to jointly voice those frustrations.

This book dedicates a section to standards. If we look, we will find that at the base of every one of the massive transformation successes we have seen over the past few years has strong standards as the foundation. Standards should be foundational. They are not as successful if you implement them when you reach the top of an issue. For example, there is no one standard web page, standard email application, standard cell phone, standard global positioning appliance or standard music player, but there sure are open international standards that address the internet, email, cell phone, GPS, and MP3 players. Yet, each manufacturer is free to deliver all kinds of innovative bells, whistles, colors and shapes in the products they sell to the customer.

We must have that same level of standardization in our industry also. If one practitioner is going to use information from another, then they need to have confidence in what it is, how it was created, and how it is managed and protected until it is received by them. Data is the base of building information modeling; data that is used for planning, design, construction, fabrication, operations, maintenance, and sustainment by everyone involved. Hence, the focus on the international standard industry foundation classes (IFC). If we cannot rally around this and make it work for everyone, then we will fail. Nonetheless, IFC research and development is currently underfunded and the product is still underutilized. This is still another example of how our community and those supporting it are not working together in its best interest, but are too focused on capturing a small part of an even smaller market for themselves. If the market is expanded through the adoption of standards, there will be plenty to go around, everyone will flourish, and the industry transformation will be realized.

Of the many application issues it addresses, one aspect presented in the book, which needs separate focus, is the use of spatial information. Sadly, spatial relationships are a significantly overlooked facet of the solution we are seeking. Essentially, every piece of data has a spatial aspect. Quite possibly, the only exception is money, but even that has spatial aspects, as it is associated with projects, or distributed through banks or ATMs, which have locational importance. Spatial aspects of information and, especially, information about an object provide an exceptional filing system since location, like time, only allows one object to occupy a space or happen concurrently. You can use a mapping program to understand how one object relates to another spatially, but you may need to get fairly granular to view the results. Look to one of the many mapping programs on the internet to see an example of this. If you are zoomed out and ask for hotels in a certain city near a location, you will see that there are many, and it is not so easy to tell which is the closest. You need to zoom in to a street level before you see where each is. You can also see a tabular report of distance from the location as well as how much they cost and peoples’ ratings of the hotels.

We need not lose sight of information normalization either, as information must only exist in one location at a point in time. Normalization will ensure that we only enter data one time in a database. This again invokes the value of location along with time. In addition, not every instance of an object needs to carry all the information about the object; it just needs the information that is unique to that instance of the object. For example, a specific object’s maintenance schedule, not the prescribed preventative maintenance schedule, should be stored with the object. Only the maintenance that has taken place on that particular object is important to that object. You can see from this discussion that a shared infor-

mation network needs to be established and sustained. It should also be noted that sustainment is not a separate task, but part of a task. If you use the information to do the job, then it is self-maintaining. An example of this is the travel program where you select the seat for your next flight. When you select the seat, you are updating the database. Someone does not have to take your information and take another step to load the information. The same is true when one of the overnight carriers delivers a package to you. When the driver scans the box, he or she is updating the database and you are instantly able to see that update. This capability exists in many areas, it is just not in our industry quite yet.

Of course, the database technology described in the previous paragraph has not always been available; in fact, it is a rather recent development. Consider what went into delivering the capability to provide real-time tracking of your package, which is now widespread and used by millions worldwide. There are actually many technologies that had to be developed to make it happen, such as wireless, handheld computers; bar codes; etc. Then some innovative entrepreneur had to combine all of them into a configuration that would give you the capability to check your package online. It did not happen all at once nor was it perfect the first day it rolled out. This same type of innovation is beginning to occur in the facilities industry and we need to encourage its growth, accept the positive change, and embrace what it will bring to practitioners as well as our customers. This change in some cases will come rapidly and potentially disruptively, but it must come.

Many of these advancements will come from fresh eyes looking at old problems. Awakening those fresh looks at the issues will come from education. While training someone on how to use a tool that exists and ensuring proficiency in the use of the tool is critical for profitability today, it is education and the awakening innovation that will truly transform the industry. Here again we have a problem. Because our industry is not investing in research and development, many of the bright minds are turning to other better-funded investigations. I know of many Ph.D candidates who have chosen other fields because of two things: lack of funding for their graduate work and the lack of metrics to expand the body of knowledge. It is somewhat a Catch-22 situation. For, if the students are not doing the research and generating the results, then others cannot build on their results. We need to focus a significant amount of effort to ensure our education programs can turn out the innovative minds to apply the new ideas that will help transform the industry. Of course, we also need the visionary leadership to hire those folks and invest in their futures that will support not only those companies but benefit the entire industry.

I am also coming to believe that one of the best tools we have to document progress is the case study of facilities that have already been completed. However, we need to set up a structure so that we can actually obtain the valuable information contained within those projects. They are not just things of beauty but are truly sources of metrics to measure progress. Just as a stopwatch is used to measure the improvement of an athlete so should we use the metrics we keep on our facilities to measure progress. If we have no metrics then we cannot measure improvement. We do have some metrics in place, but we are not using them as evaluative tools effectively. You would not consider buying a car without knowing at least how many miles per gallon it was rated to achieve, though that may not be your only criteria. Ideally, it should be the same with a facility, but currently most of the performance data is not even known. We buy facilities and residences with no idea of how well they perform. While LEED certification, is a huge step forward in the right direction we still have a ways to go until we optimize any approach. Therefore, as we begin to collect case study information, we need to include its LEED rating. But what other performance criteria will we need to collect so that we can measure improvement? This and future books will begin to answer that question.

xxx

We have much work to do. Progress is slow, but progress is truly being made. This book represents yet another line in the sand marking the increasing body of knowledge that will move a whole industry ahead. I hope that reading it will spark the innovation in you to carry the torch forward.

Dana K. Smith, FAIA, Hon. FIGP

Dana K. “Deke” Smith is a registered architect, author, and is the Executive Director of the buildingSMART alliance, a council of the National Institute of Building Sciences dedicated to interoperable and open standards to ensure the flow of information throughout the facility lifecycle.

Preface

BEING LOST OR BECOMING LOST

When Oceanic Flight 815 from Sydney to Los Angeles crashed on a mysterious tropical island in the South Pacific, none of the survivors were aware that they were actually LOST in their own lives. Instead, they were concerned with being physically LOST on an abandoned island. In fact, after 5 years of the TV Show and over 100 episodes, viewers became to realize that these ‘Losties’ could only become aware of their difficult and mysterious situation after spending several years in and out of the island.

Although a fictional TV show, similarities can be drawn from when the term Building Information Modeling (BIM) was coined through the 1990s with a similar path of destiny for the users of the digital building models in the AEC industry beginning to emerge, leaving the industry (the BIM Losties of 2010) with many questions to be answered, such as:

- Were we not actually Modeling the ‘Building Information’ in the 2D CAD era, before the term ‘Building Information Modeling’ was brought to our attention?
- When working on BIM, are we trying to establish a standard shared digital building model, a new collaborative methodology for managing projects, or are we chasing to achieve a paradigm shift for the traditional processes of the industry?
- Will BIM help us to transform the production processes in a form that is leaner, greener, and where industrial functions can be digitally managed or will it only cause us (the users/stakeholders of BIM) becoming ‘LOST’ between the complexity of real life industry processes and modeling phenomena of the AEC universe?

Questions such as these have motivated us in a hopeful search for understanding Building Information Modeling, from its roots to its functions, from its capabilities to its possibilities. In the late 1990s, Building Information Modeling was prescribed as a remedy for the illness of ‘Data Interoperability’ in AEC industry. However, it is now apparent that this ‘*magic remedy*’ can cure much more ‘*illnesses*’ than it was originally prescribed for. It can also facilitate so many different functions of the AEC industry and even beyond, such as in Urban Management. In addition, Building Information Modeling is now becoming a key vehicle for transforming the paper based and heavily fragmented processes of the AEC industry. Having discovered the ‘magic’ that this new remedy can provide the industry is now heavily concerned with implementing it in many different fields. Despite the enormous amount of effort that is being carried out, it is still not very clear whether BIM will lead the industry to find its way and transform work practices to the desired collaborative form or it will just cause the industry to become ‘LOST’ in the AEC Modeling universe till eternity.

BUILDING INFORMATION MODELING

As readers of this book will be quite familiar with, the AEC industry is highly fragmented and thus integrated ways of working are always an apparent need for the industry. The Integrated Project Delivery (IPD) approach which recently emerged in US reflects the perspective on the future of project life-cycle management and project delivery. IPD encourages early contribution of knowledge and experience and requires proactive involvement of key participants. The IPD Working Definition (2007) states that Building Information Modeling is essential in efficiently achieving the collaboration required for IPD. Input from the broader integrated team coupled with BIM tools to model and simulate the project enable the design to be brought to a higher level of completion before the documentation phase is started. Thus, the project is defined and coordinated to a much higher level prior to the start of construction, enabling more efficient construction and a shorter construction period. From an Integrated Project perspective Building Information Modeling can be defined as:

The information management process throughout the lifecycle of a building (from conception to demolition) which mainly focuses on enabling and facilitating the integrated way of project flow and delivery, by the collaborative use of semantically rich 3D digital building models in all stages of the, project and building lifecycle.

BUILDING INFORMATION MODELS

As mentioned earlier, the Building Information Modeling process is unique as it is based on digital, shared, integrated and interoperable Building Information Models. Thus, Building Information Modeling can be defined as the process and facility that enables information management, while Building Information Model is,

the (set of) semantically rich shared 3D digital building model (s) that form(s) the backbone of the Building Information Modeling process

Based on a review of a variety of academic and industrial resources, Isikdag *et al* (2007) have identified the definitive characteristics of Building Information Models as being;

1. *Object Oriented*: The models are defined in an object-oriented nature.
2. *Data-rich / Comprehensive*: Models are data rich and comprehensive as they cover and maintain all physical/functional characteristics and states of the building elements.
3. *Three dimensional*: Models always represent the geometry of the building in three dimensions.
4. *Spatially-related*: Spatial relationships between building elements are maintained in the BIMs in a hierarchical manner (allowing for several geometric representations such as Constructive Solid Geometry, Sweeping and BRep),
5. *Rich in semantics*: Models maintain a high amount of semantic (functional) information about the building elements. And finally,
6. *Models support view generation*: The model views are subsets or snapshots of the model that can be generated from the base information model. The model views can be automatically derived with respect to the user needs.

Although BIM is the key enabler of the IPD process, BIM goes beyond the management of information in the IPD process in that the process concludes with the closeout stage following construction, while the BIM process continues even beyond the demolition (disposition) stage, i.e. as a process of knowledge management for future projects.

Depending on the environment they are used, Building Information Models can have different functions such as being a *Space Linker* that links macro and micro urban spaces, an *Interoperability Enabler* which facilitates information sharing between various stakeholders and the software applications they use, a *Data Store* which stores the building information throughout the lifecycle of a building, a *Procurement Facilitator* that facilitates several procurement related tasks in the building lifecycle, a *Collaboration Supporter* through enabling the use and management of shared building information in real-time, a *Process Simulator* by facilitating the simulation of construction processes (i.e. @ nD), a *System Integrator* which enables the integration of several information systems across the industry, a *Building Information Service* which can serve real-time on-demand building information over the internet, a *Green Builder* that enables advanced analysis supporting the design and construction of environment friendly/energy efficient buildings, and a *Life Saver* which facilitates emergency response operations.

THE HANDBOOK

The Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies focuses on providing an up-to-date comprehensive and collective perspective of both the latest leading-edge research along with the current understanding and practice in the area of BIM and Construction Informatics within the global construction industry. The overall objectives of the handbook are to:

- Provide a unique comprehensive and collective perspective of BIM to-date along with the opportunity to initiate the debate towards an agreed definition.
- Bring together the current collective body of knowledge of academic research with that of industry understanding and practice in order to provide a holistic picture of Building Information Modeling within the industry.
- Provide contrasting and comparative perspectives on the latest leading-edge research from academia with the understanding and practice of both the AEC and other related knowledge domains.
- Provide a future reflection of the direction for BIM in identifying the barriers and addressing their resolve.

In order to meet these objectives the editors chose to select as many diverse perspectives as possible. *The Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies* brings together a broad field of experts from civil and mechanical engineering, architecture, computer science, software engineering, geographical information science, urban planning and management, and surveying. Additionally, the *Handbook* maintains a global approach in that the contributors are scholars and professionals from *Australia, China, Denmark, Germany, Hong Kong, Netherlands, Norway, New Zealand, Singapore, Slovenia, Taiwan, Turkey, U.K.* and the U.S. with diverse research perspectives utilizing both qualitative and quantitative methodologies. A world of authors from academia and industry and an array of research methods presented contributed to the extraordinary

quality of the chapters addressing this very timely topic of Construction Informatics which has begun to pick up pace.

CHAPTER FEATURES

Within the *Handbook* the expertise, knowledge, wisdom, scholarship, and talent of the authors are shared with the reader in nine sections. The organization of the chapter generally follows this format: abstract, introduction, background, body, conclusion, references, key terms and definitions. The *Handbook* is organized as follows.

Section 1: Introduction

This first section concentrates on exploring the conceptual aspects of both BIM and Building Information Models including examining the purpose of Building Information Models. The concepts of what is actually being modeled and the way in which these can be modeled are discussed in this section. This is complimented with the perspective of Architectural Design being presented. The Handbook begins with *Chapter 1* of van Nederveen, Beheshti and Gielingh discussing the Modeling concepts of Building Information Modeling by addressing questions such as What is Building Information Modeling? , What is a Building Information Model? along with the rationale and objectives of a Building Information Model. In the following chapter, *Chapter 2*, Çetiner provides an introductory review of Building Information Modeling from an Architectural Design perspective. In the chapter, she also discusses the capabilities of several different Building Information Modeling tools.

Section 2: Adoption

Adopting the BIM approach is not just about the technology but is also highly dependent on other ‘non-technical’ factors relating to people, process, organisational structure, work environment, etc. The focus of this section is towards exploring the issues associated with the readiness and maturity of organisations in preparing themselves for the successful adoption of BIM. The section begins with *Chapter 3*, whereby Bew and Underwood, from the premise that BIM does work and adopting such an approach in the competitive UK market is worthwhile, focus on exploring the aspects of an awareness of what is involved, understanding the evolution, and taking sensible steps to achieve the reward towards the delivery of BIM to the UK construction market sector. In *Chapter 4*, Succar in the first stage explores the multi-dimensional nature of the BIM domain and then introduces a knowledge tool BIM Maturity Matrix (BIm³) to assist individuals, organisations and project teams to assess their BIM maturity and improve their performance.

Section 3: Standards

A key element to BIM which is firmly fixed in its origin is that of standards. This section is concerned with standards from two particular aspects. The first is that of product modeling within the AEC sector in terms of an extensive historical review, the characteristics of several conceptual approaches together with the implementation of their constructs, and finally future trends through a number of on-going research

projects. The second aspect is a recent national standard which has been set up in the US is examined in relation to the current and future strengths, weaknesses, opportunities, and impact. In *Chapter 5*, Dado, Beheshti and van de Ruitenbeek provide a synopsis of product Modeling history in the Building and Construction (BC) industry based on the authors' experiences gained from various conducted research projects and also taking into account results of other research projects. After this historical overview, an analysis of the characteristics of interesting conceptual product Modeling approaches are presented and discussed. In the following chapter, *Chapter 6*, Suermann and Issa provide an overview on the strengths, weaknesses, opportunities, and impact of the National BIM Standard (NBIMS) into 2009 and beyond. The chapter focuses on some of the strengths of the NBIMS such as promulgating a standardized approach for documenting information exchanges between stakeholders, and applying the NBIMS Interactive Capability Maturity Model (I-CMM) to evaluate a project or portfolio for BIM maturity.

Section 4: Applications

This section focuses on various aspects of applications in support of the BIM process including proposed technology developments, new approaches to applications development, and conceptual implementation frameworks. The section starts with *Chapter 7* authored by Yu-Cheng Lin, which presents a pilot study on the use of Building Information Models for management of the construction/mechanical/electrical interfaces in a project. The chapter also provides an overview of a CAD-based Interface Management (CBIM) system developed during the study. The CBIM system is later applied in Taiwan to demonstrate the effectiveness of BIM in Interface Management. *Chapter 8* is authored by Olatunji and Sher and reviews the impacts of BIM on cost estimating procedures. In order to develop a conceptual framework for underpinning BIM-propelled changes in estimating practice, Computer Aided Estimating applications are categorized and compared. In addition, some features for producing automated quantities from BIMs are compared with provisions of standard methods of measurements used by estimators. In *Chapter 9*, Rebolj, Čuš Babič and Podbreznik describe methods of automating the monitoring process of a construction project before concentrating on a solution which takes into account all three aspects of project management: coordination, control and communication. In this solution the activity progress is monitored directly by using a combination of data collection methods, which are based on the Building Information Model, especially on the 4D model of the building. *Chapter 10* is authored by Spearpoint who first looks at what fire engineers would like to achieve and how BIM fits in with those goals. The chapter later discusses the types of fire simulation models that fire engineers use and provides a brief description of two particular fire growth models which use different means to represent a fire scenario. The chapter finally considers how the IFC building product model can be used to transfer building geometry and property data to fire simulation models. In the following chapter, *Chapter 11*, Olatunji and Sher review some of the capabilities of BIM which may revolutionize conventional practices in FM. The authors outline that the capabilities provided by BIM such as project visualization, simulation, auto-alert and value intelligence may stimulate major improvements in facilities management processes. *Chapter 12* is authored by Hartmann who presents a different method to design software - context sensitive software development – and he indicates that it is possible to enable application developers to adjust BIM based applications to the varying and frequently changing work processes of AEC professionals. In the final chapter of this section, *Chapter 13*, authored by London, Singh, Gu, Taylor and Brankovic, an action research study towards the development of a decision framework to support a fully integrated multi disciplinary Building Information Model using a Model Server is discussed. The Framework consists of

four inter-related key elements including a strategic purpose and scoping matrix, work process mapping, technical requirements for BIM tools and Model Servers, and framework implementation guide.

Section 5: Green Building

Green issues and sustainability are firmly high on the global agenda. This is a major concern to the AEC industry which has a significant role to play in addressing these issues. This section examines the opportunities for BIM to facilitate the delivery of green and sustainable projects and ultimately leading to a green and sustainable industry. In *Chapter 14*, Fernández-Solís and Mutis explain their propositions on Green as a concept that gives direction on what to do right (effectiveness), on Lean that captures how to do it right (efficiently), and on BIM as an enabling platform that will facilitate the implementation of this effort. BIM, Lean, and Green (BLG) will allow a rapid prototyping of design and construction, the integration of drawings, specifications, and manufacturing in a Green best practice ambient that employs benchmarked Lean principles. The following chapter, *Chapter 15*, is authored by Goh Bee Hua and focuses on describing (a proposed) rule-based system that contains decision-support rules pertaining to the assessment of (whole-life) cost to support ‘Green Building’ concept decisions.

Section 6: Spatial Applications

In recent years, the benefits of integrating the traditionally isolated areas of building and geo-spatial information have begun to be explored. This section focuses on current research efforts towards integrating BIM at the urban scale along with an industry perspective on the value that it can realise. In the first chapter of this section, *Chapter 16*, Song, Bogdahn, Hamilton and Wang review recent research into the integration of geo-spatial and building information from the perspective of an EU project focused on developing a Virtual Environmental Planning System. In the following chapter, *Chapter 17*, Wang and Hamilton provide an insight into their work on the design and development of a BIM web service - Building Feature Service (BFS) - which is defined to retrieve building information similar to OGC web services (used for retrieving geospatial information). In *Chapter 18*, Borrmann and Rank introduce a spatial query technology for BIMs that has been developed by them. The developed technology allows users and third-party application programmers to not only analyze the digital building under specific criteria but also to extract partial geometric models on demand from a full building model. *Chapter 19* authored by Paul, presents a generalizing concept which handles both “local” and “global” connectivity information (of geometric representation of the objects) in a common way and provides methods to mutually relate them in Building Information Models. The Chapter 20, authored by Isikdag, Underwood, Kuruoglu and Abdul-Rahman, presents a web service pattern enhancement that will help in facilitating information transfer from Building Information Models into the geospatial environment. In *Chapter 21*, Peters explores the value of integrating BIM and Geospatial Information Systems into a single system from an industrial perspective, and how this integration can be achieved.

Section 7: State of the Art

This section explores the current state of BIM in the AEC industry. The focus is on the positioning of BIM adoption across disciplines in relation to their current status and future expectations which are based on such factors as the tools, people and processes. The extent to which BIM has been implemented and

the factors currently both facilitating and impeding adoption within the Australian AEC industry are also explored. In the first chapter of this section, *Chapter 22*, Gu, Singh, Taylor, London and Brankovic present a comprehensive analysis of the current state of Building Information Modeling (BIM) in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry. *Chapter 23* is authored by Gerrard, Zuo, Zillante and Skitmore and reviews the development of BIM, the extent to which BIM has been implemented in Australia, and the factors which have affected the up-take of BIM.

Section 8: Training and Education

This penultimate section focuses on aspects of education and training which are becoming increasingly important in facilitating industry-wide adoption through increasing industry awareness along with the development of professionals with the necessary capability and skills. In *Chapter 24*, Harty and Laing review the barriers to BIM adoption from a training/education perspective, and indicate that an emerging professional, the Architectural Technologist, can bridge that divide and adopt the adjunct role of manager in the IPD. In the following chapter, *Chapter 25*, Tanyer presents the design and evaluation of an undergraduate course which aims to convey both the theoretical and practical principles of integrated design. In this new course, students aim to deliver a design project collaboratively by exchanging data between applications. The evaluation of the course has revealed various barriers related to implementing integrated design principles at educational programs.

Section 9: Case Studies

With BIM now being widely adopted across the globe and on a variety of projects, this final section introduces a number of real-life cases. Through these cases various issues to adopting a BIM approach together with the realised benefits and lessons learned are discussed. *Chapter 26* is authored by Moum and investigates the main factors affecting the practitioners' use of BIM, and how BIM impacts their work and interactions. The author presents a holistic research approach as well as the findings from its application in four real-life case studies. In *Chapter 27* Lostuvali, Love and Hazleton discuss the synthesis of lean production principles and techniques applied in AEC forming the basis for a Lean Project Delivery System™ (LPDS). The authors then present a case study which provides an overview of the synergy between the principles and tools of LPDS with BIM technologies. The *Handbook* concludes with *Chapter 28* authored by Riese which provides an overview to numerous different real-life cases from Hong Kong on the use of BIM / Building Lifecycle Information Management.

Jason Underwood and Umit Isikdag
Editors

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First and foremost, we would like to express that it has been an absolute privilege to have worked with so many esteemed people on this *Handbook*. The editors wish to thank all of the authors for their intuitive and insightful contributions. Without their excellent work, support and patience the *Handbook* would not have happened. As editors we would also like to acknowledge the valuable efforts of those of you from the academic community involved in the review process, without whom the project could not have been completed. Our profound gratitude goes to the publisher IGI Global and its President Dr. Khosrow-Pour. In particular, the editors wish to acknowledge Jan Travers, Kristin M. Klinger, Julia Mosemann, Joel Gamon, Rebecca Beistline, Beth Ardner, Jamie Snavely, and Sean Woznicki for their professional dedication to the project. Our final thanks go to our families, Juliette Leeks and Dr. Ugur & Zuhal Isikdag for their excellent support, encouragement and patience during this process. To all those who have helped this book to come to fruition: thank you for your generous support, patience, and encouragement.

We would like to dedicate this Handbook in memory of Professor Jeffrey Wix, in recognition to his unfaltering enthusiasm and dedication to the area of BIM and his significant contribution in taking it forward. He was a leading developer of the IFC standard and acted as a member of the Editorial Advisory Board for the *Handbook*.

“Jeffrey Wix was an engineer with extensive experience on the development of integrated ICT solutions for the building construction industry. He focused on the development and use of information development strategies for industry and government. He led the development of the IFC 2x Model, and was a member of the buildingSMART Model Support Group. He also led work on defining the connection between building construction and GIS through the IFC for GIS project. He participated in various UK national projects on product libraries, e-Safety and public health. He was a member of the core team that developed the ISO 12006-3 standard on dictionaries for construction products and services and was the original author of the Information Delivery Manual (IDM) which specifies the delivery of project data for specific business processes. In 2006, he received a recognition award from the US National Institute for Building Sciences for his contribution to the development of IFC and related technologies. Jeffrey passed away on Saturday, 4th of July 2009.”

Section 1

Introduction

Chapter 1

Modelling Concepts for BIM

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ABSTRACT

Building Information Modelling (BIM) is potentially a great technology for the expression of knowledge, supporting interoperability and communication throughout the life-cycle of a building. In fact, Building Information Modelling is not a simple technology. It requires a sound understanding of a number of abstract modelling concepts. Next to being a technology, BIM can also be regarded as a method for making a low or non-redundant (i.e. with every fact represented only once) model of an artefact that is sufficient to realize it as well as simulating it before it actually becomes physical reality. This chapter discusses the modelling concepts of BIM: what is Building Information Modelling, what is a Building Information Model and what are its rationale and objectives? A clear distinction will be made between (a) that what is being modelled, such as requirements, function, boundary conditions, building configuration, connectivity, shape, processes lifecycle aspects and discipline views, and (b) how it can be modelled, such as through parametric models, part libraries, nD models, various representations and presentations, including visualizations. Finally, there is a brief discussion of relevant methods and languages for information modelling, such as ISO 10303 (STEP, EXPRESS), BuildingSMART (IFC, IFD and IDM), process modelling and recent ontology-based approaches.

1 INTRODUCTION

Building Information Modelling (BIM) has become a major understanding in building research and innovation of recent years. It used to be a specialist

area within a group of experts working on research issues. But over the past few years, many software vendors as well as design and construction companies have been investing in the development and use of the technology. Although investments are relatively low and usage is mostly restricted to 3D

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design tools, this is expected to change once the industry sees the potential benefits.

Introduction of BIM is often accompanied by a lot of confusion. This is for a considerable part due to the fact that BIM requires abstract and conceptual thinking as well as the knowledge of a number of abstract modelling concepts that are commonly used in BIM.

This chapter discusses the most common modelling concepts of BIM. First, a few fundamental principles of BIM are explained: *What is Building Information Modelling?*, *What is a Building Information Model?* and *What are the rationale and objectives of BIM?* Next, a number of concepts are discussed that are commonly used in building information models, such as composition, configuration, connectivity, parametric modelling and part libraries, functional requirements, discipline view models, modelling of building spaces, modelling of shape, and modelling of life-cycle views. Finally, there is a brief discussion of relevant methods and languages for building information modelling, such as ISO 10303 (STEP, EXPRESS), BuildingSMART (IFC, IFD and IDM), process modelling and recent ontology-based approaches.

This chapter does *not* discuss implementation issues or experiences. The chapter is of conceptual nature, for discussion of implementation issues, industrial experiences, best practices, etc. please refer to other chapters in this book.

2 BIM PRINCIPLES

2.1 What is BIM?

There is no general consensus about what the term “Building Information Model” means. For the purpose of this book we define it as

“a model of information about a building (or building project) that comprises complete and sufficient information to support all lifecycle pro-

cesses, and which can be interpreted directly by computer applications. It comprises information about the building itself as well as its components, and comprises information about properties such as function, shape, material and processes for the building life cycle”.

The key difference with older technologies is that the building information will be stored explicitly in a formal, computer-interpretable way. Drawings, for example, are primarily intended for human interpretation. Information contained in drawings can be ambiguous because they contain redundant information: every fact may be expressed more than once. This causes the danger that information may be or become inconsistent, especially during change processes. Drawings do not contain sufficient information either, for instance process information or the rationale behind design decisions is not captured. In contrast, an ‘ideal’ BIM has every fact expressed only once (i.e. it is non-redundant) and acts as a master model for possibly derived models that do contain redundant information. This is because redundancy in practice can never be fully avoided, and is often required for different application or discipline views.

Although the term ‘Building Information Modelling’ and the abbreviation BIM are only common since about 2002 - after publications by (Laiserin, 2002) - the concepts and ideas are much older. In the eighties and nineties more commonly used terms¹ for the technology that we presently call BIM were ‘building product modelling’ or ‘product modelling of buildings’ (Eastman, 1999; Proceedings CIB W78).

These terms also show the relationship with a more generic technology: product modelling. A product model can be described as ‘a digital model of a product ...’, etcetera, similar to the definition given above for building information model. Product modelling is applied in many industry sectors, such as mechanical engineering, aerospace,

automotive and shipbuilding. Many principles of BIM originate from this product modelling technology, and/or have been more extensively applied earlier in other industry sectors.

The objective of these technologies is to enable users to develop a digital model of a product, which is in our case a building, and the model itself contains information. Information is on its turn defined as data (i.e. numbers, characters) with an associated meaning. This meaning is defined through information models. Information models are on their turn expressed in terms of a language. For the original specifications of STEP and IAI/IFC the EXPRESS language was used. Although there are today more powerful alternatives available, such as object-oriented and ontological languages, the idea remains roughly the same. Hence, it is important to keep the distinction in mind between the modelling of products (which is the ultimate goal of this technology) and the modelling of information about products (which is an enabler for the first).

2.2 Why BIM?

As mentioned above, the goal of BIM is to have a sufficiently complete set of information about a product which is formal (and thus computer-processable), consistent, non-ambiguous and non-redundant. This resolves problems that are currently caused by inconsistent information, of which the meaning can be interpreted differently by different experts or information systems. It is estimated that many process delays and errors are caused by inconsistent and ambiguous information today. In fact, many of the current quality control processes (checking, verification) are needed to avoid such errors, and will thus become obsolete. Moreover, BIM paves the way for (semi)automated execution of many processes. 3D digital designs are already used for computer numerically controlled manufacturing in many industries.

Explicit storage of building information enables meaningful exchange and sharing of build-

ing information between all involved in, affected by or can exert influence on a building project, throughout the entire building project life-cycle. This provides a state of constant transparency of processes and functions in order to reduce process conflicts, information clashes and information redundancy. This is achieved, amongst others, by standardisation of building information in a BIM.

BIM supports also the design and engineering process directly. A digital model of a building can be used directly, or through the (semi) automated generation of derived, application specific models, for analysis and simulation purposes. Virtual reality is one of the spin-offs of this technology. Hence, BIM can form a strong basis for a powerful design and engineering system with advanced ‘intelligent’ functionality. In this case effective support of the design process is the aim of BIM, whereas communication and standardisation is of less importance.

Part of the BIM philosophy is thus a belief in open systems and open standards. Closed systems can be very effective, but in the long run they can lead to supplier-dependency and to outdated systems that are difficult to upgrade.

The use of conceptual models is helpful for the development of open systems and standards. In a conceptual model, the emphasis is on *what* information should be in the system or standard, not on *how* the information structures are implemented.

3 MODELLING CONCEPTS FOR BIM

In the following paragraphs a number of common concepts and principles for Building Information Modelling are discussed. First some generic principles that are found in most product modelling approaches are discussed, i.e. the ‘central model’ principle and the concept of object orientation. Next, some basic principles for the modelling of physical objects and structures are discussed, these

Figure 1. The number of interfaces between nodes (or models) can be reduced by the use of a central node (or central model/kernel model/core model)



can be seen as a minimum set of principles that is needed for a model of the physical characteristics of a building. Following that, a number of additional concepts are discussed that go further than physical characteristics such as standard parts, libraries, parametric objects, requirements, functions, activities, discipline views, spaces, shape, and life cycle views.

3.1 The 'Central Model' Principle

A very basic principle for standardisation is the 'central model' principle. The idea is that if you want to interconnect a large number of nodes, you can reduce the number of interfaces by creating a central node. The nodes can be models of different applications, domains, or disciplines. The central node can be called the central model, or core model, or kernel model, etc. The principle is visualized in Figure 1.

Without a central node (left picture) the number of interfaces between n nodes is $n*(n-1)$, whereas the number of interfaces with a central node is reduced to $2n$.

This principle has been used for many years as an argument for the adoption of neutral standards. The rationale seems simple: instead of having to develop, for each individual computer application, interfaces with many other computer applications, only a single interface would be sufficient. In practice this is however a more complicated matter, as there may be many different sources

from which an application can import information, and many different targets towards it can export information. A single standard that could handle all of these targets and sources would necessarily be huge, in any case larger than what can be handled by each individual application. What will be implemented is therefore always a subset of such a large standard, and the question then becomes whether this subset is adequate for the required communication. This problem formed the reason for ISO 10303 to split the standard into manageable chunks called Application Protocols (AP's). And as these AP's appeared in most cases still too big, they were further split into Conformance Classes (CC's) for each anticipated kind of communication. This brings us halfway back to the left diagram in Figure 1. Only by specifying the various AP's and CC's using a shared set of resources, a degree of consistency could be accomplished. But as the meaning of information is often determined by context, it is questionable whether loss of information and/or loss of meaning can be avoided by the exchange scenario.

Also the sharing of data via a shared database is not sufficient, as the semantics of the data in an application context cannot be sufficiently guarded by a database management system. This is why today other scenarios are investigated. A scenario that gains interest is based on Service Oriented Architecture's (SOA). No longer will information be exchanged or between applications, but all users are offered one and the same application that is

made accessible via the internet. This avoids different interpretations of the information by different applications. But this solution does not yet solve the problem of information exchange or sharing between applications of different kind. For the latter problem, the development of ontologies is a possible solution. Ontology is not just a specification of the semantics of knowledge objects, but it is also an executable that can be made available on the internet for access by multiple applications. The ontology then ensures a consistent semantic interpretation of the data by all applications.

For the modelling of buildings or other products, even this is not sufficient. As stated here earlier, the goal of a BIM is to capture sufficient, consistent, non-ambiguous and non-redundant data. This means that, for every fact to be contained in the model, only one copy (and only one representation) can be accepted as the ‘master’- copy. Other expressions of this fact must be considered as ‘derived’ or ‘secondary’ copies.

Interestingly, what these scenario’s share, is that they can be depicted by the right-hand diagram of Figure 1. However, the node in the middle means something different in all cases. It may mean a shared application in the case of Service Oriented Architecture, a shared ontology for the sharing of semantic specifications, or a shared fact that avoids duplication of information in a building or product model. It is of importance to keep all these different meanings in mind when designing and implementing a BIM environment.

3.2 Object Oriented Modelling

As said above, product models and Building Information Models try to store all kinds of product characteristics in an information model. This approach fits quite well with the basic concepts of object oriented programming and modelling.

Object orientation means in simple words that everything is seen as and modelled as objects: objects with properties and behaviour. Of course, discrete products and product parts such as build-

ings, walls, floors etc. can well be described in terms of objects with properties and behaviour. But in the case of non-discrete or non-physical phenomena this is more difficult. For example: can natural phenomena that affect a building such as wind, rain, flows of water, solar radiation and habitant behaviour be ‘objectified’?

Concepts that are associated with object-oriented modelling are classes and instances, encapsulation, inheritance and polymorphism. Especially class/instance (the distinction between class descriptions for generic object information and instance descriptions for information of individual objects) and inheritance (the use of super classes and subclasses, with generic properties defined in the super classes) are key concepts in Building Information Models. There is a lot of literature on object oriented programming and modelling in which the concepts are described much more extensively, for example in (Booch, Rumbaugh and Jakobson, 1999).

3.3 Modelling Physical Objects and Structures

Building information models can become very complicated. A good way to start a simple Building Information Model is to initially stick to physical objects and structures of a building. For example:

- Building objects: such as walls, windows or floors and their properties
- Connections, relations or dependencies between these objects
- Composition levels (wholes and parts): building, building section, building element, building component, or similar
- Building systems: structural system, heating system, etc.

With these physical concepts it is already possible to capture a lot of building information. At the same time, however, the first building model-

ling issues emerge. For example, composition is easily described as the relationship between an object and its constituent parts. But what does this exactly mean? Is the whole the same as the sum of all its parts? Can objects be part of multiple composition structures? Can there be overlapping composition structures?

Composition structures relate to systems thinking. A distinction can be made between subsystems and aspect systems (Van Nederveen, 2001). In a subsystem approach, a building is composed of parts that share a (geographical or spatial) location: the northern part of a building, the top floor, etc. In an aspect system approach, a building is composed of parts that share an aspect of role. Often such aspect systems perform a distinct function, and are therefore called functional systems. An early and influential example of such functional system decomposition can be found in Turner (1989). Especially for domains such as building physics and installations, this approach is often found useful; see for example the models of the COMBINE project (Augenbroe, 1995).

These issues show that a very simple Building Information Model can already generate difficult modelling issues. Therefore sometimes people decided to keep a Building Information Model as simple as that for pragmatic reasons: they wanted to develop a simple robust model, implement it and use it in a fairly short time. An example of this is the Object Tree approach that is used in Dutch infrastructure projects (Van Nederveen, 2001). In many other (research) projects however, a number of other building information concepts are used, which will be described below.

3.4 Standard Parts, Libraries and Parametric Objects

Buildings normally contain many identical parts, or parts that belong to a product family, such as doors, windows, façade elements, and HVAC installation components. Only position and orientation are different for every occurrence (and

maybe identification or serial number). Therefore it is worthwhile to store common information of these identical parts in a standard part description, and store this in library.

This way of working is very common using CAD systems. Any CAD user who is working in the building industry knows and uses this. It should be noted that this way of working is compliant with the class-instance mechanism as used in object-oriented modelling.

The concept of standard part libraries is also useful in Building Information Models. But it can become complicated. First of all, many Building Information Models are defined as class descriptions: they do not describe a specific building, but a building class (or type). In this case, the model expresses statements such as ‘a building can have multiple storeys’. When you want to express something about standard parts, you get something like ‘a façade can have windows, each of which is defined in a standard parts library’. Then, if you look in the standard parts library model, you should find similar expressions on a more generic level. In other words, you get multiple levels of classification and genericness. To our knowledge, most building information modelling work normally stays away from these complications. Also the ISO STEP standard does not address it, but the related standard PLib does indeed.

Another complication occurs with parametric definitions. These are definitions where variables do not have a fixed value, but a parameter that can be valued when the parametric object is placed (or instantiated). For example a wall can have a thickness of 100 mm, a height of 3000 mm and a parametrically defined width of w mm. The value of w is only determined when this wall is placed (instantiated) in a building context.

In advanced CAD systems, parametric objects are common. In Building Information Modeling, parametric definitions are, again, complicated things to handle. This might explain why users have more difficulties with parametric applications than classic geometric modelling systems.

Yet another complication comes up when information is needed on the occurrence level. As stated above, information about different occurrences of the same standard part may be limited to the position and orientation of the occurrences. But in the work planning, construction, operational and maintenance stages, it can be useful to monitor the properties and status of the various occurrences. For example part A might be used much more intensively than part B, so it makes sense to swap them, such as is common practice with car tyres. This means that there are two kinds of standard part information: firstly the information that is the same for all occurrences of the standard part, secondly the information that is different for the different occurrences, such as position, orientation and status. This issue is further elaborated by Gielingh (2008).

3.5 Modelling Requirements, Functions and Activities

In the previous paragraphs only concepts have been discussed that define building objects from a physical or technical viewpoint. A building consists of storeys, rooms, walls, floors, windows, etc. All of these objects have properties, such as dimensions, material, etc. But nothing is said yet on *why* a building consists of elements *xyz*, or *why* a wall had dimensions *pqr* and is made of material *abc*. This kind of information is normally defined in terms of requirements and functions. Information on requirements and functions is essential when one needs to design or evaluate a building. Also for example for maintenance purposes it is very useful to not only know the physical properties of a building part, but also the (intended) function of the part, as well as the requirements it was designed and built for.

Initially, the modelling of requirements can be rather straightforward. Common structures used in building specifications can be used. In Systems Engineering literature a lot of knowledge has been developed on working with and structuring of

requirements. Examples are the decomposition of requirements, distinction between user requirements and system requirements etc.

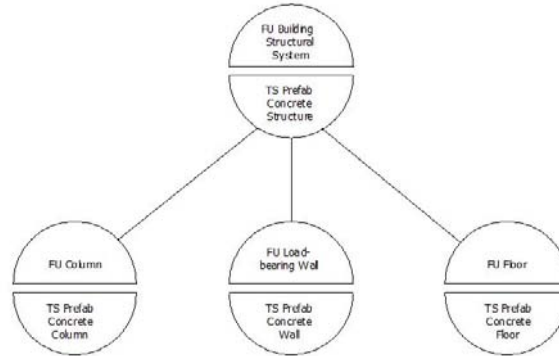
But the difficult part comes when one tries to link requirements to physical objects. If requirements and physical objects are modelled independent of each other, then the link between the models is almost certainly a complicated many-to-many relationship, which is very difficult to manage. This is because an object is normally designed with several requirements in mind, and, reversely, a requirement is normally fulfilled by several objects.

A well-known approach to deal with the relationship between requirements and physical objects is the Functional Unit/Technical Solution approach (FU/TS) as described in the GARM by Gielingh (1988). In this approach, building information is defined in terms of Functional Units and Technical Solutions. Functional Units (FUs) describe objects ‘as required’ and have ‘required characteristics’. Technical Solutions (TSes) describe objects ‘as designed’ and have ‘expected characteristics’. It should be noted that FUs and TSes have a one-to-one relationship; one can say that the FU and TS describe different views on the same object. When this approach is followed systematically, it will result in a well-structured and manageable Building Information Model.

Moreover, the GARM combines the FU/TS approach with composition and decomposition. This is done as follows: An FU is fulfilled by TS; TSes decompose into lower level FUs; these FUs are in turn fulfilled by lower level TSes, etc, see Figure 2.

A slightly different approach for the linking of requirements with physical objects is by using the concept of *function*. A physical object has a function, and from that function, specific requirements are derived. In the GARM, function means basically the role that a component plays within a system (the larger whole). The FU defines constraints and boundary conditions for a ‘TS’, such that the ‘TS’ can interoperate with other TS’s.

Figure 2. FU/TS Decomposition as proposed in the GARM



Technical Solutions can play different roles (and thus have different functions) depending on the system of which they are part. A TS can have an ‘intended function’, but its actual function depends on its usage, and is thus determined by the FU.

Another meaning of the term function may be the *intended* role of an object. In the function-structure-behaviour model that is proposed by Gero (1992a, 1992b), function is associated with structure and behaviour.

Yet another way to deal with requirements, especially in buildings, is to start from *activities*. The purpose of a building is normally the housing of activities. So one can start with the definition and modelling of activities, and work from there towards the physical objects. For this purpose it is necessary to pay special attention to the modelling of building spaces. This will be further discussed in 3.7.

3.6 Modelling Discipline Views

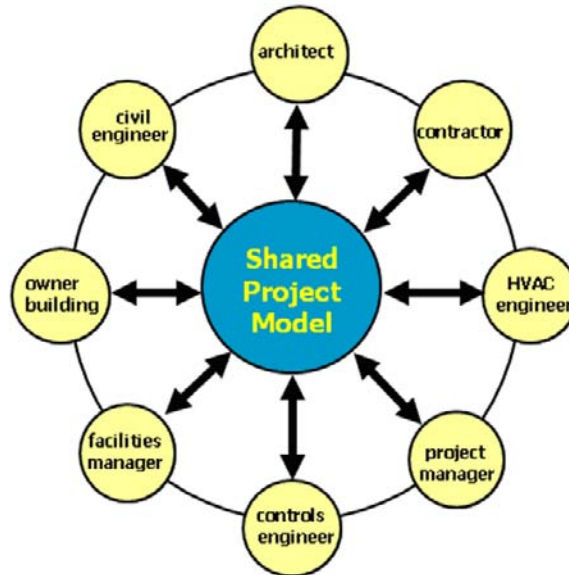
In the previous paragraphs of this chapter, the Building Information Model has been considered as a model that could serve anyone’s needs. As practically all disciplines in construction ‘see’ walls, floors and windows, a Building Information Model has to support these concepts.

In practice, however, different actors in a design project have different interests. In order to keep their models of a building as simple as possible, they ignore many aspects and details that are considered as irrelevant. These abstractions are called *views* on a building model. Architects have different interests than structural engineers, and thus have different views. This could be supported by different view-specific building information models with only the information that is needed. But as disciplines have to collaborate, they must also use a shared building project model. This idea is depicted in Figure 3.

In order to support construction projects in an efficient way, local view models must be defined, in which the building information is described in an adequate way for the each user. For example, the architect’s view model should give information on building spaces, usability of spaces, building appearance, colour and texture of materials etc. The structural engineer’s model should give detailed information on the structural properties of the building: dimensions, material, forces, tensions etc.

But the tricky part is the relationship between these models. A simple approach for support of discipline view models is to treat the view models as sub-models of an all-encompassing central

Figure 3. Different participants can exchange and share building information using a shared Project Model (Building Information Model)



model. In other words, the shared project model contains all information as well as the union of all view models that are defined subsets of the central model. This approach seems similar to the way views are applied in database technology that is relatively easy to implement.

But if you look closer to what disciplines do when they work with building information, then you can see that a discipline view is not a simple subset of 'all' building information. Information is filtered, idealised and transformed. Sometimes new information is added, only for the sake of analysis (think about external forces or catastrophes that are incorporated in a structural model before it can be declared as being safe). A structural engineer analyses a building design and creates his own view model by filtering, idealisation and transformation. Components that do not have a primary structural function are considered as loads. Irrelevant information such as colour or thermal properties is disregarded. This means that the generation of a semantically rich discipline view model is much more complicated than just making a selection.

The next question is what happens in the communication from discipline model to central model. Information generated by the discipline must be transformed and integrated into the central model. This requires transformation and integration rules that can become complicated. Moreover, it requires a mechanism that takes care of consistency and prevents redundancy.

Experiences in the past (e.g. in the ATLAS-project) have taught that it is quite difficult to implement a model structure that supports discipline view models as described above. Remarkably, the most difficult part turned out to be the mapping of different shape representations. In order to define these mappings, complex conversion algorithms were needed, resulting in a lot of programming work.²

In later projects, usually a more pragmatic approach is taken, see for example the IFD Model View Definitions (Hietanen, 2006), in which view models are treated as sub-models. One of the key issues still remaining is the redundancy issue i.e., any solution that allows that the same information is stored in multiple places is fundamentally

wrong and will sooner or later cause consistency problems.

3.7 Modelling of Building Spaces and Enclosing Structures

The functional units in Buildings that add the most value are in fact empty spaces that are formed by their surrounding walls, floors and ceilings. As a result, a Building Information Model needs to have explicit space objects, although from a technical/physical point of view, where the spaces are formed by their surrounding objects.³

This indicates that there are two complementary ways of defining spaces. One way is based on the complete physical boundary and separation of the space from other spaces. The other way to define a space is as the locus of a homogeneous activity (Bjork, 1992). The first way can be called a technical, indirect definition of space; the second one can be called a functional, direct definition.⁴ It can be noted that in most common CAD-systems spaces can only be drawn by drawing its boundaries, while only some advanced architectural CAD systems do support the direct drawing of spaces. For architects and end users, however, spaces are in fact the primary objects they are interested in. They formulate requirements on spaces and evaluate a design by looking at the spaces. Also building physicians are interested in spaces, for analysis of energy performance, or acoustic performance, etc.

Modelling of spaces as such is not very difficult. The tricky part is, once again, in the relationships. The first modelling decisions concern decomposition: a building can be decomposed in spaces, and several space decomposition levels can be used. But is it necessary to define space decomposition levels? Must the decomposition be complete, in a way that all spaces are included in the decomposition tree? Is overlapping of spaces allowed, or is it necessary that the building space is the same as the sum of all constituent spaces?

Things get more complicated with the relationship between spaces. It is possible to state that space *x* is adjacent to space *y*. But this expression can be elaborated further: the separation between space *x* and space *y* can be defined as a separation element (to be fulfilled by a wall, for example). This separation element may separate two spaces, but it could also be more than two (for example the façade of a building). Next, the surface of the separation element is related to the separation element but also to the space. For example, the function of the space puts requirements on the surface of the wall. Similar issues occur with the modelling of openings in separation elements, such as doors and windows.

The examples given here demonstrate that there are many ways to model building spaces and enclosing structures. Over the years, there have been many efforts to define an appropriate model for building spaces and enclosures, see for example Bjork (1992), Augenbroe (1995) and Eastman (1999). Currently, the IFC specification (IAI, 2008) is regarded as a default standard for BIM including building spaces, but IFC does not yet address all issues that have been raised over the years, of which the questions above give an indication. Architects, end users and building physicians can reason with spaces in a complicated and semantically rich way that is difficult to capture in an information model.

3.8 Modelling of Shape Information

As said above, a Building Information Model stores information on properties of building parts. Of course that includes shape properties. But in many cases BIMs are used in combination with CAD-systems. In that case the way shape is represented (2D, 3D Surface model, 3D B-rep Solid model, 3D CSG Solid model, either parametric or not, etc.) is dependent on the CAD-system.

The information structures of these shape representations are all complex. In Part 42 of the

ISO-STEP standard (ISO 10303⁵, 1999-2008), a data model is specified with the aim of supporting all conventional geometric and topological representation methods. This had led to a very sophisticated but also very complicated part of the STEP standard. The result is that implementations of systems for the exchange of geometric data based on STEP are always considerable efforts.⁶

In IAI, simpler structures for shape representation have been chosen. But also with IFCs implementations of CAD exchange have been considerable efforts, with many problems to be solved on the way (see for example Liebich, 2001).

A fundamental issue with exchange of shape information is how to avoid redundancy problems. Suppose for example that the Building Information Model says that the area of living room x is 40 m², and that the living room is represented by rectangle y in AutoCAD with 8 m length and 5 m width. But what happens if one of the values is changed, either on the BIM-side or on the CAD side? How do you keep everything consistent? It seems reasonable to say that the BIM is leading and the CAD application must follow the BIM data. On the other hand, the CAD application is likely to have a good user interface, which means that it might be better to make the CAD application leading. This issue gets even more complicated when there are two CAD applications that need to exchange information.

In addition to the complex subject of exchange of geometry data, there has been a lot of interest in the AEC/BIM domain for *topology*. Topology is the mathematical term for connectivity structures, and has a theoretical basis in graph theory. In the building domain connectivity is an important aspect of building designs and several researchers have done work in the application of topological principles in the AEC-domain, see for example Willems (1988), Augenbroe (1995), Willems (1997) and more recently Paul and Borrmann (2008). However, topology in the IFC

specification is until now only defined in a generic, ISO-STEP-like way, and does not say much about connections between building objects.⁷

3.9 Modelling of Life-Cycle Views

Traditional design describes a building for one single stage of its lifecycle, namely after completion of the building project. But one of the objectives of BIM is information integration throughout the life-cycle. Design information of building objects must therefore be related to information from the construction phase, the use and maintenance phase and the demolition phase of the very same object. In integral design, the building design is also analysed for the building process itself, i.e. it has to support various stages of completion of the building. Also the accessibility of the building for maintenance and the possibilities of (partial) building modification or renovation need to be examined.

Further, there is an increasing need for building information ‘as built’ and ‘as maintained’, because this may differ from the ‘as designed’ specification. In industrial sectors that have strong safety and security requirements, such as the process industries, the availability of ‘as maintained’ plant data is even demanded.

CAD systems offer increasing support for the modelling of various stages of a building lifecycle, including different discipline views on the building. This is called 4D or nD modelling; where time forms the fourth dimension and different aspect views add higher ‘dimensions’.

But to support the modelling of a building for all of its lifecycle phases correctly is a more complicated matter. Older proposals on this subject support a more or less sequential ordering of stages, such as design, planning, construction, commissioning, operation, maintenance and demolition. For the building as a whole, this seems appropriate, but the lifecycle of parts of a building may be quite different. In maintenance and renovation, parts of a building may be removed and

replaced by new ones. In fact, a major renovation project is not that different from designing and constructing a new building - some parts of the old building are reused while others are replaced by new ones.

A pure sequential ordering is therefore inappropriate. It makes more sense to identify a few fundamental principles in the building lifecycle, such as described by (Gielingh 2005).

The first principle is to make a distinction between models of a building that does not yet physically exist, and models of a building that does exist. The first may be called an 'imaginary building' and the second an 'actual building'. In integral design, all lifecycle stages may be simulated before they actually happen - we then speak about 'imaginary construction', 'imaginary maintenance' etcetera. Once the building is in the construction phase and (partially) does exist, the actual dimensions, locations and properties may be measured providing an 'actual (partial) building model'. During operation its performance may be monitored, also providing information about the actual building. A comparison between imaginary and actual building models may help to find discrepancies between them that support further improvement of building processes as well as the improvement of building process simulation models.

The second fundamental principle is to distinguish between static and dynamic views of a building or any part or component of a building. The concept 'process' refers to the notion of change, such as the change of shape and material properties. What can be a process for one discipline may not be visible for another discipline. For instance, the expansion and shrinkage of a building structure due to temperature changes, and the deformation of a structure due to changing loads, are visible for a structural engineer, but not for most other disciplines. The models produced by a CAD system usually reflect a static view on the building. With this principle we can now develop a dynamic model of a building that resembles a

movie. A movie consists of still images, where each image records a scene for an instant of time. In between these images, the scene changes, causing the images to be slightly different. What happens between these images is what we call a 'process'. In the case of building modelling it is not needed to have models at fixed intervals of time. When we look at a process, there is always a (static) initial situation, and a (static) final situation. Only these two situations need to be represented in a dynamic model. If static models of intermediate situations are desired, they can be represented by splitting the process into parts.

The third fundamental principle is indeed to distinguish between different discipline views, a subject that was discussed earlier.

In modelling the building lifecycle, it remains important to keep an eye on system integrity. Each part of a system has a function in order to play properly its role within that system. The functional description of that part should contain a set of boundary conditions: the values of properties that the part needs to have in order to function properly. If the actual property values change but stay inside the boundary conditions, there should be no problem. But if they move outside the boundary conditions, there may be a reason for concern. It may lead to the malfunctioning of the part and/or of the system as a whole. This principle is becoming more and more important with the advent of condition monitoring technology. Through the monitoring of actual conditions, a possible breakdown of a system can be forecasted and avoided through timely action. Condition based maintenance is generally the most optimal form of maintenance.

The described principle is also of importance if the function of a building changes. Such functional changes set new boundary conditions for the parts of a system, and the principle enables then verification whether parts are still useful or have to be replaced.

In many countries the focus of the building industry is slowly moving from building new

buildings to maintenance and refurbishment of existing buildings. A similar development can be seen in civil works: maintenance of roads and bridges is getting more important. Moreover, the global issues of climate change, shortage of fossil energy, cradle-to-cradle thinking (McDonough & Braungart, 2002) and concepts such as remanufacturing (Steinhilper, 1998) cause a growing interest in information on building usage, maintenance and demolition, as well as in design systems, in which it is possible to simulate usage, maintenance and demolition. This kind of next-generation design systems will certainly need a Building Information Model that supports the full life cycle of buildings and, even more, of building parts (since building parts might be remanufactured and used in another building when the initial building is dismantled).

4 METHODS, LANGUAGES AND TOOLS SUITABLE FOR BIM

There are many methods, languages and tools for Information Modelling available (for instance EXPRESS, UML, OWL, etc.). Many building information models are developed using these information modelling languages, i.e. modelling languages with *entities* or *objects* as key elements, connected by *relationships*. An example is the EXPRESS language (ISO 10303 part 11), the data modelling language of the ISO standard 10303, the STEP standard.⁸ EXPRESS/G⁹ is also the default language in IAI IFCs.

An alternative is the Class Diagram of UML, which is widely known among software engineers and computer scientists, since it is the most popular object-oriented modelling language. An advantage of UML Class Diagrams is that it provides a useful syntax for behaviour of objects.

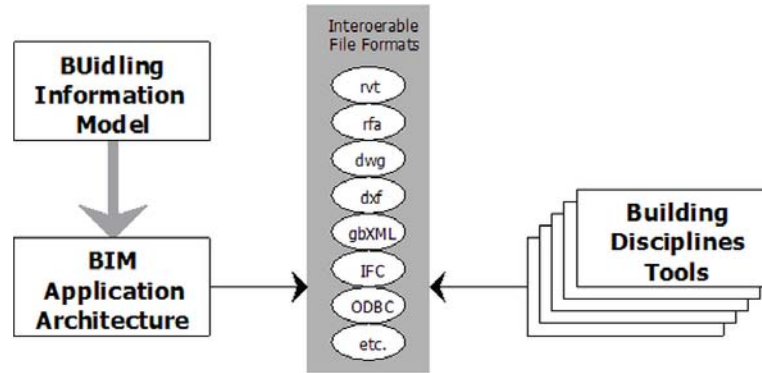
A recent alternative is OWL, the Ontology Web Language, developed by the World Wide Web Consortium (W3C). In OWL (so-called) ontologies are defined in which, a specific part

of the Universe of Discourse is modelled. OWL is closely related to the Semantic Web vision as expressed by Berners-Lee (2001). OWL is currently applied in the EU-project SWOP (Semantic Web-based Ontology for Product Modelling) (SWOP 2007).

Apart from the data modelling languages mentioned above, also process models can be very useful for BIM. Process models can be used for example for the identification of requirements of BIM data models. A rather old but still very useful example of a process modelling language is IDEF0.¹⁰

With the definition of BIM or building product model, the product model standards that are required for the B-C industry are, neither standards for the exchange of electronic versions of traditional technical drawings, nor standards for the exchange of geometric data form is only one of the relevant aspects. In fact, there is a need for standards that capture the project information semantically. From such a semantically rich Building Information Model, other models, such a geometrical model, or a Finite Element Model (FEM) can be derived automatically. Additionally, 2D-drawings or 3D models, and other documents could be generated from the same building product model. Since their debut in 1987, Graphisoft implemented this concept into their product ArchiCAD. This concept became known as the Virtual Building concept and has been followed by a number of other CAD vendors like Autodesk/Revit, Bentley and Nemetschek. Although these products do indeed provide the B-C industry some degree of interoperability, vendor-specific product models and supporting technologies are not the right solution. What is needed are standardized (preferable ISO) product models as technical basis for a future CIC. Due to the ad-hoc nature of the B-C industry and the lack of rich and dedicated market leaders, it is extremely difficult to come up with something useful for B-C. In this regard, even ISO STEP AEC proved to be the wrong platform to accomplish this task.

Figure 4. Interoperable file formats enabling communication of discipline tools in a dynamic BIM environment (adapted from Kumar. S., 2008)



5 EPILOGUE

In this chapter a number of modelling concepts for Building Information Modeling (BIM) are discussed. Many modelling concepts have been defined and used in BIM research and practice over the years, and more than one BIM efforts have suffered from conceptual issues that were very difficult to solve. Examples are, the relationship between requirements and design, the integration of discipline views and the modelling of shape information in a BIM context.

It can be concluded that application of BIM in a practical setting with time and cost constraints, requires clear decisions on, BIM concepts that will be used and concepts that will not be used.

Another conclusion that can be drawn is that the development of BIM and IFC towards a robust *de-facto* standard is a slow process that takes time, but will eventually lead to instruments that will significantly enhance the performance of the building industry.

At the same time, we need to point to alternative approaches as BIM is a concept that is still under development and hence new approaches, concepts and developments emerge to replace existing commonly used practices. We need to clear up things. For instance the notion that BIM theory should not be built up on top of informa-

tion modelling concepts. We need to go back to the basics:

What is a Building? What determines the performance of a building (internal and external factors)? How does a Building change over time? How do we model that? How do you proceed in a design process from problem to solution, with intermediate stages in between? How do different disciplines interact? How do we model that?

Current CAD systems do not support design in a true sense of the word. They are only geometric modelling systems. But form follows function and you cannot develop a true BIM by augmenting a 3D CAD model.

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KEY TERMS AND DEFINITIONS

Building Information Model (BIM): BIM is an information model of a building (or building project) that comprises complete and sufficient information to support all lifecycle processes, and which can be interpreted directly by computer applications. It comprises information about the building itself as well as its components, and comprises information about properties such as function, shape, material and processes for the building life cycle.

Model: A model is a representation containing some essential structure of some object or event in the real world. The boundaries and type of this representation is influenced by the scope, purpose and the viewpoint of the model (Adopted from Stockburger, 1996).

Object Orientation: The object-oriented paradigm is a different way of viewing applications. With the object-oriented approach, you divide an application into many small parts (or objects), that are fairly independent of one other. An object is a concrete manifestation of an abstraction; an entity with a well-defined boundary and identity that encapsulates state and behaviour - an instance of a class. A class is description of a set of objects that share the same attributes, operations, relationships, and semantics.

Parametric Object: A building is composed of geometric components and the geometric information is substantial for BIM. Parametric modelling provides mechanisms to translate and

embed domain expertise as explicit geometric expressions that can automate generation of the building information—especially geometric information and that can facilitate the generation of a rich building model (Lee, G. et al, 2006). We define parametric objects as objects (or components) of which we all know, if the parameters that describe the object, are known. These are items where not designed to and have to be calculated. An example of a parametric object construction is a standard pre-element, a wall element or a plate for example. Although such items in terms of building and / or exact form are often quite complicated, there are only a few parameters needed to describe a body.

EXPRESS / EXPRESS-G: EXPRESS is a modelling notation to use to represent various aspects of a system. EXPRESS-G is a graphical representation of EXPRESS but does not include the full richness of the data definition language.

UML: One important consideration in visual modelling is what graphical notation to use to represent various aspects of a system. This notation needs to be conveyed to all interested parties or the model will not be very useful. Many people proposed notations for visual modelling. UML stands for Unified Modelling Language. It is an object modelling technique that evolved as a result of the combined work of James Rumbaugh, Grady Booch and Ivar Jacobson. The Object Management Group (OMG) adopted UML as a standard for software modelling in late 1997. UML is now the de-facto standard for software modelling.

IFC: The Industry Foundation Classes (IFC) data model is a neutral and open specification that is not controlled by a single vendor or group of vendors. It is an object oriented file format with a data model developed by the International Alliance for Interoperability (IAI) to facilitate interoperability in the building industry, and is a commonly used format for Building Information Modelling (Wikipedia, http://en.wikipedia.org/wiki/Industry_Foundation_Classes, Accessed 7 July 2009).

ENDNOTES

- ¹ The term PIM (Plant Information Management) was already used in the late 90s by the process industries. It is not the same as modelling, however.
- ² Conversions should be avoided. Not by prescribing a single representation for all discipline views, but by making a single discipline responsible for the specification of a particular property. The view and representation used by this discipline will be the primary view and representation. On the instance level, a representant of this discipline is the author and his/her model is the master model.
- ³ The FU's and TSs can be anything, including spaces, material objects or modifications of material objects (in the case of connections and nodes). This is not only valid in construction, but also in other product types.
- ⁴ Material and non-material spaces are treated in the same way, i.e. it is not the case that spaces are FU's while material spaces are TS's. This distinction between material space and void is defined as a feature of topological space. The shape of a material object can be built up as an aggregate of multiple TS's which refer either to material spaces or to voids. This approach enables a smooth integration with procedural geometric representations such as CSG.
- ⁵ ISO 10303 is an ISO standard for the computer-interpretable representation and exchange of industrial product data. Its official title is 'Industrial automation systems and integration - Product data representation and exchange', known as STEP or 'Standard for the Exchange of Product model data' [en. wikipedia.org/wiki/ISO_10303].
- ⁶ That is because semantics is left out in STEP AP203. These problems can be solved with feature technology, but most CAD systems do not support features.

- ⁷ ISO-STEP and IFC support Euler topology. There is however a need to map connectivity networks to topological structures of different dimensional order. The latter is needed because different levels of idealization are possible in a model; for instance the representation of a column by a line (an edge) or a wall by planar geometric element (a face), although they may also be represented as 3D solids. Information associated with these topological elements should not get lost in the process of idealization (converting nD to $(n-1)D$) or its reverse (converting nD to $(n+1)D$). This is what the work of Willems supports.
- ⁸ STEP consists of 100's of parts of which EXPRESS is only one (10303-part 11).
- ⁹ EXPRESS-G is a graphical representation of EXPRESS but does not include the full richness of the data definition language.
- ¹⁰ Most process models for the building construction industry are now being developed using the 'Business Process Modelling Notation' (BPMN) which is more useful as it allows the exchange of information between actors in a business process to be captured.

Chapter 2

A Review of Building Information Modeling Tools from an Architectural Design Perspective

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ABSTRACT

Building Information Modeling (BIM) continues to evolve and grow along with its respective application in practice. One of the key advantages of BIM is that it facilitates the development of detailed information and analysis much earlier in the building process to improve decision making and reduce downstream changes. This chapter provides a review on the BIM tools from an Architectural Design Perspective.

1 INTRODUCTION

The developments in computers and communication systems accelerated providing the most intensive computer services in architecture, systems offer great opportunities in terms of design and drawing in order to increase productivity and quality in design. The transfer of the complicated studies to paper in any desired scale, is an advantage that can only be obtained by using computers. Thanks to its features, IT provides more productivity, better quality and more economical design by facilitating studies that cannot be realized by using traditional methods. The use of Building Information Modeling on projects allows the information to be pushed upstream in

the design development. The added details allows planners, designers and builders to better coordinate information amongst the multiple parties involved in the process of developing and executing construction projects. However, the challenge lies in bringing these knowledge bases together and carrying information from one stage to the next. The building industry is intrinsically fragmented and is often polluted with duplication of efforts that do not add value to the end product.

The utilization of every Building Information Modeling option available is not always the right application for every project or its respective stages. Organizational changes required in the utilization of BIM also provide hurdles in opposition to the successful utilization of Building Information Modeling tools. The use of Building Information Modeling

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also provides the increased opportunity for owners, designers and builders to collaboratively coordinate the overall supply chain of the building process which is a key element in optimizing its value stream (Manning and Messner, 2008).

2 BUILDING INFORMATION MODELING

Building Information Modeling (BIM) systems is the latest generation of Object-Oriented CAD systems in which all of the intelligent building objects that combine to make up a building design can coexist in a single 'project database' or 'virtual building' that captures everything known about the building. A Building Information Model provides a single, logical, consistent source for all information associated with the building.

A Building Information Model is a digital representation of the physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onwards (Smith, 2007).

The concept of Building Information Modeling is to build a building virtually, prior to building it physically, in order to work out problems, and simulate and analyze potential impacts. The heart of Building Information Modeling is an authoritative building information model.

The reality is that all information for a building already exists electronically is the catalyst which makes implementing BIM a possibility. Therefore the challenge should be to pull all the information together for the specific building being developed. The creation of a building information model begins with the first thoughts of the project. From that point forward the model is used as the authoritative source for information about the building. When completed the model will be delivered to the operator and sustainer of the facility and any modifications or improvements will be recorded in the model. The model is the

authoritative source and it will be used to plan and execute changes throughout the life of the facility (Smith, 2007). BIM includes continuous collection of data and building of knowledge at various stages of the building life cycle.

Building Information Modeling (BIM) refers to the creation and coordinated use of a collection of digital information about a building project. The information can include cost, schedule, fabrication, maintenance, energy, and 3D models which are used for design decision-making, production of high-quality construction documents, predicting performance, cost estimating, and construction planning, and eventually, for managing and operating the facility (FMI Research Report, 2007).

Building Information Modeling (BIM) is an innovative method to seamlessly bridge communication within the architecture, engineering and construction industries which is the power of BIM. With Building Information Modeling, architects and engineers efficiently generate and exchange information, create digital representations of all stages of the building process, and simulate real-world performance-streamlining workflow, increasing productivity and improving quality (Autodesk, Inc. Website, 2008). These are some descriptions of Building Information Modeling from different groups (Eastman, 2007):

- A computable representation of the physical and functional characteristics of a facility and its related project/life-cycle information using open industry standards to inform business decision making for realizing better value (NIBS - Facility Information Council)
- Information use, reuse, and exchange with integrated 3D-2D model-based technology, of which electronic documents are just a single component (AIA, 2008). A single repository including both graphical documents - drawings - and non-graphical documents - specification, schedules, and other data (ArchiCAD)

- A modeling of both graphical and non graphical aspect of the entire Building Life cycle in a federated database management system (Bentley)
- A building design and documentation methodology characterized by the creation and use of coordinated, internally consistent computable information about a building project in design and construction (AutoDesk)

3 BUILDING INFORMATION MODELING SYSTEMS

Building Information Modeling systems have evolved through several versions of software upgrades, and industry leading firms are adopting BIM on live projects (Howell & Batcheler, 2005). To provide a comprehensive solution, Building Information Modeling must eventually address the full building lifecycle: feasibility planning, design, engineering, construction coordination, shop-level fabrication, commissioning, facility management and operation (Eastman et al., 2004).

BIM allows exploring projects in greater depth than ever before, because a single intelligent model can be used to generate construction documents, explore building assemblies or constructability, estimate costs, simulate building performance and even build physical models using the latest in rapid prototyping. Specific knowledge of the discipline being modeled is also required (Camps, 2008).

BIM software is required, to coordinate between the separate models, for example by the contractor for coordinating the models of sub-contractors, addressing the coordination among shop drawings. Different BIM tools should be responding to these different building construction purposes (Eastman et al, 2004). Some requirements for such platforms can be outlined as;

- strong geometric modeling capabilities; so as to allow full modeling of all building parts, at varied levels of detail.

- the geometric modeling capabilities must be parametric; supporting both automatic layout and updating according to design rules.
- Defined domain-specific semantics (e.g., objects, attributes and identification tags), capturing the classification and functional properties of building components.
- reliance on a single integrated model, allowing all data and relations to be carried in an associative structure, facilitating consistency and integrity management over all data;
- automatic report generation from the building model, allowing all drawings, specifications, other production information, bills of material and other reports to be consistently generated from the integrated building model;
- easy import of design model data
- easy export of subsets of design data
- extensibility, to allow the above capabilities to be easily applied to new classes of design objects and assemblies, easily defined by a designer;
- scalability, supporting interactive parametric design of 10^5 to 10^7 objects on current standard hardware;
- concurrent access and management: only a small project can be designed by one person in a practical timeframe (Eastman et al., 2004).

No system has effectively realized all of these requirements, but they are being worked on.

4 BIM: BENEFITS AND CHALLENGES

The use of an architectural BIM tool in concept planning allows quickly expressing sectional and isometric details to the end users so that the overall concept could be refined prior to contracting and articulated to the design-builder.

This is especially valuable in the coordination of the various spaces, areas that are noted as being a continual challenge for the projects. The level of detail developed in the conceptual BIM planning, allows time during the database execution stage to be focused on additional details versus limited to trying to establish a common baseline. Casework modifications later were minimal and are related to building type changes (from modular pre-fabrication to a pre-engineered steel structure) (Manning & Messner, 2008).

The benefits of the utilized BIM tools include:

- Instant 3D visualization of spaces and alternatives that could quickly be evaluated by technical and non-technical staff alike
- Sections, perspectives, plan views and quantity take offs could quickly (in many cases automatically) be updated to effectively ascertain potential costs
- The parametric attributes allowed programming information to quickly be compiled for comparison to original authorization documents with a high degree of confidence in its accuracy

The challenges of the utilized tools include:

- Data transfer from one project stage to another and internally during concept development reviews
- Unfamiliarity with parametric concepts in general and
- Lack of parametric objects/families (Manning & Messner, 2008; Van, 2006).

There are also some other challenges that are faced during implementation of BIM such as, control of the model, rethinking the process, model verification, new project delivery paradigms, new business models for firms, culture in the profession and the industry.

5 BUILDING INFORMATION MODELING TOOLS

The traditional five project phases will not make sense under a model-based paradigm. Due to the strategy of storing information in databases, Building Information Modeling permits the work on a project to be distributed in different ways. Once a piece of information has been entered in the model, it remains there until modified or deleted. Information is continually added to the model so that it evolves continuously from a “schematic” model to a “construction documents” model. The information in a model is much more easily manipulated, modified and updated than that in traditional CAD files. A crucial instance is the ability of BIM software to exchange information with other computer applications. Known in the computer industry as interoperability, this capability is the key to effective collaboration within the project team. Common set of standards is being established and implemented by all software vendors in the industry.

To a great extent, BIM users will have to rely on software developers to give them tools that permit them the greatest possible flexibility in design while maintaining the intelligence that makes BIM useful. The effort on the part of the programmers is to build in the intelligence to allow the tool to work properly under all circumstances. The architectural profession needs to build effective communication with software developers to co-design the tools to be used. BIM software will make it possible for architects to custom-design their own objects and tools. Some of the BIM products on the market already permit this, but making full use of this feature requires knowledge of computer programming. Firms at the forefront of BIM are hiring programmers to create custom tools and objects and build information “bridges” between their BIM software and other applications

The Building Information Modeling tools can be classified as; Preliminary Tools (Preliminary

Space Planning Tools, Preliminary Massing and Sketching Tools, Preliminary Environmental Analysis Tools, Preliminary Cost Estimation Tools, BIM Design Tools, Structural Design Tools, BIM Construction Tools, Fabrication Tools, Environmental Analysis Tools, Construction Management Tools, Cost Estimation Tools, Specification Tools, Facility Management Tools, Mechanical Tools (AEC Integration Lab., 2008). Table 1 provides an overview of design related functionalities of some BIM tools on the market.

Autodesk REVIT is perhaps the most literal interpretation of a single Building Information Modeling as a central project database. The strength of this approach is the ability to coordinate every building element in one database, thus providing users the ability to immediately see the results of any design revisions made in the model, have them reflected in the associated view (drawings), as well as to detect any coordination issues.

Bentley Systems interprets BIM differently as an integrated project model which comprises a family of application modules that include Bentley Architecture, Bentley Structures, Bentley HVAC, etc. Bentley describes this approach as an evolutionary path that allows its Microstation users to migrate work practices that still have their origins based on using CAD tools. Access to project data is provided with DWG and IFC file formats, i.e. both are being supported. However, the highest levels of interoperability are only achieved when the entire family of Bentley products is deployed on a project.

Graphisoft's approach to BIM is to create a virtual building model, i.e. ArchiCAD application is viewed as one of many satellite applications orbiting a virtual building model rather than being seen as the central repository for the entire model. In addition to ArchiCAD being conceived as a BIM system from its inception over 20 years ago, Graphisoft is now working with a consortia of application partners to deploy technology's IFC-based model server as a virtual building re-

pository, possibly the most innovative technical approach to the future of BIM.

Nemetschek provides a fourth alternative with its Building Information Modeling platform approach. The AllPlan database is wrapped by the Nemetschek Object Interface (NOI) layer to allow third-party design and analysis applications to interface with the building objects in the model. This NOI layer is a published which also supports IFC objects.

Building Information Modeling is certainly viable and offers many realizable advantages over Computer Aided Design (Table 2). However, the ability to share the intelligent building information being generated in a BIM to/from/between the other purpose-built models is critically important (Howell & Batcheler, 2005).

AEC industry will continue to learn effective ways to plan, design, and execute projects using BIM. A full understanding of all aspects of BIM is not a requirement for implementation, or to see tangible results. While the benefits are increasing with knowledge of BIM, there are still challenges. Even with known challenges that may limit the use of a BIM tool to its maximum extent, the incremental value added is still beneficial and empowering to the AEC team. BIM tools can increase the effectiveness with which owners, designer, and builders effectively and efficiently develop and execute the projects (Manning & Messner, 2008).

Building Information Modeling promises and does actually deliver many advantages as a single source of building information as;

- Plans, elevations and section drawings, generated as "views" from a single design model, are always consistent
- Coordination of building objects created across different disciplines in a single model resolves clashes between design elements
- Comprehensive (door, window, room, equipment) schedules associated with

Table 1. Example for building information modeling design tools (adopted from AEC Integration Lab., 2008).

Software	Properties	
Bentley Architecture	Main Functions	BIM-enabled Architectural design, solid modeling, model-based drawing generation, 3D visualization
	Applications Type	BIM Design Tools
	Basic Objects	Solid model with features, Contoured site model, Space, Column, Column grid, Roof, Wall (linear, arc, curve), Door, Window, Casework, Plumbing fixture, Floor, Slab, Stair
	Parametric functionality	Dimension-driven creation and modification of building components, embedded parameters, rules, and constraints. Parametric curved surfaces and solids
	Export Format	Microstation DGN V8 (dgn), IFC 2X2 (ifc, stp), AP203 (stp), AP214 (stp), VRML (wrl), ACIS (sat), Stereolithography Format (stl), Universal 3D Standard (u3d)
	Import Format	AP203 (stp), AP214 (stp), ACIS (sat), Stereolithography Format (stl)
	Programming Interface	MDL (VB, Java)
ArchiCAD	Main Functions	Surface & solid geometry modeling, Parametric CAD, BIM
	Applications Type	BIM Design Tools
	Basic Objects	Wall, Wall End, Door, Window, Corner window, Skylight, Roof, Beam, Column, Stair, Lamp, Mesh, Zone
	Parametric functionality	Pre-defined parametric object. User definable parametric object (By GDL)
	Export Format	IFC 2X2 (ifc, stp), AutoCAD DWF (dwf), Plot Maker Drawing (pmk), GDL Script (gdl), IFC 2 (ifc, stp), IFCXML 2X2 (xml)
	Import Format	AutoCAD DWG 2004 (dwg), AutoCAD DXF 2004 (dxf), AutoCAD DWG 2000 (dwg), AutoCAD DXF 2000 (dxf), IFC 2X2 (ifc, stp)
	Programming Interface	API Development Kit 6.1 (C, C++), GDL (Graphisoft's proprietary scripting language)
Revit Building	Main Functions	Parametric modeling, Quantity Take off, Rendering
	Applications Type	BIM Design Tools
	Basic Objects	Site(Toposurface, Pad, Parking space), Wall, Door, Window, Column, Roof, Floor, Ceiling, Stairs, Railing, Ramp, Curtain System, Mullion
	Parametric functionality	Parametric Object Parametric relationship between objects
	Export Format	AutoCAD DWG 2004 (dwg), AutoCAD DXF 2004 (dxf), AutoCAD DWG 2000 (dwg), AutoCAD DXF 2000 (dxf), Microstation DGN V7 (dgn), ACIS 3.00 (sat), IFC 2X2 (ifc, stp), CIS/2 LPM/5 (stp), Revit 8 (rvt), AutoCAD DWF (dwf)
	Import Format	AutoCAD DWG 2004 (dwg), AutoCAD DXF 2004 (dxf), AutoCAD DWG 2000 (dwg), AutoCAD DXF 2000 (dxf), Microstation DGN V7 (dgn), ACIS 3.00 (sat)
	Programming Interface	.NET API, COM API(depreciated), C, C++, VB, C#

the building are easily generated and kept up-to-date with any changes to the model

- The availability of a single BIM makes it possible to capture additional information throughout design, procurement and

Table 2. From computer aided design to building information modeling (Trehen, 2008)

CAD	Pre-Design	Schematic Design	Design Development	Construction Documents	Construction	Closeout
BIM	Conceptualization	Criteria Design	Detailed Design	Implementation Documents	Construction	Closeout

construction of a building, serving as a living record of the building for operations and maintenance throughout its lifecycle (Howell & Batcheler, 2005).

Building Information Modeling is a process which goes far beyond switching to a new software. It requires changes to the definition of traditional architectural phases and more data sharing than most architects and engineers are used to.

A process refinement effort can be enabled by technology and BIM in particular, to produce bottom-line impact by streamlining the design and construction efforts. It can successfully increase labor productivity, thereby lowering the net cost, change and reduce the amount of materials used and wasted on a job site to lower their net cost, and construction costs can be modeled more accurately to the point that some of the more expensive site options available became financially viable.

Even with the advent and adoption of Building Information Modeling, what is really happening industry-wide is the use of a growing number of purpose-built models. This trend is being driven by a number of different factors; the availability of more sophisticated building systems; higher expectations for building performance and energy efficiency; new fabrication methods; an increased awareness by owners to make decisions based upon building lifecycle costs versus initial capital cost; increasing reliance on technology to perform more detailed analysis and computed designs (Howell & Batcheler, 2005).

While BIM is proving itself as a very powerful architectural design and coordination tool, researches conducted show that the limitations

identified, represent recurring difficulties in the use of BIM for project-wide design and documentation. The subsequent analysis shows that rather than being dependent on a single building model, project team members typically rely on a number of purpose-built models including: 3D conceptual design model (for pre-design, sketch phases), Detailed geometric design model (for usage of creating Architectural, Structural, and HVAC projects for example), Structural finite element analysis model, Structural steel fabrication model, Design coordination model (assembling from multiple sources of design information), Construction planning and sequencing model (Virtual Construction solutions), Energy analysis model, Fire/life safety and egress model, Cost model, Resource planning model.

These design applications and the purpose-built model that created and managed has been highly optimized for the precise needs of the discipline/trade involved, and for the specific project process they support.

Due to reluctance on the part of the architect to share their models out of liability concerns, some innovative general contractors began developing their own construction phase models. The contractors routinely develop their own construction phase models, because architects and contractors idealize/model a building in completely different ways. Contractors find the greatest value from a construction model that they create themselves, specifically for their purposes in managing the construction process. With BIM the project information being created and maintained across all of these purpose-built models which, in aggregate, fully describes everything that is known about a project.

Table 3. Characteristics of BIMs

Comprises of digital “objects”	...having the properties that describe those of physical construction elements. The model’s construction corresponds piece by piece to the building’s construction, making it a virtual representation of the actual construction of the project. This obliges the designers to think through the construction process, creating a stronger relationship between design and construction than is now typically the case. Designers can better anticipate and resolve spatial conflicts and other construction problems before they arise in the field.
Strategy of storing all the project information in databases	The computer translates building data into whatever form is required by the user, such as graphics, tables, spreadsheets and text. The data can also be translated between formats used by other software applications.
Centralized storage of information	The information gathered during any phase of the project is stored for use in later phases. The model may include information generated by the architects, engineers and other consultants, manufacturers, fabricators, contractors, owners and others. Participants can view each other’s work and resolve conflicts during the design phase.
Parametric nature of BIM objects	This allows a relatively small number of objects to define an unlimited number of construction elements. Being composed of parametric objects allows an entire BIM project to be parametric. Complex rules can be written into a project by creating relationships among individual parameters.
Direct communication between the BIM and computer-driven tools that fabricate building components	This uses existing computer-aided manufacturing (CAM) technology, enhanced by the fact that every part of a BIM- based project already has a digital representation. Designers can thus directly control the manufacture of certain components, giving them direct control over some aspects of construction.

It is shown in the researches that BIM is viewed as just one of many purpose-built models, as a “source” of information about the building, rather than being viewed as a “destination” for every item of information about the project. BIM is primarily a geometric model with the advantage that its parametric variables and associated non-graphic properties provide richer transfer of building information to/from related purpose-built models used for design analysis, building performance and simulation.

BIMs contain many types of objects. The most commonly understood are object representing the physical elements of the building, such as Wall, Door, Window, Column, Beam, Floor Slab. BIMs also include many other object types that define abstract concepts and relationships like of relationships (connection and adjacency), object type definition (wall type and door type), hierarchies (containment), and grouping (zones and systems). Properties are attached to BIM objects to identify or describe them in some way. The range of possibilities for these properties is as wide as all the contexts in which they will be considered in a project, from design through construction and

operation. BIM improve upon processes and software tools used in the past because they enable a higher level of model analysis than properties only (See, 2007).

Building Information Modeling organizes the information surrounding a building project in one or more databases. Using this technology, the architect does not directly create drawings, but generates information in these databases using a variety of means. Primary among these (for architects) is a graphic environment that looks deceptively like Computer Aided Design. Table 3 provides some key characteristics of BIMs.

6 CONCLUSION

Building Information Modeling covers geometry, spatial relationships, quantities and properties of building components (for example manufacturers’ details). Building Information Modeling can be used to illustrate the entire building life cycle including the processes of construction and facility operation. BIM is able to achieve such improvements by modeling representations of the actual

parts and pieces being used to build a building. This is a substantial shift from the traditional computer aided drafting method of drawing with vector file based lines that combine to represent objects. Architecture (as a profession) needs to be deeply engaged in the development of BIM technology. It is about efficiency and business opportunities. It is also about creative freedom and expanding the horizons of what an architect can imagine and build.

The significance of BIM is in that it may allow regaining the control of the building process while better serving the clients and society. It may be the tool that allows the architect, the generalist with the broad view, to once again set the agenda for building.

Building Information Modeling provides the potential for a virtual information model to be handed from Design Team (architects, surveyors, consulting engineers, and others) to Contractor and Subcontractors and then to the Owner, each adding their own additional discipline-specific knowledge and tracking of changes to the single model. The result is anticipated to greatly reduce the information loss that occurs, when a new team takes “ownership” of the project, as well as in delivering extensive information to owners of complex structures far beyond that which they are currently accustomed to have.

BIM can greatly decrease errors made by design team members and the construction team (Contractors and Subcontractors) by allowing the use of conflict detection where the computer actually informs team members about parts of the building in conflict or clashing, and through detailed computer visualization of each part in relation to the total building. The error reduction is a great part of cost savings, realized by all members of a project. Reduction in time required to complete construction directly contributes to the cost savings numbers as well. It's important to realize that this decrease can only be accomplished if the models are sufficiently developed in the Design Development phase.

Good design is directly proportional with the information quality. The access to the requested information at the desired time, in the desired format and in the desired scope is also in parallel with the existing information quantity and quality. As creating digital libraries and projects facilitates reaching different resources of building information, architectural offices and educational institutions now need to focus more on utilizing BIM technologies.

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KEY TERMS AND DEFINITIONS

AEC Industry: The architecture, engineering, and construction industry

BIM: Building Information Modeling

BIM Software: BIM capable design Tools i.e. Autodesk REVIT, Bentley Systems (Microstation Triforma), Graphisoft's (ArchiCAD), Nemetschek (AllPlan)

BIM Tools: Preliminary Tools, BIM Design Tools, Structural Design Tools, BIM Construction Tools, Fabrication Tools, Environmental Analysis Tools, Construction Management Tools, Cost Estimation Tools, Specification Tools, Facility Management Tools, Mechanical Tools

CAD: Computer Aided Design

Database Systems: Computer database system consists of database, database management systems, adaptation software, forms, interface, operating system and user

IFC: Industry Foundation Classes

Section 2

Adoption

Chapter 3

Delivering BIM to the UK Market

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ABSTRACT

Technology has developed dramatically over the past five and particularly three decades. The way we live our lives has changed and is set to change ever more with the effects this technology has on our planet's environment. Construction is one of the world's oldest industries and has been slow to adapt and change with the arrival of these developing technologies. For example, it has been nearly two decades since Building Information Modelling (BIM) was first mooted and we still await significant adoption. The UK picture is further burdened with a fragmented supply chain, slow consolidation and generally low investment in the industry. However, BIM is not CAD. It is so much more; like the move from old accounting packages to Enterprise Resource Planning (ERP), it includes the formal management of processes on a consistent, repeatable basis. Like ERP, this is a very difficult transition to make. The product vendors have not helped through creating a confused market, with patchy product capability and no process management tools available on a scalable production basis. Furthermore, the construction industry's approach to contracts, training and education also need attention if it is to deliver this operating model. However, the key questions are: does it work and is it worth pursuing in the competitive UK market? The answer to both questions is yes, but it is important to be aware of what is involved, to understand the evolution and to take sensible steps to achieve the reward. The focus of this chapter is to begin exploring the issues towards the delivery of BIM to the UK construction market sector.

1 INTRODUCTION

Building Information Modelling – What is it all about?

The past twenty years has seen an amazing transformation in people's perception of the world, and much of this change has been driven by the introduction of technologies which previously could not have been dreamed of. The same opportunities

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have presented themselves to the UK construction and real estate sector but how has it responded? Clearly not as well as some other industry vertical sectors and there are some perfectly reasonable mitigations, it is a large disparate industry, highly fragmented with low barriers to entry. The contractual rules of engagement have changed very little from when they were originally drafted at the end of the Victorian era and the industry has also stopped developing and training engineers and tradesmen in the quantity and to the levels of the past. The margins are low and most innovation is carried out when the market tightens and businesses are faced with survival options, and not through client pressure as no one client is large enough or suitably inclined to sufficiently affect the market (the opposite to the automotive or aerospace market).

So with all this opportunity and all these challenges how does a member of the construction supply chain community go about adopting Building Information Modelling (BIM) technologies and processes to improve their business and their offerings to their clients, while still remaining profitable enough to satisfy local stakeholders in the shorter term. Clearly the first hurdle is to establish what BIM really is and to understand what it means to the individual and their business. Once this is understood, an evolutionary approach to adoption can be implemented, thus ensuring the level of e-readiness, technology and processes are in place within both the business and the wider supply chain, including amongst clients and operators.

What is clear is this is a collaborative activity and no one player in the supply chain or the market has or is likely to make an individual commercial fortune on a short term basis. This is counter to market pressure where short term goals and returns are seen as essential. The key, however, is to ensure that whatever the chosen strategy, it makes sense for the particular business and stakeholders involved. There is little point in being ahead of the game; while a business may have

the most technically elegant solution available it is essential to consider where this technology fits within an overall business strategy and whether this investment would be better made in the training or business development budget.

To consider all of these issues is beyond the scope of a single chapter but the following will consider some of the misinformation surrounding BIM and its adoption specifically in the UK market. It will commence with a positioning of both the BIM products and the market, with specific reference to the people, processes and technology now available. This will provide a rounded view of the current environment and an opportunity with which to go forward in the light of the prevailing economic conditions. Some key elements of the evolutionary adoption process, the maturity of some key elements and how these maturities can be measured and articulated will also be considered. Finally, some of the key elements that are missing from the current vendor offerings will be reviewed.

2 BACKGROUND

What is Building Information Modelling?

Lack of a Universal Definition and Consequential Industry Understanding

BIM evolved from the early product modelling efforts, such as the STEP international standard for the exchange of product model data (ISO 10303: Industrial Automation Systems – Product Data Representation and Exchange). Emerging in 1983, STEP defined product modelling as the long-term ambition to improve the communication of engineering information (including manufacturing, ship building and construction) and to enable integration through the co-ordination of open standards for data exchange and sharing. In the mid-1990s, an alliance of non-profit building industry organisations

was launched. Taking the principles of STEP as a basis, buildingSMART's (formerly International Alliance for Interoperability - IAI) goal was to define, promote and publish a common language (Industry Foundation Classes) specifically for the facilities industry as a basis for information sharing through the project life cycle and across disciplines and technical applications.

More recently, some government clients in the US, Denmark and Finland have begun to set up National Standards as a statement of intention in order to support the BIM approach. With each of these National Standards, further definitions have been proffered. According to NBIMS (National Building Information Model Standard) Committee in the US (2006), "BIM is a computable representation of all the physical and functional characteristics of a building and its related project/life-cycle information, which is intended to be a repository of information for the building owner/operator to use and maintain throughout the lifecycle of a building" (NBIMS, 2006). The US General Services Administration (GSA, 2007) views BIM as "the development and use of a multi-faceted computer software data model that not only documents a building design, but also simulates the construction and operation of a new capital facility or a recapitalised (modernised) facility. The resulting Building Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback on and improvement to the facility design". On the other hand, Associated General Contractors Guide (AGC, 2007) defines BIM as "a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility". In comparison, the American Institute of Architects (AIA, 2009) has defined BIM as "a model-based technology

linked with a database of project information", and this reflects the general reliance on database technology as a foundation. In the future, it may be possible to search structured text documents, such as specifications, and to link them to regional, national, and international standards.

Looking at the vendors' side, Autodesk (2003) defines BIM as "an approach to building design, construction, and management. It supports the continuous and immediate availability of project design scope, schedule, and cost information that is high quality, reliable, integrated, and fully coordinated. Though it is not itself a technology, it is supported to varying degrees by different technologies". Autodesk explains that BIM is, essentially, the intersection of two critical ideas that by:

- keeping critical design information in digital form makes it easier to update and share and more valuable to the firms creating and using it.
- creating real-time, consistent relationships between digital design data, with innovative parametric building modelling technology, it is possible to save significant amounts of time and money and increase project productivity and quality.

From Bentley's (2008) perspective, "BIM is a new way of approaching the design and documentation of building projects. It does so by applying information and model-based technology solutions in order to allow the automatic generation of drawings and reports, the analysis of design, the scheduling of simulation, facilities management, and more – ultimately enabling the building team to focus on the information and their decisions, rather than the documentation tools and process".

Other definitions have also been proffered including that of leading experts and academics such as Eastman, et al (2008) who interestingly identify what is not "BIM Technology":

- Models that contain 3D data only and no object attributes.
- Models with no support of behaviour.
- Models that are composed of 2D CAD reference files that must be combined to define the building.
- Models that allow changes to dimensions in one view that are not automatically reflected in other views.

As Eastman also offers, some people have called the building model “a BIM” such that Revit, ArchiCAD and Bentley generate a BIM. Others say that the representation is not as important as the process of moving to machine readable model(s) because machine readability opens up so many opportunities for further integration. This chapter has thus far referred to a building model as the basis for BIM, and implied that BIM is a process. This definition is consistent with that outlined by the GSA. The process of BIM is revolutionary because it provides the opportunity to migrate from practices that are centred on trades and craftsmanship to a more automated approach and all that this might imply.

BIM covers geometry, spatial relationships, geographic information, and quantities and properties of building components (for example manufacturers’ details). BIM can be used to demonstrate the entire building lifecycle, including the processes of construction and facility operation. Quantities and shared properties of materials can easily be extracted and the scope of work can be isolated and defined. Finally, systems, assemblies, and sequences can be shown in a relative scale with the entire facility or group of facilities.

The interoperability requirements of construction documents include the drawings, procurement details, environmental conditions, submittal processes and other specifications necessary for building quality. It is anticipated by proponents that BIM can be utilised to bridge the information loss associated with handing a project from the design team, to the construction team and the

building owner/operator, by allowing each group to add to and reference back to all information they acquire during their period of contribution to the BIM model. This interoperable element is vital for a number of reasons. Firstly, there is little evidence that there will be any single tool that will contain all the data relating to the entire building for its entire life. Smith and Tardif (2009) discuss this as well, stating that:

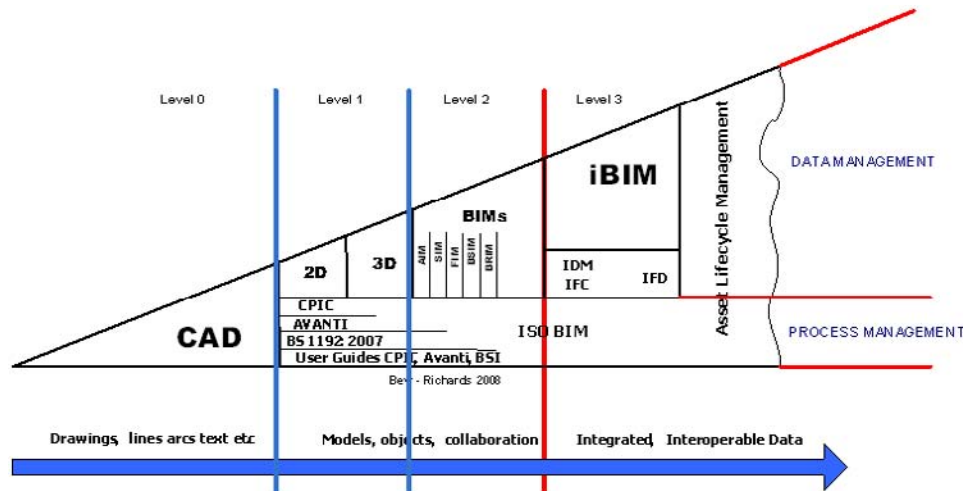
- The entire building lifecycle of business process and workflows is too complex to be modelled effectively in one system.
- Business processes vary too much across the industry.
- A single project model would involve too much change to existing information management infrastructure and business processes to support viable migration paths from existing workflows to new ones.
- The cost and technical challenges of such a system would be prohibitive.

Therefore, an open non-proprietary exchange method for data and processes are an essential element of any BIM system.

There have been attempts at creating a BIM for older, pre-existing facilities. They generally reference key metrics, such as the Facility Condition Index (FCI). The validity of these models will need to be monitored over time, because trying to model a building constructed in, for example, 1927 requires numerous assumptions about design standards, building codes, construction methods, materials, etc., and therefore is far more complex than building a BIM at the time of the initial design. However, the need to apply retrospective carbon reduction measures is likely to accelerate this requirement.

Observations of all of these seem to lead to significant consistency regarding the definition of BIM (or not BIM), but all of these fall short of a clear, concise definition that could be placed before a Client or CEO. This has proved to be the

Figure 1. BIM evolutionary ramp – construction perspective



biggest downfall in the UK market. The industry has failed to articulate the silver bullet and so has not progressed significantly. It has, however, moved slowly but surely with both the market and technology creeping along through two recessions and two booms and, with the notable exception of some excellent case studies, little evidence of performance improvement for BIM has been gained. The industry is now faced with a new economic situation that equally threatens and offers opportunity. The authors will save their own definition until the end of this chapter but they believe that how the industry has evolved to this point, since the move from drawing boards in the 1970's and 80's, is useful, especially when the BIM vision is extrapolated forward to form a strategic view. The industry's progress can be viewed in an evolutionary model following the same Darwinian process as the natural world in which we exist.

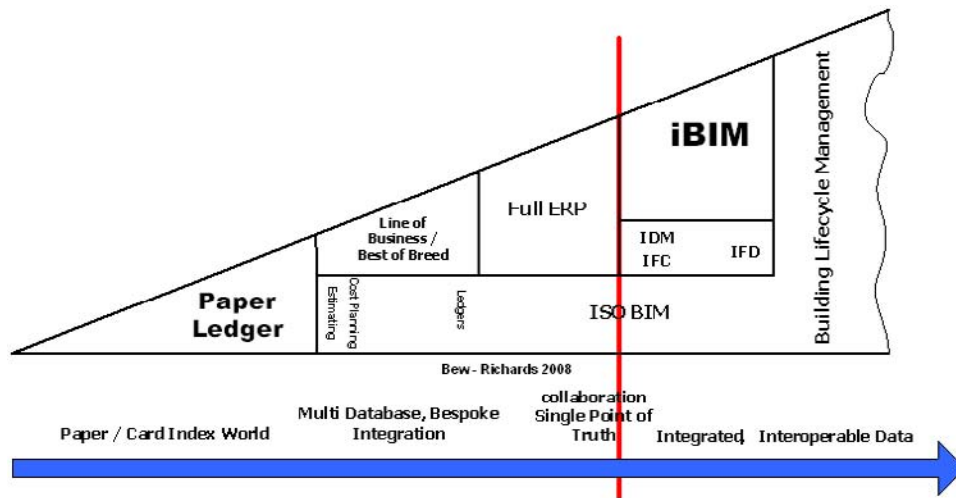
The model shown in Figure 1 (developed by Bew & Richards 2008) recognises that all forms of asset data managed in a collaborative way form part of what could loosely be called a BIM, and in the context of the model outlined this would indicate anything post level one. The model also separates the management of data and process;

an important theme in the development of any implementation and adoption strategy.

Levels have been identified to enable a simple identification for the level of BIM a business or project is using. From the case studies reviewed tangible savings have been identified at each level as progress is made along the evolution. The level definitions are:

0. Unmanaged CAD, probably 2D, with paper as the most likely data exchange mechanism.
1. Managed CAD in 2 or 3D format using BS1192:2007 with a collaboration tool providing a common data environment, possibly some standard data structures and formats. Commercial data managed by standalone finance and cost management packages with no integration.
2. Managed 3D environment held in separate discipline "BIM" tools with attached data. Commercial data managed by an ERP. Integration on the basis of proprietary interfaces or bespoke middleware could be regarded as "*pBIM*". The approach may utilise 4D Programme data and 5D cost elements.

Figure 2. BIM evolutionary ramp – commercial systems



3. Fully open process and data integration enabled by IFC / IFD. Managed by a collaborative model server and could be regarded as iBIM or integrated BIM, potentially employing concurrent engineering processes.

Later stages where there are fully interoperable models will need new technologies to deliver the concept, maybe using Atomic or Federated BIM, to enable effective large data model sharing. This may need advanced Identity Lifecycle Management systems controlling the access and security. This is discussed further in section 4, entitled Future Trends.

As can be seen from these definitions, 3D CAD data or model data alone is only a small part of the story and tools that create data and enable processes to act on that data are the vital differentiator in the world of true BIM. Clearly all of these tools have a similar evolution to create, save and transact processes over asset data. Leading players in the ERP and environmental markets have been active in enabling their products with the features to enable BIM like operation.

The model shown in Figure 2 shows the parallel route the “commercial systems” (ERP) market is taking, developing more and more functionality

that could support moving BIM into the core ERP toolset. This is also evidenced by consolidation at the top of the market with large players such as Oracle acquiring businesses such as Symmetry and Primavera to give object viewing, planning/project control and lifecycle management capabilities.

While there are obvious common characteristics in our definitions with respect to the people, process and technology aspects, the wide variety of definitions that exist have emanated from the perspectives and vested interests of individual industry stakeholders. It is noteworthy that none of these definitions are from the practicing UK industry itself. As a consequence, this has significantly contributed to what appears to be a distinct lack of understanding and awareness of BIM across the UK industry; for example, BIM currently means different things to different stakeholders. This in turn is potentially stalling progress towards a significant uptake and critical mass of industry-wide adoption. Therefore, in driving towards industry-wide BIM adoption, there needs to be a concerted effort towards agreeing and establishing a universal, industry-wide definition and benefits statement to facilitate greater awareness and a coherent understanding across the sector.

One of the most important factors to consider when reviewing any BIM strategy is the fact

that, on average, 80% of the cost of an asset is spent during the operation of that asset and not in its capital cost at the design and construction phases. It is significant, however, that the number of Facilities Management (FM) case studies that were available for sourcing was very low. Nevertheless, it is vital that if the industry is going to deliver better, lower carbon and cost buildings and assets then good quality operational data must be fed back in a useful form to enable the design phase to be better informed with performance information.

Therefore, if it was possible to offer a definition of a BIM to suit the UK market it would have to be all of the things discussed, together with a governance framework underwritten by contractually binding controls to ensure that projects could deploy auditable processes on reliable interoperable data throughout the delivery and operational cycle of the asset. Most importantly, the approach would have to be carefully articulated in terms of cost and benefit to ensure all supply chain members were bought in.

3 TAKING BIM TO THE UK MARKET

The failure to articulate the benefits of the BIM approach has led to very slow adoption. This is strange considering all that has happened to the remainder of UK industries, for example cars, shipping and rail, in contrast with key advanced high-tech businesses, such as motorsport and aerospace. By looking at the published data regarding merchant productivity it is possible to see an opportunity for the UK construction market to improve. Data from the UK and US confirms that both markets have failed to keep pace with continuous improvement in other industries. Construction is the last bastion of UK traditional industry, but it is not alone. Figure 3 shows the US Labour productivity index for US Construction compared to all other non-farming industries, and Figure 4 shows the UK Comparison of Output

Figure 3. US labour productivity output



Price indices. Both show, in different ways, how the construction industry has failed to maintain performance parity with other industries.

A separate study by the US National Institute of Standards and Technology (NIST) estimated that in 2002 \$15.8B was lost due to “significant inefficiency and lost opportunity costs associated with interoperability” in the industry (Gallagher, O’Connor, Dettbarn Jr., & Gilday, 2004)

The UK construction market has not changed drastically over the past 10 years in terms of size. The graph in Figure 5 indicates the volume of new orders and Figure 6 shows headcount indicating no reduction in headcount with respect to orders, and therefore no significant productivity improvement over the decade.

Also of note is the amount of consolidation in the market place. From 1996 to 2006 small sized firms (1-13 employees) continued to make up the bulk of the industry, dropping from 95% to 91%; the mid size firms (14-79 employees) increased from 3.2% to 5.9%; and, the large firms (80+ employees) increased from 0.4% to 0.7%. The industry, therefore, has a large, fragmented market and supply chain with many small businesses, indicating very low barriers to entry and a lack of appetite to dramatically improve the service the supply chain delivers to its customers. It is important to ask why this should be as it is not as if the industry cannot change.

Figure 4. UK comparison of output price indices

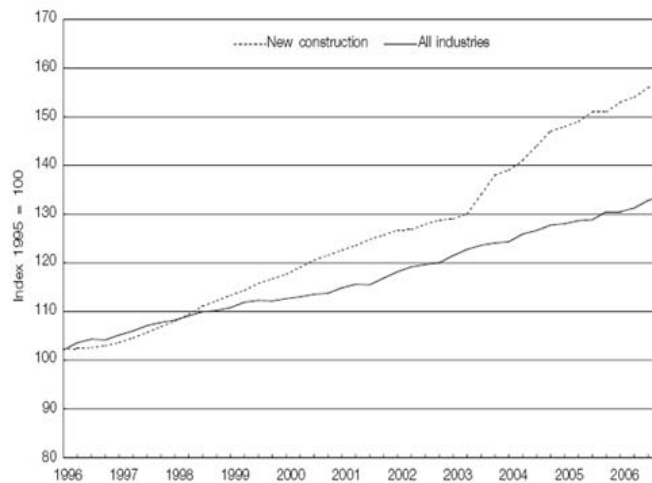
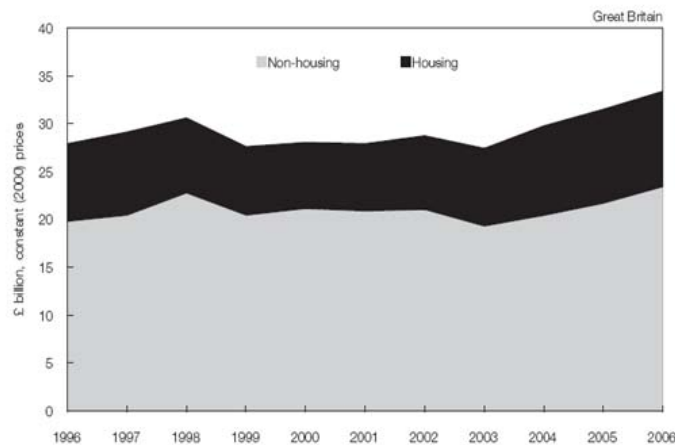


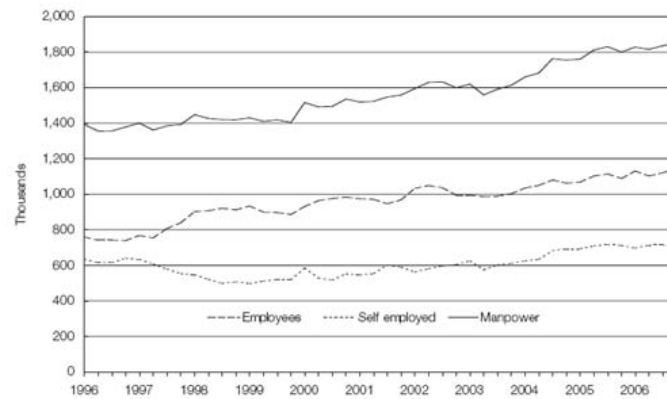
Figure 5. UK volume of new orders 1996-2006



When looking at areas of business practice that have changed significantly over the years few better examples spring to mind than the changes made in the area of Health & Safety. The industry changed its whole culture and approach to the way it works from the top to the bottom. Since the 1960's the growing intolerance of poor safety performance has lead to dramatic falls in the number of people killed and injured in the industry (Figure 7).

This dramatic improvement in performance has been made possible by a clear articulation of the problem through measurement and awareness, understanding the cost of both personal and commercial accountability, brought about through legislation, moral and commercial pressure. Making directors and employees accountable for performance and individuals aware of their responsibility for themselves and those around them has been essential. Potentially the next event

Figure 6. UK manpower (headcount) 1996 – 2006



that will motivate a change of attitude will be the realisation of the impact on the planet's environment, the problems that globalisation will bring in feeding growing populations, and the impact this will all have on lives and the way we lead them. The industry is responsible for providing and maintaining the built environment and will therefore need to play its part in achieving the goals set at Kyoto and Copenhagen.

One of the key methods to achieve a more sustainable design, delivery and performance of a building is to increase the amount of work undertaken off site. The cost, safety, usage and overall performance of the building created using this approach is significantly better. Key to this approach is the management of data and processes throughout the design and delivery cycle and this is where BIM could play a significant part. The development of designs using library object designs, and the feeding back of performance data to inform that design is surely a significant step to better design and products. It is important to identify what will catalyse widespread improvements in the products, productivity and performance of the industry. A key element will involve developing an understanding of the market, the capabilities of BIM and the associated technologies and how they are appointed. It is also important that the culture of the organisation is ready to adopt

change and that they have developed good supply chain relationships between those with whom they interact. To explore these issues, the following discussion has been categorised into People, Processes and Technology as these polarise all of the key variables that need to be considered in delivering any change programme.

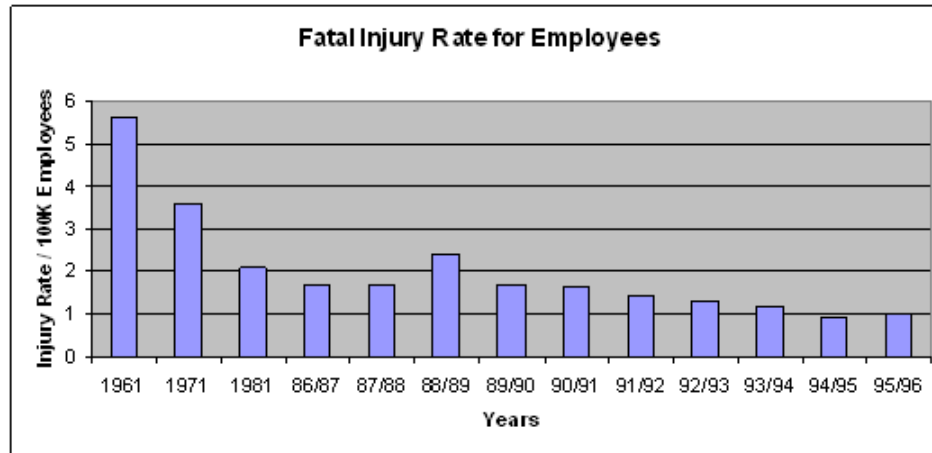
People

People are the industry's key resource. Construction remains a very labour intensive industry with many small (less than five) people businesses, particularly in the design and trade contractor ends of the supply chain. There is consolidation but progress is slow in many key trades and new approaches such as build off site have already started to make significant progress.

Organisational eReadiness

A recent European task force study on ICT sector competitiveness and uptake (European Commission, 2006) highlighted the importance of ICT based innovation in bringing productivity improvements and competitive advantage to industry. It showed a constant decline in labour productivity since the mid-90s which is partly attributed to the lack of ICT related investment.

Figure 7. UK fatality rates 1961-1996



Evidence shows that the higher productivity growth rates observed in the US and Europe's other world trade partners result from greater use/integration of ICTs by all segments of the economy. However, industries have not been in a position to capitalise on the investment in terms of productivity growth (OECD, 2003).

For example, the construction industry contributes one of the largest shares of wealth creation to Europe's business economy, accounting for 9.7% of gross domestic product and almost 60% of gross fixed capital formation. Despite embracing ICT over the past decade, construction industry investment is still inward looking with pockets of improvements failing to bring about sustainable competitive advantage to organisations. Salah (2003) showed that 75% of ICT investments in construction did not meet their business objectives. Furthermore, funding projects that are abandoned, significantly redirected or kept alive despite business integration failure, cost businesses directly and the dissolution of ICT's strategic benefits have resulted in decreasing levels of investment (Goulding & Alshawi, 2004; Peppard & Ward, 2004; Zuhairi & Alshawi, 2004).

A Construct IT for Business study (Alshawi, Khosrowshahi, Goulding, Lou, & Underwood, 2008) assessed Construction Executive thinking

about ICT investment and identified that the main inhibitor to ICT investment was the lack of know-how for the successful absorption of new technologies into work practices. Basu and Jarnagin (2008) stated that business executives do not fully recognise the functionality and full value of technology to the business, while IT personnel do not possess an understanding of the business and its strategic objectives. In many cases, ICT is still considered by the management of organisations as purely a cost cutting tool or a utility that is owned and managed by their ICT departments. This technology push approach alone, although to some extent is still dominating many industries like construction and engineering, will not harness the full business potential of Information Systems/Information Technology (IS/IT) and therefore is unable to lead to sustainable competitive advantage. While the implementation of a few advanced IT applications may bring about 'first comer' advantage to an organisation, sustainable competitive advantage can only be ensured by improving processes in line with management objectives using ICT as an enabler (Alshawi, 2007). To achieve this, the organisation must be 'e-ready' by preparing itself with the required capability to effectively absorb ICT enabled innovation and business improvement into its work practices (Hafez & Alshawi, 2005).

Organisational capability is the ability to initiate, absorb, develop and implement new improvement ideas in support of the organisation's business objectives (Alshawi, 2007). It is also referred to as the strategic applications of competencies (Kangas, 1999; Moingeon, Ramanantsoa, Me'tais, & Orton, 1998). The process of building organisational capability is the development and deployment of specific organisational competencies. The competencies that an organisation needs to develop in order to acquire the capability to strategically benefit from IS/IT prior to IS/IT investment, falls under four main elements, namely people, process, work environment and IT infrastructure. These elements are highly interrelated whereby developing competencies in one element requires improvement in the others. The core competency that an organisation has to develop in order to achieve the required IS/IT capability is process improvement. However, implementing process improvements requires people with the necessary skills and power (at all levels within the organisation). This in turn requires management consent together with the creation of an environment that can facilitate the proposed change (implementation) through such activities as motivation, empowerment and change management. A flexible and advanced IT infrastructure can then enable a high level of integration between these elements (Alshawi, 2007).

People and process are key to change and improvement, while work environment and IT infrastructure are enablers without which the first two elements cannot be sustained. The 'acceptable' level of IS/IT that can be successfully utilised in an organisation to ensure its business benefits are realised therefore depends on assessing a range of critical issues needed to ensure a balance between the organisation's readiness (mainly the factors required to adapt to the proposed change) against the level and complexity of the proposed IS/IT (which often hinders or limits success). This balance often includes many issues such as capital expenditure, resource availability, the

organisation's maturity and readiness, its culture and vision, and available IS/IT skills (Salah & Alshawi, 2005).

On the other hand, the time required for an organisation to build its IS/IT capability is highly dependent on the level of maturity of the organisation in each of the four elements. In terms of maturity, this is the adoption of 'good practice' in relation to a framework which encourages repeatable, stable and well-defined results. It is defined by the degree to which organisational processes and activities are executed following principles of good practice. Therefore mature organisations systematically undertake activities that are applied consistently across the organisation, while the outcomes of immature organisations are improvised through individuals. The development of an organisation is normally described in a simplified way using a limited number of maturity levels through which it sequentially progresses. Each level is described by a set of criteria that characterises an organisation at that particular level. These levels of maturity do not provide guidance on how to run an organisation, but rather a way to measure how mature an organisation is based on key processes and practices. Therefore, a maturity level is an indication of the effectiveness and efficiency of the organisation (Alshawi, 2007).

If an organisation is to achieve the required level of capability to address IS/IT based innovation and continuous improvement, then it has to:

- ***Create an innovative work environment:*** focused on developing and sustaining a highly skilled and flexible workforce which will have the skills and competencies to continuously introduce improvement through better and more streamlined business processes enabled by advanced IT. In this context, organisational learning and knowledge management become a necessity for organisations to sustain business improvements and competitive advantage from their IS/IT investments.

- ***Achieve effective business process and improvement:*** focused on improving the organisation's efficiency by directly IS/IT with the corporate, strategic and operational needs. This ensures IS/IT resources are 'in line' with business imperatives.

IS/IT Evaluation Approaches

A wide range of evaluation IS/IT approaches exist which can be divided into three different categories according to the focus of the evaluation.

- IS/IT as a product which is concerned mainly with evaluating the technical success, user satisfaction, use, and financial impact.
- The processes which underpin the development of an IS from which the measures are developed with the aim of improving the IS/IT development processes.
- The maturity of IS/IT within an organisation in terms of IS planning, infrastructure, utilisation, and management towards IS/IT effectively achieving the intended business objectives.

Each of these categories of existing evaluation measures have been criticised in the literature for suffering serious shortcomings, particularly in the way in which they evaluate IS/IT (Irani, 2002; Chan, 2000). Combined with this, the majority of the current IS/IT evaluation approaches are mainly post-investment, which attempt to assist managers in reviewing the results of their decisions on IS/IT investments and to assist them in future related investments. Therefore, in not fully addressing the critical factors/competencies (mentioned above) they do not address whether organisations are able to carefully prepare the appropriate 'organisational' conditions required for IS/IT projects to be successfully and seamlessly absorbed into their work practices. This clearly highlights the lack of organisational related and pre-investment

evaluation approaches that are required to embrace the key organisational elements, which can hinder the successful implementation of IS projects. If an organisation is to develop an IS/IT capability then it needs to rethink its processes, structure, work environment and people. This necessitates a 'forward looking' management evaluation approach which will enable managers to:

1. Undertake a general assessment of the 'current capabilities' of the organisation with regard to the key organisational elements and those associated aspects that impact on the development of the required capabilities, i.e. establishing the current state of an organisation's readiness.
2. Predict the 'required level' of change and resources to develop the target/required capabilities, i.e. identifying the organisation's 'readiness gap' for developing and adopting specific capabilities.

This process is illustrated in Figure 8.

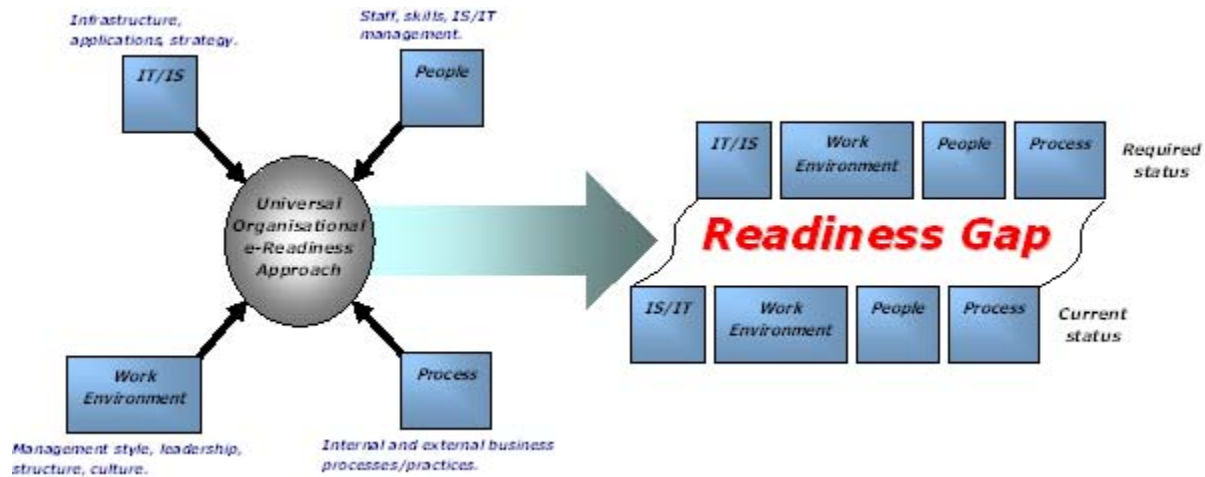
Assessing the Readiness of Organisations

Saleh & Alshawhi (2005) examined the IS/IT investment of a public-sector institution and a major oil company in terms of the key organisational competencies/factors of people, process, work environment and IT infrastructure to evaluate the readiness of the organisation. The purpose of these case studies is to demonstrate the importance of the key organisational competencies/factors as discussed above on the successful investment and implementation of IS/IT.

Public-Sector Organisation: Technology Driven Implementation Case Study

The first case study is a public-sector organisation that provides services and receives public and government money which it invests. The assets

Figure 8. Organisational e-readiness approach



owned and managed by the organisation equates to around US \$10 billion while their annual revenue equals approximately US \$1 billion. The IS/IT project was a total re-systemisation from the mainly batch-based processing system that had reached its maximum capacity, to a large 'stand alone' personnel information system, based on an inverted-relational database management system that was to accommodate approximately 800 employees. The basis of the decision to re-systemise originated from top management who had been informed by external sources that many local organisations had been successful in converting to a database environment. Four years from the time the project started and at a cost of between US \$7 to 10 million, the project was declared a failure. Over a decade has passed from the time the first study for a new system was conducted and the organisation still has its existing 20 year-old mainframe system.

Several issues in relation to the key competencies contributing to the failure of the IS/IT investment were identified. In terms of people, it was established that experienced (vendor) staff agreed upon by the organisation were only assigned for a short period during the early stages of the project and then were subsequently replaced by inexperienced staff. The organisation had not addressed

the issue of the qualifications held by the vendor's staff, prior approval for any change, or new recruitment, etc. within the contract but rather simply relied on the assurance of the vendor's initial agreement. This withdrawal of experienced staff also negatively affected the organisation's trust in the vendor. A culture also existed within the organisation that was individual and uncooperative in nature. There was a distinct lack of key staff to cooperate with the project team in that personnel believed by keeping their knowledge and experience to themselves as a job security tool, it would make them indispensable and increase their value to the organisation. Such an individualistic culture almost entirely prohibited the existence of in-house training programmes for new and junior staff by senior and key staff. In addition, the project team made no effort to relieve the tension in the relationship that occurred with users caused by the introduction of the project. This should have been addressed through the introduction of an awareness programme to explain the benefit of the project and to work towards eliminating unfounded suspicions amongst users.

From the perspective of the work environment, a distinct lack of positive relationships between different groups was present in the organisation, which caused resistance to needed change in both

structure and processes. A lack of strong support from the top management also prevented the project team from implementing necessary changes in the processes and structure. This decisive leadership allowed conflicts between different entities in the organisation to escalate right up until the end of the project, which had a negative effect on the overall project success. As top management caved in under the pressure of both the IS/IT unit and user groups, the project team was not allowed to modify the organisational structure when it was obviously needed to solve some of the design problems that appeared later in the project.

In relation to the IS/IT competencies, as the design of the new system was not successful in resolving the ownership of the data within the organisation this caused additional user resistance to the project. This was further fuelled by the vendor treating the project as a new system within an organisation that had no prior systems and thereby changing all the interfaces and environment that the user was familiar with. The implication to key users was that they were to forget their experience and knowledge that they had built over many years and which they considered gave them their value in the organisation. Many users believed the new system would mean returning to square one and consequently deprive them of the status they had gained.

The issues associated with process included the processes not being clearly defined and documented prior to the project, while process change was not suggested by the vendor or allowed by top management and users, although the project team recognised the need later in the project. This inability to reengineer processes resulted in the adoption of ‘corner-cutting’ and ‘go around’ techniques, e.g. allowing two units to access, modify, and delete the same data. This further caused problems and conflicts for the project team with users and among user groups.

Finally, the ‘strategic study’ (detailed requirement specifications) that was undertaken by the vendor did not address the real problems with the

system in that many of the performance indicators were not applicable to the actual situation. They were important for the vendor’s own experience in other countries’ environment, e.g. saving time and money, ensuring customer satisfaction, etc., but were not the actual indicators for the user manager. The project leader believed the vendor purposely avoided highly sensitive areas such as culture, processes and structure as their main concern at that time was to simply win the contract.

Middle Eastern Major Oil Company: Business Driven Implementation Case Study

The second case study is a Middle Eastern oil company that was established in 1934 by two major international oil companies in a partnership with the country’s government. The IS/IT project emerged from the ambitious plan set out by the company as part of major rehabilitation activities following the extensive destruction of the organisation’s installations and infrastructure (including its IS/IT). As part of the rebuilding activities of the destroyed infrastructure, the main objective of the Data Management project was to migrate multi-disciplinary data related to production, reservoir, geologic, geophysical, petroleum, drilling and surface facilities from several legacy systems, hard copies and/ tapes to a modern, secure and robust integrated database system. Staff productivity was expected to be greatly enhanced through easy data access to the integrated database, e.g. an internal company study had shown that the company’s geoscientists spend about 35% of their time on data searching from a variety of sources and formats, reformatting and re-organising. This project was to cover the data for four predetermined geographical oil-producing areas in the country (North, West, East and South) and to make the data accessible to the company’s geoscientists, petroleum engineers, technical supervisors and their associated managers. A change of top management that occurred mid-way into the

project life, who became interested in having the project succeed and gave it the necessary support that was previously lacking, ultimately prevented the project from being terminated. However, the system is currently not being used by users in the way it should be, and they are still relying on their old ways to conduct a considerable amount of the work tasks.

In terms of the organisational competencies/factors overall, the project did not address the preparation of any of them before it began; therefore they (and thus the organisation) were not prepared for the project, and neither was the need for Business Process Re-engineering (BPR) or process changes. The final proposal by the vendor did not address many of the needed IT infrastructure capabilities along with those associated with training, processes, organisational structure, skills, user and management issues, etc. Instead, the company team attempted to address these issues during, rather than before, the start of the project, which continued even after the project ended. Although some were achieved, there was still insufficient progress to make the project a success. For the company team, the project has turned out to be more of a rescue mission in that they were attempting (and continue to attempt) to implement some of what should have been implemented prior to the development of the system, e.g. improving relationship with users.

More specifically, in relation to the organisational factor of people the IS/IT awareness maturity of the old top management of the company was low and it appeared that the success of the project for the old top management was not as important as the prestige of having the particular well reputed software system at the company. The system was widely used by the major oil companies in the regional countries. During the time, the old company top management were under heavy criticism in relation to their integrity and competence in managing the oil company, which eventually led to their sacking. Announcing the computerisation of the company's operations to-

gether with implementing a well reputed software system would have relieved some of the criticism. Also, the project started without the level of skills (of both the organisation and vendor) it actually required to be successful. The project leader came to the project only a month prior to the official start date set by the contract. Almost all, including the project leader, had no prior experience in IS/IT-related projects and were not aware of the nature of the project. Major changes in staff status occurred during the project due to the introduction of newly hired staff and the support given by the new top management to bring in more qualified personnel from other areas of the company. In addition, the company project team were not fully dedicated to the project at its initial stages and this was mostly resolved towards the end of the project. A lack of adequate human resources in terms of quantity and quality existed until the late stages of the project life. The vendor/consultant staff also went through changes throughout the project life. While the project was not suffering from any shortage of technical skill, the users' skills still required some training and support, even though improvement was apparent from the initial stage.

From the perspective of the work environment, the old company's top management did not want to pay for the full solution/project in the beginning and the project team were informed to ask for more as and when the money was required, although the budget-approval process in the company took over a year. The view of IS/IT and the project by the company top management shifted with the change in top management personnel, which in turn lead to an improved situation where budgets were approved without constraints. The new top company management were regularly kept informed of the project status through various mediums. The perception by the new top management of the project was that of a technical nature and not administrative, which was a source of some problem at the beginning of the project when the team was under an administrative-oriented divi-

sion. This subsequently resulted in the promotion of the project leader along with the movement of the team from a division supplying administration services to a function under a technical division. This gave the team more power and they began demanding more cooperation from user groups. Furthermore, users were not involved from the beginning of the project which resulted in a lack of trust and communication between IS/IT and user groups. The execution of an awareness and support programme improved communication between the project team on one side and users and management on the other (culture), which not only had an effect on improving the usage of the system but also the survival of the project.

In terms of process, although the vendor's feasibility study recommended BPR, the old company top management did not implement it as a budget had not been allocated for the activity. BPR was conducted later during the project, however, since the team were not experienced in process improvement or BPR, the improvement on the process factor was slow and it appears that the team continues to improve the process by 'trial and error'.

When focusing on the IS/IT infrastructure element, it was established that the company project team began the project with little hardware capability as insufficient budget was approved by the old senior management at the beginning. It was during deployment that the team recognised that more licences and a bigger server with bigger storage and power were necessary. The impact of the lack of hardware capability was to cause delays, which continued right up until the extra budget was approved by the new senior management.

Albeit post-investment, the evaluation of the two different case studies demonstrate the impact of the organisational competencies/factors on IS/IT implementation failure. In terms of the first implementation, a technology-driven solution within a public sector organisation, the result saw the project terminated and the organisation's continuation with the old system. Although the second

implementation project, (originally) a business-driven solution within a major oil company, was not terminated, the impact was that the system did not meet the original business objectives and it subsequently having, in many instances, to resort back to previous ways of working. Hence, both case studies clearly highlight the importance for organisations to both assess and as necessary build their organisational capabilities associated with people, process, IT infrastructure, and working environment prior to investment. This will facilitate preparing the organisation in achieving a successful and sustainable IS/IT implementation from their investments.

This can be extrapolated onto the same, but more complex, task of implementing BIM where the technology and most project teams have yet to reach the level necessary to successfully deliver repeatable benefits and are far less likely to succeed in a constantly changing virtual project environment. Successful implementation requires clear leadership and ownership from the leadership teams in the supply chain, especially the Client. Until now, no single member of the UK supply chain has been able to sufficiently demonstrate to itself the benefits of the BIM approach to enable them to adopt the approach on an ongoing, sustained basis. This has been mainly due to the difficulties in organising a disparate supply chain. However, as the client and contracting community continue to develop their understanding of the management of BIM in the supply chain and as the tools improve, this situation will change and evolve.

Alshawi (2007) offers a number of measurement techniques to assess the level of 'e-readiness' and an area of future development should be to re-visit this area with specific focus on BIM and interworking within a variable supply chain. The benefits and their measurement are discussed further in the case studies later in this chapter. Furthermore, the training and education of both new and existing people in the supply chain is of vital significance. The industry, as a whole, needs

to deliver enthused, aware and capable leaders, workers and tradesmen throughout the industry. This approach needs to address all levels and ages and must include:

- Academic and Further Education to develop future professionals.
- Tradesmen and craft skilled employees.
- On the job training.
- CPD for existing staff.
- Institutions and trade bodies support through knowledge networks.

The final element which cannot be overlooked is that of developing leaders with the necessary knowledge and expertise who, at all levels, can successfully take BIM forward in a sustainable manner.

Process

Davenport (1993) states that “a process is simply a structured, measured set of activities designed to produce a specified output for a particular customer or market” and he continues by stating that “processes are the structure by which an organisation does what is necessary to produce value for its customers.” This holds true to this day and it is interesting to observe how processes have really only risen to the top of the agenda since businesses have discovered how to transact with third parties outside the corporation. In the Mainframe days and in a proprietary world, this was straightforward. All users operated on a single system and remained under the control of the host system. However, in the internet age communication to the wider supply chain must be more formal or the processes will break down, creating poor data management which may result in mistakes and none of the benefits of working in a collaborative way being realised.

The industry’s old paper processes were slow and methodical, while data definition was simple (usually only 4 layers of tracing paper or film).

The length of time it took to complete a drawing was generally known, all employees could read and use drawing issue sheets, and everyone had a paper copy of every drawing on the rack. Digital systems have brought advances in accuracy and productivity especially in rework, but have also brought a whole raft of other management issues. In 1995, the Process Protocol (Kagioglou, et al., 1998) project agreed with the conclusions of Latham (1994) who in turn confirmed all the previous studies, concluding that the fragmented nature of the industry, a lack of common processes and very poor adoption and use were major factors that contributed to the poor communication between all parties working on construction projects. Some of the major outcomes of this investigation were as follows (Latham, 1994):

- Although a number of changes have been identified in previous investigations of the construction industry, the majority of them have not been implemented. This shows that the construction industry might be inherently resistant to change.
- Clients are the main parties who could instigate changes in the industry; therefore they have a responsibility and a part to play in this change process and none more so than the government itself.
- There is a need for more effective collaboration between clients and contractors.
- There is also a need for effective processes throughout the construction life cycle starting from the management of the client brief to the selection of the supply chain participants and eventual construction/on-site processes.

The main outcome and recommendation of the Latham report is that it calls for significant cost savings by the utilisation and formulation of effective construction processes, which in turn will lead to increased performance. The recommendations of the Latham report are repeated

by Sir John Egan's report entitled "Rethinking Construction" (1998). This report identified five key drivers of change which need to form the agenda for the construction industry:

- Committed leadership.
- Focus on the customer.
- Integrated processes and teams.
- Quality driven agenda.
- Commitment to people.

Within the focus for integrated processes and teams, four key elements are identified which include: product development; project implementation; partnering the supply chain; production of components. Furthermore, the Egan (1998) report calls for a total performance improvement of 30%, requiring significant improvements in the way the construction process is enacted. This still requires a significant re-engineering of construction process involved in the end to end delivery of a construction based asset, through into operations and demolition/recycling.

There have been other more generic approaches at the implementation of processes and some initiatives which probably did the cause a disservice, such as BS5750. However, its successor ISO9001 has, together with more sophisticated approaches such as EFQM, begun to get the whole understanding of process management. The undeniable linkage between well run businesses with good well implemented processes is coincidental to those which enjoy good levels of commercial success. There are few documented examples of this in the UK but one such business, Costain Ltd a UK based contractor, embarked on a combined business, technology and process improvement strategy and demonstrated that as their level of business process compliance improved so did their volume and profit. The following quote is taken from their 2007 Annual Report.

"Measurement and Compliance with Business Processes is measured in Costain through the Implementing Best Practice (IBP) programme,

which involves each project being formally assessed at 6, 10 and 26 weeks after project commencement. These assessments check compliance with the Mandatory Gates and Controls as defined in IBP. These assessments are formally recorded and reports are issued to the appropriate Project Team and Sector/Regional Director. Each measurement is a percentage of the mandatory parts of IBP that have been complied with at the time of the assessment and therefore target compliance should always be 100% (Figure 9 & 10).

There is a clear correlation between the IBP Compliance at six weeks into a project and the performance of the project in terms of cost, profit and time (Figure 11). Integrated with the process, Costain also produces reports on all health, safety and environmental issues and incidents.

Therefore the IBP Compliance provides an early indication of the probable outcome of a project. Targets are established each year and progress towards that target is measured monthly and discussed at board level, with senior management tasked with providing action plans as necessary to bring about improved compliance and performance."

This approach is now being repeated in a number of organisations as the message and continued consistency in improvement is seen as a necessity for survival in such a competitive, low margin sector. One differentiator in the Costain example was the integration of the business, process and technology strategies. To enable these changes two key enabling technologies; the Enterprise Collaboration System (ECS) and ERP System were deployed. To ensure this investment was adopted over five thousand man days of training were delivered by the organisation. This had the effect of ensuring the vision, process and technology were all clearly understood by the whole organisation.

The structural steel marketplace has benefited from significant technological development, mainly sponsored from the Process Engineering sector, which has enabled the end to end full

Figure 9. Process improvement, Oct 05–Dec 07

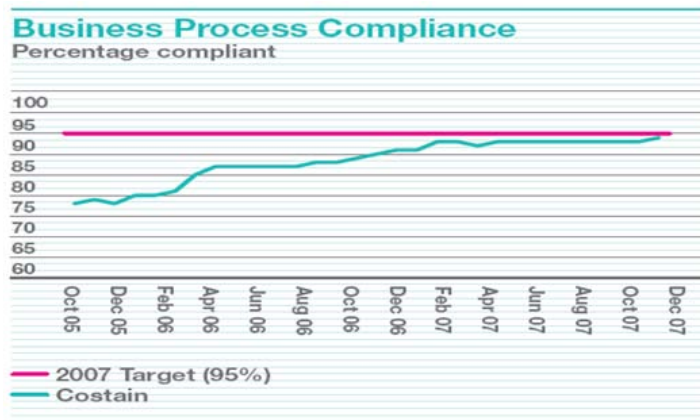
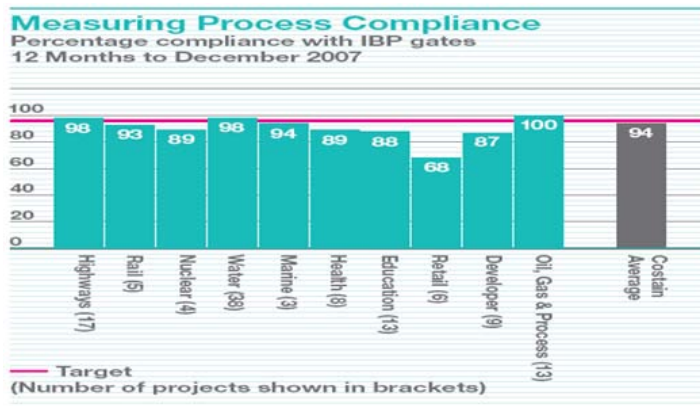


Figure 10. Improvement by market sector

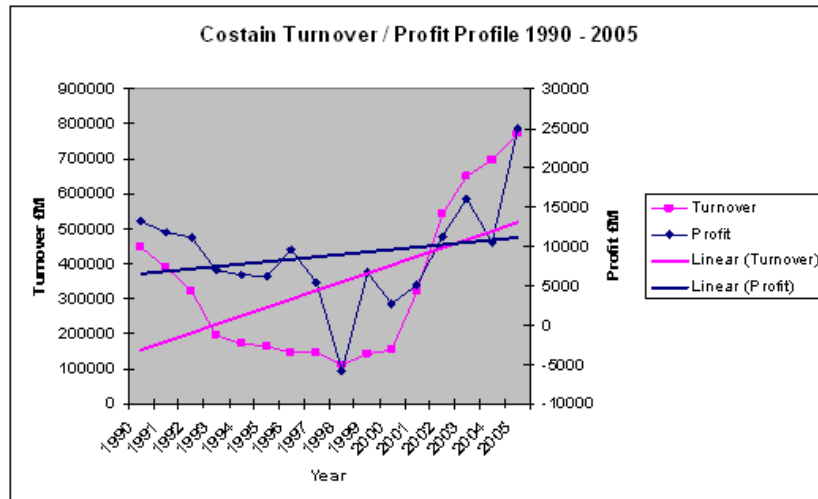


digital integration of the production lifecycle. It is important to establish why these capabilities have been available for over a decade and yet the level of adoption is tiny with respect to the size of the market. The technology is available and the data definition and exchange tools have been in place for many years, but there are no consistent standard processes for production, sharing and most importantly for checking and approving the data. So, by default, none of the data created have formal status and a sub-set of the data has to be created (called a drawing) to enable the design to be checked and approved for use. This, coupled with poor understanding of the process, has led

to the low level of trust amongst users in the available data (for whatever reason), with many preferring to trace and take off new drawings from the available 2D records.

The location of checking points throughout the delivery process are various and are derived from the need to guarantee the integrity of a structure or member, to ensure the satisfaction of legislation or planning or the recovery of fees or other payments due. There are many procurement routes defined by various forms of contract, each purporting to be specific to a need or circumstance. In the main, design and construction contracts of all descriptions tend towards the various forms

Figure 11. Costain turnover/profit profile 1990-2005



of JCT, which were developed to satisfy a very different traditional approach. While successful in achieving some form of cost certainty and protection to the client, the approach has very rarely been held up as the most collaborative and best value methodology, although moves are afoot to address these issues. Some clients are aware of the problem and, seeking to capitalise on the benefits of getting best value as well as best cost, have moved to the more collaborative models, such as NEC and the various target cost methods. These draw on the attractive features of “construction management” and “management construction” to deliver a product that meets the client’s requirements without incurring the tension associated with the traditional routes throughout the supply chain. This is because pricing is achieved at a point of understanding.

The differences in various procurement routes are further confused by language and taxonomy variations between the various routes and disciplines. This is exemplified by the names given to design stages by the building and civil engineering communities. (RIBA/GRIP/etc) Furthermore, if the procurement route (contract), technical and legislation checking points were standardised

together with the structural and quality checking processes, this would give a number of process “focus” points throughout the delivery process. The responsibility of the individual organisations to maintain consistency and profitability would remain their own but it would be clear as to what the supply chain needed in terms of process as well as data at each point.

The approach is now beginning to be formalised in the file base collaborative world of design. BS1192:2007 has, for the first time, a clear description of the business processes required to deliver “Construction Production Information”. The BIM equivalent to this is the Information Delivery Manual (IDM) which is developing the definition of processes to deliver the overall Building Information Model product. However, to get to the point whereby an IDM can be used from a process point of view, industry needs to have moved its way up the evolutionary “ramp” discussed above. It took over twenty years of CAD to get a defined process and data management standard in the UK. How long will adoption of this take? Also how long will it take to complete the IDM and the tools needed for it to be fit for use in the delivery of production BIM information?

However, all is not lost in the short term as Costain has demonstrated. There is a good commercial case to start this journey wherever an organisation is located within the supply chain and from this begin to progress up the BIM ramp.

Technology

For the industry to move towards the ubiquitous use of BIM there needs to be an evolutionary process of change. However, there is no need to wait for a complete solution to emerge before making use of what is available, for there are significant benefits to be gained by the adoption of existing technologies. For instance, interoperability consistently comes top of the wish lists in major surveys but that does not mean organisations should wait for perfection in IFC-based interoperability before buying whichever application suits them. It is also true that this whole subject is so complex that it will be a long time before any one system will be capable of all elements of BIM, if at all.

The situation in fact reflects that of Word processing 20/25 years ago, when there was a market leader (WordStar), and there was simple text based file exchange (tags used for mark up were different for individual applications). Nowadays there is still a market leader (MS Word) but there has also been the very rapid emergence of XML based open document formats that are based on international rather than proprietary standards, thus enabling the simple sharing of documents, especially over the Web.

For a project to make use of BIM technology, a strategic review should be undertaken as early as possible in the life of the scheme to establish how the project will be designed, procured, built and operated. The later in the project lifecycle that this is done the fewer options are open to derive benefits. There is not sufficient space in this chapter to discuss all the options but clearly the strategy should set out a selection of criteria pertinent to the project, including consideration of:

- Risk Profile.
- Whole Life Cost.
- Site Considerations.
- Supply Chain.
- Asset Type and Use.
- Specific Site Risks and Use.
- Environmental Issues.

This would then allow a technology strategy to be developed to satisfy these considerations; for example, a hotel refurbishment let on a design and build basis would differ from an Early Contractor Involvement highway scheme. The diagram in Figure 12 indicates some of the tools that may be used in the creation of the data sets in a typical scheme.

The sharing and reuse of data is also of key consideration at this strategic stage. This includes whether all the parties will use the same toolset and standards. If not, then the useful exchange of data may be offset by the labour involved in formatting it for re-use. Issues to be aware of, even if the same toolset is used, are settings, versions and the configuration of software. All of these will need to be specifically managed during the lifetime of the scheme. If a number of tools are going to be used it may make sense to use a neutral viewing and clash detection tool, such as Navisworks. This, in effect, reads all viable model files into a network viewing format. While this is very helpful from a tactical point of view; however, in reality it only serves to move the proprietary problem down the line.

Other consumers of data may want to view the asset data through other more mainstream mediums. This may include the Geospatial Information Systems (GIS) community or the emerging Virtual Earth and Web users who are becoming accustomed to working with large volumes of data from disparate web services, all delivered via a lightweight web format.

Figure 13 shows the data hierarchy between the hierarchical level breakdown of a building held in a BIM and the abstraction possible if integrated

Figure 12. Tools matrix

RIBA Work Stages		
Preparation	A Appraisal	Massing Tools Cost Planning Risk Management Office Applications Collaboration
	B Design Brief	
Design	C Concept	CAD Tools BIM Tools Visualisation ERP – Commercial Systems Structural Analysis Environmental Analysis Sustainability
	D Design Development	
	E Technical Design	
Pre-Construction	F Production Information	CAD Tools BIM Tools Visualisation ERP – Commercial Systems Collaboration Programme Tools
	G Tender Documentation	
	H Tender Action	
Construction	I Mobilisation	CAD Tools BIM Tools Visualisation ERP – Commercial Systems Collaboration Programme Tools
	J Construction to Practical Completion	
Use	K Post Practical Completion	Asset Management Facilities Management Building Management Systems

as part of an overall GIS – BIM – VE (Virtual Earth) world.

Currently all of these options require specific strategies to use proprietary formats for the delivery of data and information. Key issues with these approaches are the closed nature of the formats, inherent scalability issues for large schemes and the inability of our existing infrastructure to share these large files. For this reason an open standard was tabled around a decade ago for the development and delivery of interoperable BIM data.

The Exchange Format Industry Foundation Class (IFC)

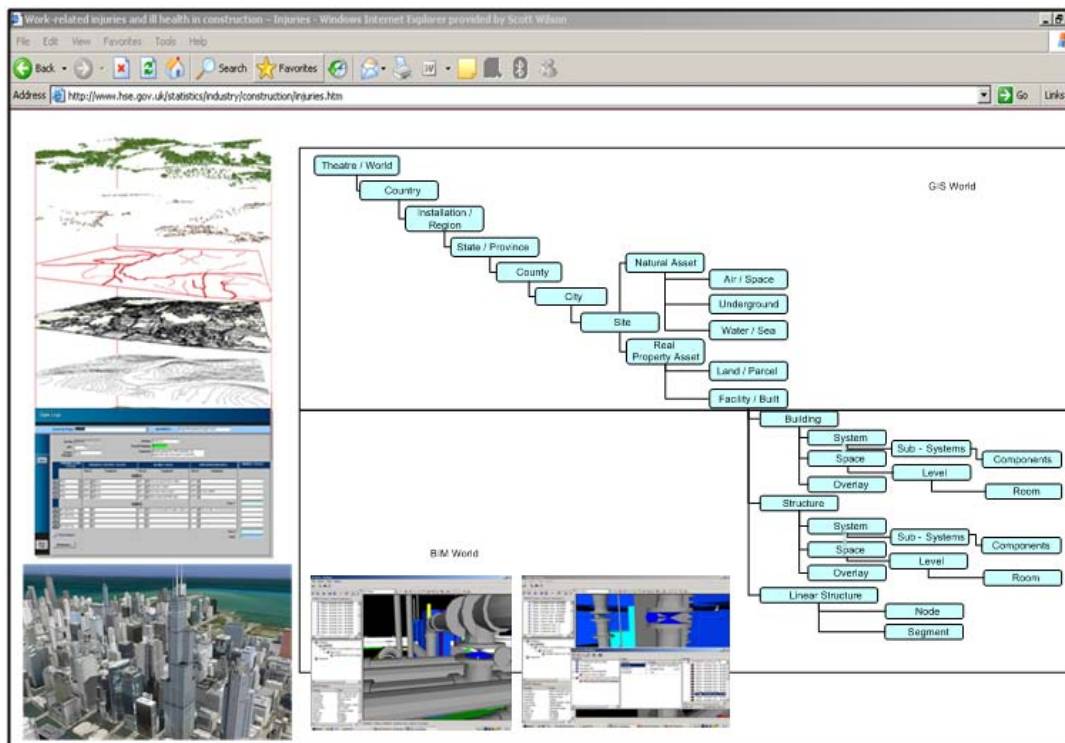
The open international standard IFC, defines an exchange format for information or data related to a building and its surroundings. The currently

released version web file 2x3g of the IFC standard includes facilities to exchange GIS data, e.g. where the building is located and information about surrounding buildings, and facilities to tag all information with a globally unique ID from an internationally agreed ontology. Thus the IFC's provide a computer understandable format in which all relevant building information can be exchanged between two parties.

What Information to Exchange (Information Delivery Manual - IDM)

The IFC's allow various data to be exchanged in various ways. If a receiver of information wants to be sure they can utilise the information they receive, the sender and receiver need to agree on exactly which information to exchange. The

Figure 13. Hierarchical data level breakdown of BIM and GIS worlds



Information Delivery Manual (IDM) specification provides this. The aim of the IDM is to specify exactly which information is to be exchanged in each exchange scenario. For example, when an architect designs a building, they need to make sure that they receive information from the structural engineer about which walls and columns are load bearing and which are not. At the same time the structural engineer needs to know the function of each of the spaces in the building in order to calculate the right design loads for the structure. IDM's should typically be included in the initial contracts in the early stages of the building process. They will also have a formal part in explaining the exchange scenario in plain text for human readability, and in a technical way to enable implementation of automatic checks and validations in applications. For example, the engineer in the above example can run a quick test through a computer and verify that the architect

has sent of enough information to get started on the work.

What is the Quality of What you are Actually Exchanging (International Framework for Dictionaries - IFD)

In order to automatically verify the information in an exchange process (as described above) it is necessary to detail the information further than the general level of the IFC standard. For example, when the architect supplies information about the type of materials in the beams and columns, they must do so using a plain text string. Even if they spell this correctly, there is no guarantee that the receiving application will understand exactly what this text string means. This is further complicated if they use a different language, dialect or the plural form of the word. Ideally, the computer should be able to understand even this type of information in the IFC formatted information received. This

is typically the scenario addressed in semantic searches on the web. However, in order to interpret the semantic then the semantic needs to be described first.

The Evidence

The search for working case studies has helped polarise the view that the red line on the ‘ramp’ diagrams is the line between current best practice and the most optimistic view of where the authors would like to see iBIM’s. The examples described below have been selected as representative of each of the various stages of evolutionary development described by the ‘ramp’. Unfortunately the various methods of benefit measurement are inconsistent over the projects but attempts have been made to draw some overall observations and characteristics.

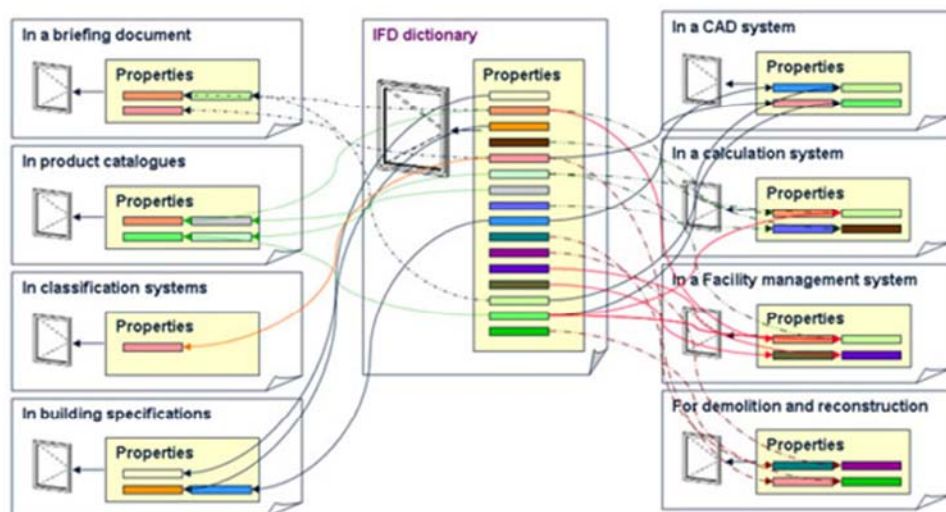
BIM Evaluation, as discussed, is a journey of building data and process sets and improving as the organisation progresses. The benefits that can be accrued at each evolutionary step can be seen through the case studies to improve incrementally and it is anticipated that the step to stage three will yield even more significant returns.

The concept of using a level rating system was discussed previously in the “Background” section, and the case studies below have been selected to demonstrate the characteristics of how the various projects have approached key issues of technology, contracts, training, etc., to all deliver significant improvements in performance over their traditionally run projects.

BIM Level “0”

Case studies at this level of the evolution have purposely not been presented in this chapter as the focus is towards the top of the evolutionary ramp. It is however worth noting the figures quoted by the research into the US market by the National Institute of Standards and Technology (NIST) in 2002. This stated that the cost of poor interoperability was estimated to be \$15.8M which they considered to be conservative. This represents around 2% of the industry’s revenue. If this figure was extrapolated to the UK market, which employs 2.1 million people in 250,000 companies which are responsible for 8.2% of Gross Value Added, it could represent a proportionally larger number based on a more complex, bespoke market.

Figure 14. IFD operational schematic



BIM Level “1”

The Managed CAD Environment model is where the vast majority of businesses are now seriously attempting to move into. The leading businesses, including Laing, were achieving good results in early production pilots in the early 1990's using these techniques and work they pioneered has resulted in the publication of the new BS1192:2007 and Avanti Processes.

Case Studies

Endeavour House

The Endeavour House project was the proof of concept of a government funded Partners in Technology (PIT) research project in partnership with the University of Salford. The project was based on research into the use of a 3D object model based Project Information Management system and including the use of a Project Extranet.

Two similar buildings had been constructed as part of BAA framework contracts with its supply chain. The object of the framework was to prove that project costs could be reduced if the learning of one project was passed onto the next and in particular, when using the same team. This did not turn out to be true as the first building was

delivered 25% over budget and the second, whose budget was reduced due to the perceived learning on the first, was delivered 25% over that cost.

For the third building a decision was taken to use a fully structured and managed process, based on the concept of a Project Information Model including a 3D object oriented project model. The whole process of collection management and dissemination of the models, documents and information used a bespoke in-house developed collaboration tool (Project Extranet). The project's commercial performance identified a measured saving of 10% of final project costs. This included a 50% reduction in the contract growth seen on the previous two buildings.

Heathrow Express

After the collapse of the tunnels on the Heathrow Express project BAA set up an innovation team to suggest better processes for the management of design information and project documentation. It set the scene for a totally collaborative process based around a 3D modelling environment including:

- CAD and Documentation Standard Method and Protocol.
- Fully Managed Single Model Environment.

Figure 15. Endeavour House, Stansted Airport

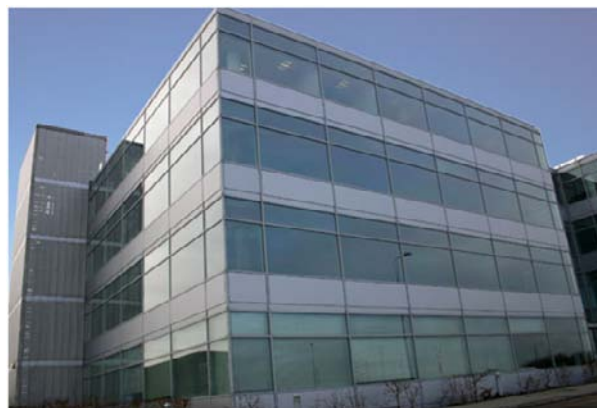


Figure 16. Heathrow Express

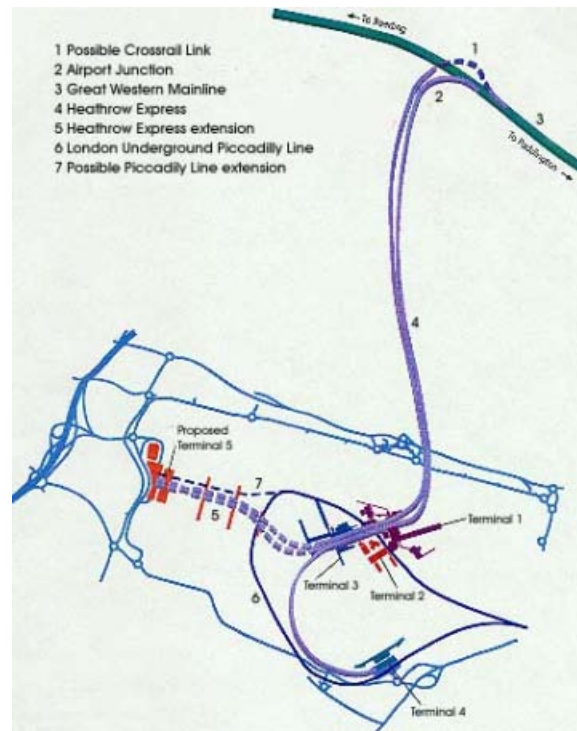


Figure 17. HEX Paddington Station



- ISDN Collaborative network to site and printers.
- Electronic drawing management.
- 2/3D Modelling.
- Integration and spatial co-ordination.

- Visualisation and Animation using early Virtual Reality Software.

The project identified savings of £720,000 on printing within the SME team. It saved 18% Drawing Production Costs and designed the signal sighting in a Virtual Construction Model saving early design programme time, with the project being delivered three weeks ahead of program. Measurements carried out by the client consultants concluded that the savings to the project were estimated to be in excess of 10% of the overall construction cost.

Basingstoke Festival Place

This project was a client led design team project with the contractor employed on a traditional JCT D&B contract. The contractor decided to build a full 3D model from the design team's drawings/ documentation having been checked, reviewed and

Figure 18. Basingstoke Shopping Centre external visualisation



signed off ‘fit for construction’. The project also had a bespoke in-house collaboration system available for model, document and project information control. No data management was attempted on this project. All errors and clashes identified in the model using Navisworks were recorded and RFI’s were raised. The RFI’s were not fully dealt with and the contract growth was approximately 25%. Some of the growth was due to client changes but some £10M was attributed to design ambiguity and represented 9% of the final construction cost that could have been avoided.

It was accepted that it would have been better if the design supply chain collaborated and produced the 3D models as part of the normal design development activity. However, on those projects where the design teams do not have the required skills models built as a secondary activity are effective in reducing cost and risk. The investment in building a model is approximately 0.5%-1.5% of the project cost with a reduction of 50% of the normal package growth of 25%. This equates to 10% of the final construction cost for material cost only.

Figure 19. Basingstoke Shopping Centre internal visualisation



BIM Level “2”

Enfield Town Centre Project, London

One of the first projects to employ the standards supported by Avanti was a multi-use development in Enfield, North London, designed by Reid Architecture. Client ING funded the £25 million scheme of largely retail/restaurant/health club users, but it also included a civic facility incorporating council offices, a library and a public theatre. When Costain was appointed as the main contractor the decision was taken to adopt Avanti Standards and operate in a shared model environment. Costain’s bespoke extranet iCosnet was employed and the collaborative model was built using active .dwg files.

Critically, the team exchanged and built on live model files; the orientation, origin point and scaling of which were completely aligned which avoided the necessity of swapping fragments of digital information, PDF’s and/or frame (print) files appended to emails. The process of restructuring the previously completed CAD work to achieve this alignment required considerable concentration and effort but the benefits, according to the lead Reid project architect, far outweighed the initial reticence. Subsequent coordination of the work of subcontractors, all of whom were obliged to

Figure 20. Enfield Palace Exchange - montage Image developed from BIM model



participate in using the system, was vastly simplified. Bourne Steel also used the model data, together with Revit software, as the basis for its own detailed modelling.

The 3-D expression of the shared model was facilitated, managed and updated by a third-party company employed by Costain, called TruAxis Ltd. They assisted the team with the coordination activity, focusing on 3-D clash detection, but also provided construction sequence simulations (4D) that were used by Costain to improve the efficiency of construction programming. The model was also used as the basis for photorealistic renderings for marketing. The models were built using 3D object tools including Autodesk Architectural Desktop, Tekla, Multisuite and BS Link, with the various models

brought together for coordination in Navisworks.

Costain claims that very considerable cost savings have been made by adopting a BIM approach. There were also very appreciable benefits experienced by the entire team associated with the clarity, simplicity and efficiency of use of the model for the everyday processes of information gathering, design creation and data exchange. The team estimates that at least 20 weeks were saved in the time needed to prepare information for issue to others.

BIM Level “3”

As yet there are no true end to end implementations of “iBIM” as there are no production environments

Figure 21. Enfield Palace Exchange - night time image developed from BIM model



available to implement the IFC data exchange, and the IDM process models are still under development. This does not mean, however, that no one has yet achieved great things with the technology in the specific line of business, including the environmental market. Development is progressing rapidly and strenuous efforts are in place to bring the approach to the market.

The Benefits

The case studies presented above have all been selected as they are amongst the few key UK projects that have been formally measured to record and demonstrate the investments and return shown in hard commercial terms. Unfortunately, the benefits gained in each of the cases were not measured in any consistent manner in relation to the adopted method of measurement, specifically relating to what was measured, and the phase(s) within the lifecycle of the asset/facility where the

benefits were realised. Nevertheless, these cases provide clear evidence that there are benefits to be gained. Figure 22 summarises these benefits, bringing them together to begin to build a collective picture of the potential benefits across the whole lifecycle of the asset/facility.

Based on the current evidence there is, in particular, a lack of data available at the early concept and post-construction stages of UK projects on the real, tangible savings/benefits. However, evidence in the form of empirical data indicates opportunities for future savings at the early concept stages, potentially through the availability of performance-related information and knowledge from previous projects that can facilitate better informed early design. At the post-construction phases the opportunities mainly lie in the availability of information to enable a more efficient and proactive management of assets and plant.

Focusing on the phases of design, pre-construction and construction, the evidence in relation to

Figure 22. Summary of case study benefits

RIBA Work Stages		
Preparation	A Appraisal	There is little data other than empirical to indicate tangible savings at the early stages of projects in the UK to date. It is expected that the majority of future savings will be made through the use of data available from the result of feeding performance information into the project libraries and enabling better informed early design
	B Design Brief	
Design	C Concept	All case study projects identified improvements at the actual deliver of design stages with "understanding" and "spatial coordination" the two clear big wins. The data sample is too small for us to draw final conclusions but was between 8 – 18% on design fee
	D Design Development	
	E Technical Design	
Pre-Construction	F Production Information	Again the sample sizes make this data set very difficult, but clearly there are savings made on the coordination of trade contractor design information and shop design. The sample is more consistent and shows figures of between 8-10% of construction cost
	G Tender Documentation	
	H Tender Action	
Construction	J Mobilisation	Again the sample sizes make this data set very difficult, but clearly there are savings made on the coordination of trade contractor design information and shop design. The sample is more consistent and shows figures of between 8-10% of construction cost
	K Construction to Practical Completion	
Use	L Post Practical Completion	There is little data other than empirical to indicate tangible savings at the late stages of projects in the UK to date. It is expected that the majority of future savings will be made through the use of data available to better manage assets and plant to reduce costs through applying proactive techniques

the potential savings is more tangible, although somewhat indicative due to the limited number of UK project cases and the inconsistency in the formal measurements. However, improvements during the design stages were realised in the range of 8-18% on the design fee with the significant contributors being in improved understanding and spatial co-ordination, clash detection, etc. At pre-construction and construction, savings of between 8-10% of the overall construction cost were achieved mainly through the co-ordination of trade contractor design information and shop design.

4 FUTURE TRENDS FOR BIM

Focusing on future trends, these are likely to be heavily influenced by the pace of activity in a number of key areas.

- Technology
 - How quickly will the Virtual Earth, GIS and BIM technology come together into a single seamless infrastructure to give simple open access to all users through a simple internet browser interface?
 - How can the work started on integrating GIS and BIM be completed?
 - How will the infrastructure providers deliver a secure, scalable platform to enable integrated delivery of all related data and processes through the use of the model server?
 - How can only the pieces of data a user needs to perform the intervention they need be delivered? The data delivered needs to be wrapped in a process set to ensure it maintains referential integrity both with its related data but also the processes which will act upon it. (e.g. RIBA stage D data should not be available to an MEP maintenance contractor)
- How can the identity control and security be managed?
- How will libraries and the feedback processes to inform better design be managed?
- Process
 - How well can standard processes across the whole supply chain or at least at the interfaces of non participating organisations to allow the process to propagate be defined?
 - Will the fixing of processes stifle entrepreneurial flair and approach?
 - Will legislation fix some processes (e.g. Part L and sustainability?)
 - How quickly will the contract writing bodies respond to the new ways of working?
 - How do organisations deliver competition along with transparency in the delivery process?
 - How can the alignment and adoption of the contractual and legislative controls with the BIM delivery model, and most particularly the alignment of the IDM be achieved?
- People
 - When a suitable end to end digital infrastructure is delivered it will become much easier for the academic and vocational training establishments to deliver useful meaningful education to people coming into the industry
 - Businesses in the current supply chain need to develop both Business and Technical strategies that enable staff to be developed with the basic skills to use the emerging tool sets.
 - How can cultural, political and transparency issues be addressed?

- How will people react to the needs of delivering a sustainable world?

To deliver an online virtual community that can access data about the world, community or project they are interested in via a simple web interface is, in concept, not a massive leap. In conjunction, Google Earth is currently used and the possibilities are apparent. However, to be able to manage the vast quantities of data needs careful consideration.

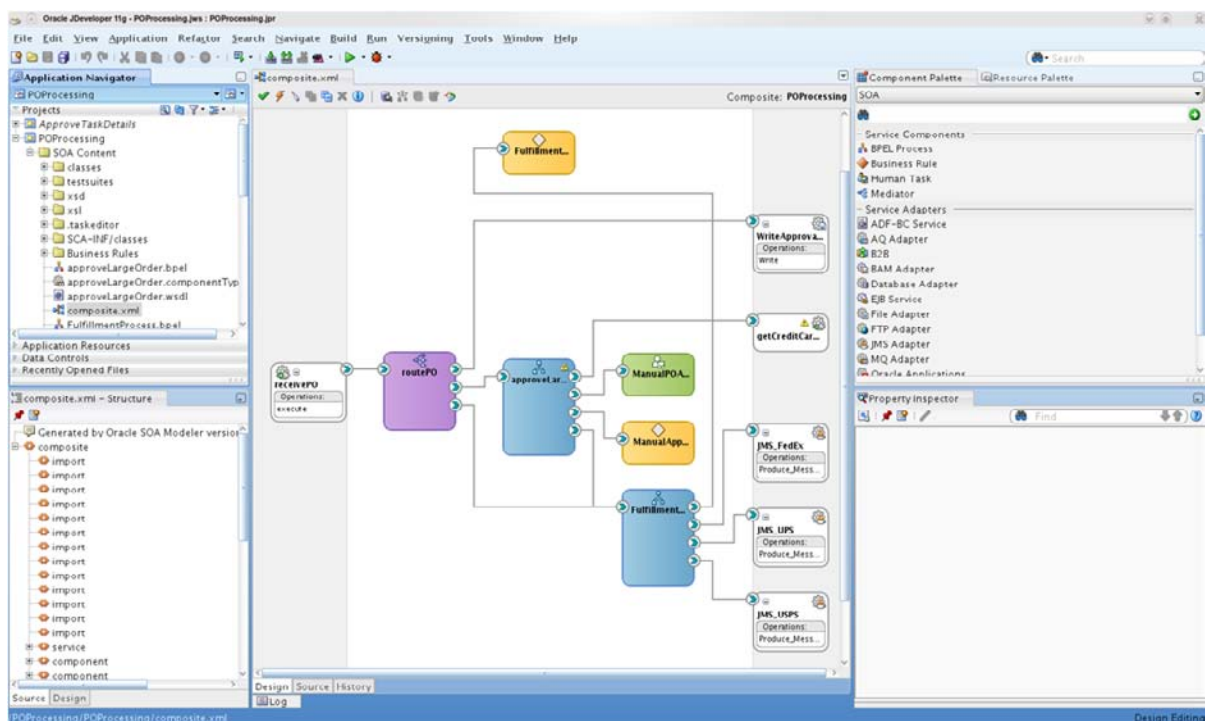
GIS data is now routinely hosted in spatially aware relational databases allowing the security and integrity of such tools to provide appropriate data to those who have rights over it to view, use and update. To make BIM data available on a similar basis, these vast quantities of data created by the various tools need to be stored in a similar way to the GIS model. Only then can all of this data begin to be brought together in a clear and transparent way that delivers the strategic

benefits of BIM throughout the whole lifecycle of the project. The cloud computing technologies now emerging will soon provide the capacity, transport mechanisms and processing power to achieve the goals.

The advantage of the database and transaction based approach is that it is now possible to implement workflows such as Business Process Execution Language (BPEL) (Figure 23) over such data sources to enforce consistent transactions as have been seen in the ERP workflows. It is also possible within these transactions to only send the data set needed to complete the specific task rather than the entire DWG/DGN file, thus reducing traffic and transaction blockages to an absolute minimum.

Ownership and management are both related to the contract and procurement routes. These are being discussed and developed by all of the industry's institutions, including the AIA and the GSA in the States and organisations such as

Figure 23. Oracle BPEL engine operating over the E-Business Suite.



RIBA and RICS in the UK. Clearly the adversarial methods of the Victorian based routes do not easily lend themselves to collaborative working but the transparency of open data access and the transfer of information opens new doors where, over the last decade, some early collaborative contracts have struggled.

Once the data is held in a robust method and there are process management trials in place, it is easy to start to see how to begin to manage data sets on a more granular, repeatable, reliable manner. It will then be possible to see how standardisation and the library management of objects will become vital to the design and delivery process and also offer a processing and storage host for the gathering of performance data of all types to inform emerging new designs.

The closest parallel with this approach is the retail trade with the use of the store management and Electronic Point of Sale (EPOS) systems, now seen in retail businesses of all sizes. Clearly this situation is some way off, especially when considering that an average office building may have around twice the number of line items of even the largest retailers.

5 CONCLUSION

How Can UK Organisations Adopt and Benefit?

Clearly, as discussed, there is an evolutionary approach to implementing BIM and organisations must be realistic as to their current capability and progress through the evolution. Some of the characteristics of the three key influencers in terms of people, process and technology have been discussed and it has been identified that there are significant benefits at any stage in the adoption of BIM as long as it is done well and is matched to the e-readiness of the business and to some extent its supply chain.

It is here that a problem arises because as much as businesses can point at the lack of technology progress at the high end of the BIM model, and it is true there are significant gaps in the technology offerings, the real issue is that there are simply not enough good quality trained people in “e-ready” businesses in the market to reach anywhere near critical mass, other than at the point we have defined as BIM Level “1”.

The improvement in the value the industry could deliver as it progresses through level 1 and 2 are clear and both industry businesses and technology providers should be encouraged together to share and communicate and learn so the benefits are available to all.

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KEY TERMS AND DEFINITIONS

BIM Evolution: Following in a similar manner to Darwinian process of the natural world in which we exist, BIM evolution describes how the industry has progressed since the move from drawing boards in the 1970's & 80's to its current situation, while also providing a strategic view through extrapolating the BIM vision forward towards complete process and data integration.

Within this are also incorporated levels of BIM usage as a simple identification to the level of BIM adoption within a business or on a project.

Organisational e-readiness: “e-readiness” is the measure of how “ready” or “prepared” organisations are to adopt and use the available IT to improve their business performance and bring sustainable competitive advantage. It reflects the organisational soft issues such as business processes, management structure, change management, people and culture such that IT is effectively absorbed into their work practices. The competencies that an organisation needs to develop in order to acquire the capability to strategically benefit from IS/IT, prior to its investment, falls under four main elements; people, process, work environment and IT infrastructure.

UK Construction Market Sector: The UK Construction Market Sector refers to the construction industry specifically focused on the UK market sector.

Process: A process is “simply a structured, measured set of activities designed to produce a specified output for a particular customer or market. Processes are the structure by which an organisation does what is necessary to produce value for its customers” (Davenport, 1993).

Industry Foundation Classes: The Industry Foundation Classes (IFC) is a neutral and open specification that is not controlled by a single vendor or group of vendors. Developed by buildingSMART (formerly the International Alliance for Interoperability - IAI), it is an object oriented file format with a data model to facilitate interoperability in the building industry, and is a commonly used format for Building Information Modelling (BIM).

Information Delivery Manual: The Information Delivery Manual (IDM) is a methodology that aims to provide the integrated reference for process and data required by BIM. The IDM identifies the discrete processes undertaken within building construction, the information required for their execution and the results of that activity. More

specifically, it specifies where a process fits and its relevance, the actors creating, consuming and benefitting from the information, the information created and consumed, and how the information should be supported by software solutions.

Information Framework for Dictionaries:
Information Framework for Dictionaries (IFD) is a

mechanism (standard) that facilitates creating multilingual dictionaries, terminologies, or ontology's. IFD provides a feasible method to link IFCs (based BIM) to existing knowledge systems, project and product specific databases, etc. Furthermore, IFD provides multilingual and translation capabilities to IFC-based BIM information.

Chapter 4

Building Information Modelling Maturity Matrix

Bilal Succar

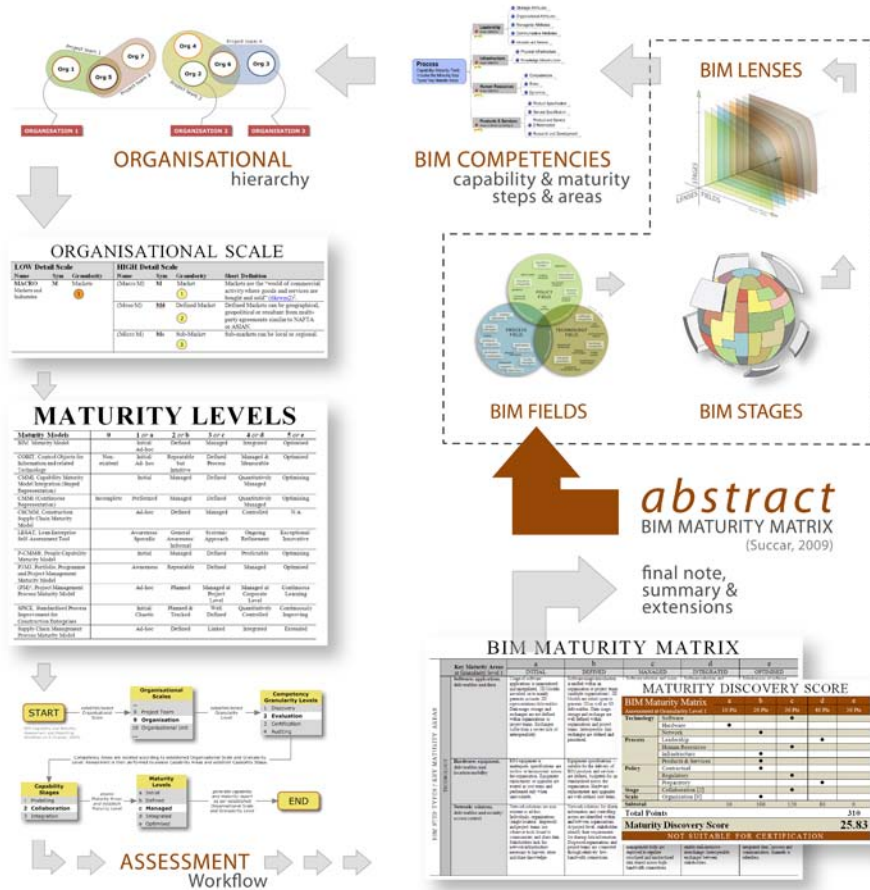
ChangeAgents AEC, Australia

ABSTRACT

Building Information Modelling (BIM) is an expanding collection of concepts and tools which have been attributed with transformative capabilities within the Architecture, Engineering, Construction and Operations (AECO) industry. BIM discussions have grown to accommodate increasing software capabilities, infinitely varied deliverables, and competing standards emanating from an abundance of overlapping definitions attempting to delineate the BIM term. This chapter will steer away from providing its own definition of BIM yet concurs with those identifying it as a catalyst for change (Bernstein, 2005) poised to reduce industry's fragmentation (CWIC, 2004), improve its efficiency (Hampson & Brandon, 2004) and lower its high costs of inadequate interoperability (NIST, 2004). In essence, BIM represents an array of possibilities and challenges which need to be understood and met respectively through a measurable and repeatable approach. This chapter briefly explores the multi-dimensional nature of the BIM domain and then introduces a knowledge tool to assist individuals, organisations and project teams to assess their BIM capability, maturity and improve their performance (Figure 1). The first section introduces BIM Fields and Stages which lay the foundations for measuring capability and maturity. Section 2 introduces BIM Competencies which can be used as active implementation steps or as performance assessment areas. Section 3 introduces an Organisational Hierarchy/Scale suitable for tailoring capability and maturity assessments according to markets, industries, disciplines and organisational sizes. Section 4 explores the concepts behind 'capability maturity models' and then adopts a five-level BIM-specific Maturity Index (BIMMI). Section 5 introduces the BIM Maturity Matrix (BIM³), a performance measurement and improvement tool which identifies the correlation between BIM Stages, Competency Sets, Maturity Levels and Organisational Scales. Finally, Section 6 introduces a Competency Granularity Filter which enables the tailoring of BIM tools, guides and reports according to four different levels of assessment granularity.

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Figure 1. Visual Abstract



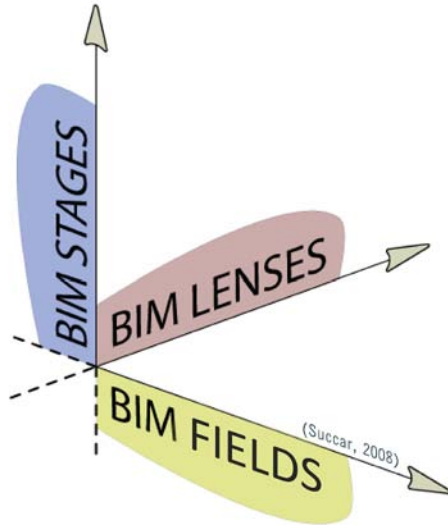
1 BUILDING INFORMATION MODELLING: A BRIEF INTRODUCTION

Building Information Modelling is a set of interacting policies, processes and technologies (Succar, 2009) generating a “methodology to manage the essential building design and project data in digital format throughout the building’s life-cycle” (Penttilä, 2006). This definition is one of tens of attempts to delimit the BIM domain which - as a term- continues to expand in coverage and connotation. It is important – if we acknowledge BIM’s value in assisting the AECO industry and are inclined to assist in its systematic adoption - to

identify the domain’s knowledge structures, internal dynamics and implementation requirements. These can be best represented through a tri-axial understanding of the BIM domain (Figure 2):

- *BIM Fields* of activity identifying domain ‘players’, their ‘requirements’ and ‘deliverables’.
- *BIM Stages* delineating minimum capability benchmarks.
- *BIM Lenses* providing the depth and breadth of enquiry necessary to identify, assess and qualify BIM Fields and BIM Stages.

Figure 2. BIM framework: Fields, Stages and Lenses – tri-axial model



BIM Fields

The BIM domain is comprised of three interlocking yet distinctive *fields of activity* (Figure 3). Technology, Process and Policy. Each one of these BIM fields has its own players, requirements and deliverables. BIM players can be individuals, teams, organisations or other groupings as discussed later in Section 3.

BIM Fields have been identified using ‘conceptual clustering’ of observable knowledge objects within the AECO industry. These clusters have been ‘inductively inferred’ through a strategy of observation and discovery (Michalski, 1987). The three BIM Fields interact within the AECO industry generating new products, services and roles. Table 1 summarises each of the three fields, their interactions and overlaps.

BIM Stages

There are voluminous possibilities attributed to BIM representing an array of challenges which need to be addressed by Architecture, Engineering,

Construction and Operations (AECO) stakeholders. Having identified the BIM Fields, this section identifies the multiple stages which delineate capability milestones.

BIM capability is the *basic ability* to perform a task, deliver a service or generate a product. BIM Capability Stages (or BIM Stages) define the major milestones to be achieved by teams and organisations as they adopt BIM technologies and concepts. BIM Stages identify a fixed starting point (the status before BIM implementation), three fixed BIM stages and a variable ending point which allows for unforeseen future advancements in technology. This chapter uses the term Pre-BIM to represent industry status prior to BIM implementation and Integrated Project Delivery (IPD) to denote an *approach to* or an *ultimate goal of* implementing BIM (AIA, 2007). BIM Stages include technology, process and policy components and are as follows:

- **BIM Stage 1:** object-based modelling
- **BIM Stage 2:** model-based collaboration
- **BIM Stage 3:** network-based integration

BIM Stages are defined by their *minimum requirements*. As an example, for an organisation to be considered at BIM Capability Stage 1, it needs to have deployed an object-based modelling software tool. Similarly for BIM Capability Stage 2, an organisation needs to be part of a multidisciplinary model-based collaborative project. To be considered at BIM Capability Stage 3, an organisation must be using a network-based solution (like a model server) to share object-based models with at least two other disciplines. Table 2 expands on the above BIM Capability Stages starting with Pre-BIM and ending with a brief description of Integrated Project Delivery (IPD).

BIM Lenses

BIM Lenses are distinctive layers of analysis (Figure 4) applied to Fields and Stages to generate

Figure 3. Three interlocking Fields of BIM activity– venn diagram

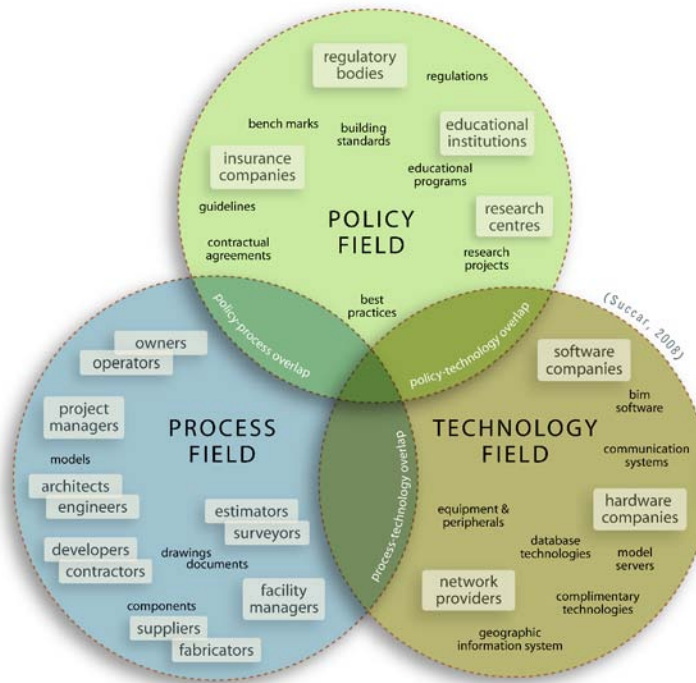
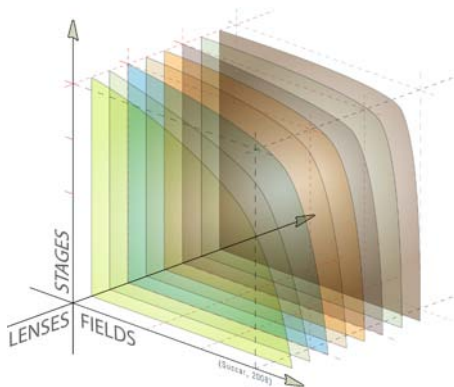


Figure 4. BIM Lenses – tri-axial model



knowledge views which ‘abstract’ the BIM domain and control its complexity by removing unnecessary detail (Kao & Archer, 1997). Lenses allow domain researchers to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out

those that do not. In this chapter, a ‘scoping’ lens/filter (Succar, 2009) will be transparently applied to identify Organisational Scales (Section 3) and assessment Granularity Levels (Section 5).

2 BIM COMPETENCY SETS

A BIM Competency represents a BIM Player’s ability to satisfy a BIM Requirement or generate a BIM Deliverable. A BIM Competency Set is a hierarchical collection of individual competencies identified for the purposes of BIM implementation and assessment. BIM Competency Sets follow the same classification as BIM Fields and are explored in Figure 5. A short description is also provided below:

- *Technology Sets* in software, hardware and networks. For example, the availability

Table 1. BIM Fields, their interactions and overlaps

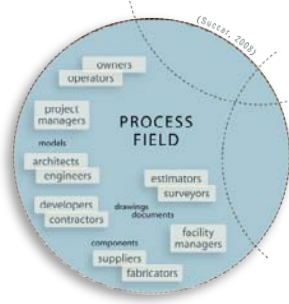
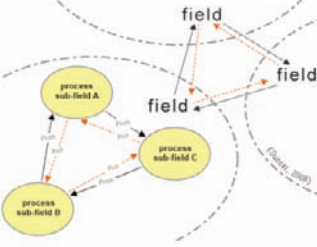
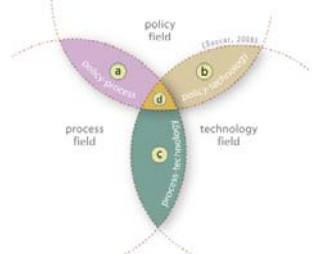
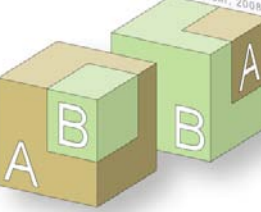
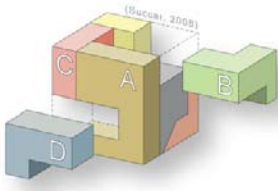
	The Technology Field clusters a group of players who specialise in developing software, hardware, equipment and networking systems necessary to increase efficiency, productivity and profitability of AECO sectors. These include organisations which generate software solutions and equipment of direct and indirect applicability to the design, construction and operation of facilities.
	The Process Field clusters a group of players who procure, design, construct, manufacture, use, manage and maintain structures. These include facility owners, architects, engineers, contractors, facility managers and all other AECO industry players involved in the ownership, delivery and operations of buildings or structures.
	The Policy Field clusters a group of players focused on preparing practitioners, delivering research, distributing benefits, allocating risks and minimising conflicts within the AECO industry. These players do not generate any construction products but are specialised organisations - like insurance companies, research centres, educational institutions and regulatory bodies – which play a pivotal preparatory, regulatory and contractual roles in the design, construction and operations process.
	BIM Interactions are push-pull knowledge transactions occurring within or between fields. Push mechanisms (Holsapple & Joshi, 2006) transfer knowledge from one player or field to another while pull mechanisms transfer knowledge to satisfy a request by another player or field. Sample transactions include data transfers, team dynamics and contractual relationships between fields and their players.
	The three distinct fields overlap as they share players, requirements and deliverables. These BIM Overlaps between fields are exemplified in two cases below: Case 1: when a BIM deliverable requires input from two or more players or fields. For example, the development and implementation of non-proprietary interoperable schema (like Industry Foundation Classes) necessitates the joint effort of Policy players (researchers) as well as Technology players (software developers). Case 2: when players pertaining to one field generate deliverables classified in another. For example, the Australian Institute of Architects is an 'industry body' - whose members are Process players (architects) - generating Policy deliverables (guidelines and best practices).

Table 2. Pre-BIM, BIM Capability Stages and Integrated Project Delivery

Pre-BIM status <i>Disjointed Project Delivery</i> 	The construction industry is characterised by adversarial relationships where contractual arrangements encourage risk avoidance and risk shedding. Much dependence is placed on 2D documentation to describe a 3D reality. Even when some 3D visualisations are generated, these are often disjointed and reliant on two-dimensional documentation and detailing. Quantities, cost estimates and specifications are generally neither derived from the visualisation model nor linked to documentation. Similarly, collaborative practices between stakeholders are not prioritised and workflow is linear and asynchronous. Under pre-BIM conditions, industry suffers from low investment in technology and lack of interoperability (CWIC, 2004) (NIST, 2004). <i>The graphical symbol (left) represents 2D hand-drawn, 2D computer-aided drafting or 3D non-object based software technologies similar to AutoCAD® and SketchUP®.</i>
BIM Stage 1 <i>Object-based Modelling</i>  <i>The graphical symbol above represents a single-disciplinary 3D model exemplified by an architect's ArchiCAD®, a structural engineer's Revit® or a steel detailer's Tekla® model.</i>	BIM implementation is initiated through the deployment of an 'object-based 3D parametric software tool' similar to ArchiCAD®, Revit®, Digital Project® and Tekla®. At Stage 1, users generate single-disciplinary models within either design [D], construction [C] or operations [O] – the three Project Lifecycle Phases. Modelling deliverables include architectural design models [D] and duct fabrication models [C] used primarily to automate generation and coordination of 2D documentation and 3D visualisation. Other deliverables include basic data exports (e.g. door schedules, concrete volumes, FFE costs,...) and light-weight 3D models (e.g. 3D DWF, 3D PDF, NWD, etc...) which have no modifiable parametric attributes. Collaborative practices at Stage 1 are similar to pre-BIM status and there are no significant model-based interchanges between different disciplines. Data exchanges between project stakeholders are uni-directional and communications continue to be asynchronous and disjointed. As only minor process changes occur at Stage 1, pre-BIM contractual relations, risk allocations and organisational behaviour persist. However, the semantic nature of object-based models and their 'hunger' for early and detailed resolution of design and construction challenges encourage 'fast-tracking' of Project Lifecycle Phases - when a project is still executed in a phased manner yet design and construction activities are overlapped to save time (Jaafari, 1997).
BIM Stage 2 <i>Model-based Collaboration</i>  <i>The graphical symbol (above) represents the interchange of 3D models between two different disciplines (A and B). This can be exemplified by two-way linking of Revit® Architectural and Structural models (a proprietary interoperable exchange) or the interchange of IFC-files exported out of multi-disciplinary BIM applications (a non-proprietary interoperable exchange).</i>	Having developed single-disciplinary modelling expertise during Stage 1 implementations, Stage 2 players actively collaborate with other disciplinary players. Collaboration may occur in several technical ways following each player's selection of BIM software tools. Two different examples of model-based collaboration include the interchange (interoperable exchange) of models or part-models through 'proprietary' formats (e.g. between Revit® Architecture and Revit® Structure through the .RVT file format) and non-proprietary formats (e.g. between ArchiCAD® and Tekla® using the IFC file format). Model-based collaboration can occur within one or between two Project Lifecycle Phases. Examples of this include the Design-Design interchange of architectural and structural models [DD], the Design-Construction interchange of structural and steel models [DC] and the Design-Operations interchange of architectural and facility maintenance models [DO]. It is important to note that only one 'collaborative model' needs to hold 3D geometric data to allow for semantic BIM interchanges between two disciplines. An example of this is the [DC] interchange between a 3D object-based model (e.g. Digital Project®), scheduling database (e.g. Primavera® or MS project®) or a cost estimating database (e.g. Rawlinsons or Timberline®). Such interchanges allow the generation of 4D (time analysis) and 5D (cost estimating) studies respectively. Although communications between BIM players continue to be asynchronous, pre-BIM demarcation lines separating roles, disciplines and lifecycle phases start to fade. Some contractual amendments become necessary as model-based interchanges augment and start replacing document-based workflows. Stage 2 also alters the granularity of modelling performed at each lifecycle phase as higher-detail construction models move forward and replace (partially or fully) lower-detail design models.

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Table 2. continued

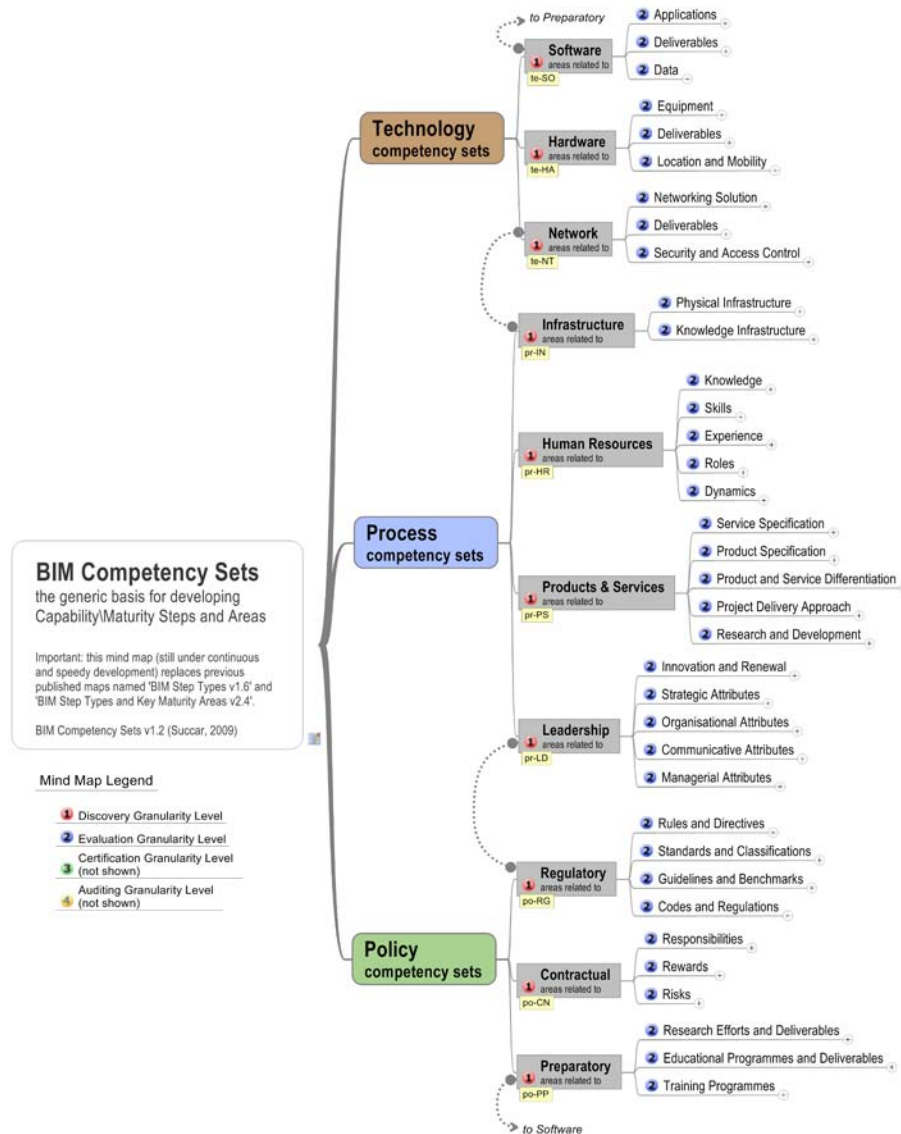
BIM Stage 3 <i>Network-based Integration</i> 	At this capability stage, semantically-rich integrated models are created, shared and maintained collaboratively across Project Lifecycle Phases. This integration can be achieved through ‘model server’ technologies (using proprietary, open or non-proprietary formats), single-integrated/distributed-federated databases (Bentley, 2003) (Liaserin, 2003), Cloud Computing or SaaS (Software as a Service)(Wilkinson, 2008). BIM Stage 3 models become interdisciplinary nD models (Lee et al., 2003) allowing complex analyses at early stages of virtual design and construction. At this Stage, model deliverables extend beyond semantic object properties to include business intelligence, lean construction principles, green policies and whole lifecycle costing. Collaborative work now ‘spirals iteratively’ around an extensive, unified and sharable data model (Edgar, 2007). From a process perspective, synchronous interchange of model and document-based data cause project lifecycle phases to overlap extensively forming a phase-less process.
<i>The graphical symbol (above) represents the integration of 3D models using a network-based technology. Each of the single-disciplinary models (represented by capital letters) is an integral part of the resulting inter-disciplinary model.</i>	
Integrated Project Delivery <i>Interdependent, real-time models</i> 	Integrated Project Delivery, a term popularised by the American Institute of Architects California Council (AIA, 2007) is, in the author’s view, suitable for representing a long-term vision of BIM as an amalgamation of domain technologies, processes and policies. The term is generic enough and potentially more readily understandable by industry than “Fully Integrated and Automated Technology” (FIATECH, 2005), Integrated Design Solutions (ILAL, 2007) or “nD Modelling” (Lee et al., 2003) as three prominent examples. The selection of Integrated Project Delivery (IPD) as the ‘goal’ of BIM implementations is not to the exclusion of other visions appearing under different names. On the contrary, the path from Pre-BIM (a fixed starting point), passing through three well defined Stages towards a loosely defined IPD is an attempt to include all pertinent BIM visions irrespective of their originating sources.
<i>The graphical symbol (above) represents the delivery and continuous evolution of a highly integrated multi-dimensional model connected to multiple external databases and knowledge sources in real-time. These include services 'grid, building management systems, geographic information systems (GIS), cost databases, operations business logic, etc...</i>	

of a BIM tool allows the migration from drafting-based to object-based workflow (BIM Stage 1)

- *Process Sets in Leadership, Infrastructure, Human Resources and Products/Services.* For example, collaboration processes and database-sharing skills are necessary to allow model-based collaboration (BIM Stage 2).
- *Policy Sets in contracts, regulations and research/education.* For example, alliance-based and risk-sharing contractual agreements are pre-requisites to network-based integration (BIM Stage 3).

BIM Competencies are employed to establish BIM *Capability* or BIM *Maturity*¹ benchmarks. They can also be used by teams and organisations to either *implement* BIM or *assess* its implementation. If BIM Competencies are used for the purposes of active implementation², then they are referred to as BIM Steps. However, if they are used for assessing existing implementations, then they are referred to as BIM Areas. Not all BIM Competencies are of the same significance and can thus be separated into Key and non-Key Competencies.

Figure 5. Indicative list of BIM Competency Sets v1.2 –mind map at Granularity Level 2

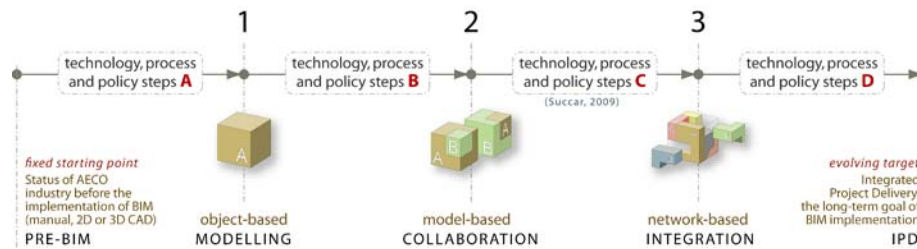


BIM Steps

The volume and complexity of changes required to achieve each of the three BIM Stages (refer to Table 2) are *transformational* and even *radical* (Henderson & Clark, 1990) (Taylor & Levitt, 2005). However, the passage from Pre-BIM to BIM Stage 1, through each of the three Stages and towards Integrated Project Delivery is populated

by *incremental* or *evolutionary* steps. Identifying these BIM Steps is instrumental in enabling organisations and individuals to increase their BIM capability and maturity in a systematic way. Each BIM Stage has its own requirements and deliverables giving rise to numerous BIM Steps. These are collated into 'sets' according to their location on the implementation continuum (Figure 6):

Figure 6. Step Sets leading to or separating BIM Stages – linear model v1.0



- *A Steps*: from pre-BIM leading to BIM Stage 1
- *B Steps*: from BIM Stage 1 leading towards BIM Stage 2
- *C Steps*: from BIM Stage 2 leading towards BIM Stage 3
- *D Steps*: from BIM Stage 3 leading towards Integrated Project Delivery

3 BIM ORGANISATIONAL HIERARCHY

In the construction industry, every building, road or bridge construction project is a *unique* prototype involving a *similar* set of process stages (Wegelius-Lehtonen, 2001). This uniqueness, on one hand, is driven by multiple factors including the transient nature of project teams and the distinctive locational and environmental criteria of each project site. The similarity, on the other hand, is driven by long-held views of how construction projects should be conducted, reasonably stable organisational structures, slow-changing educational concepts and risk-averse insurance policies. This challenging duality of ‘uniqueness’ and ‘similarity’ is addressed by the BIM Framework through the development of an Organisational Hierarchy (Figure 7) and a granular Organisational Scale (Table 3). Both the Hierarchy and the Scale are based on the notions of *flexibility* - to cater for ‘uniqueness’ - and *uniformity* to cater for ‘similarity’:

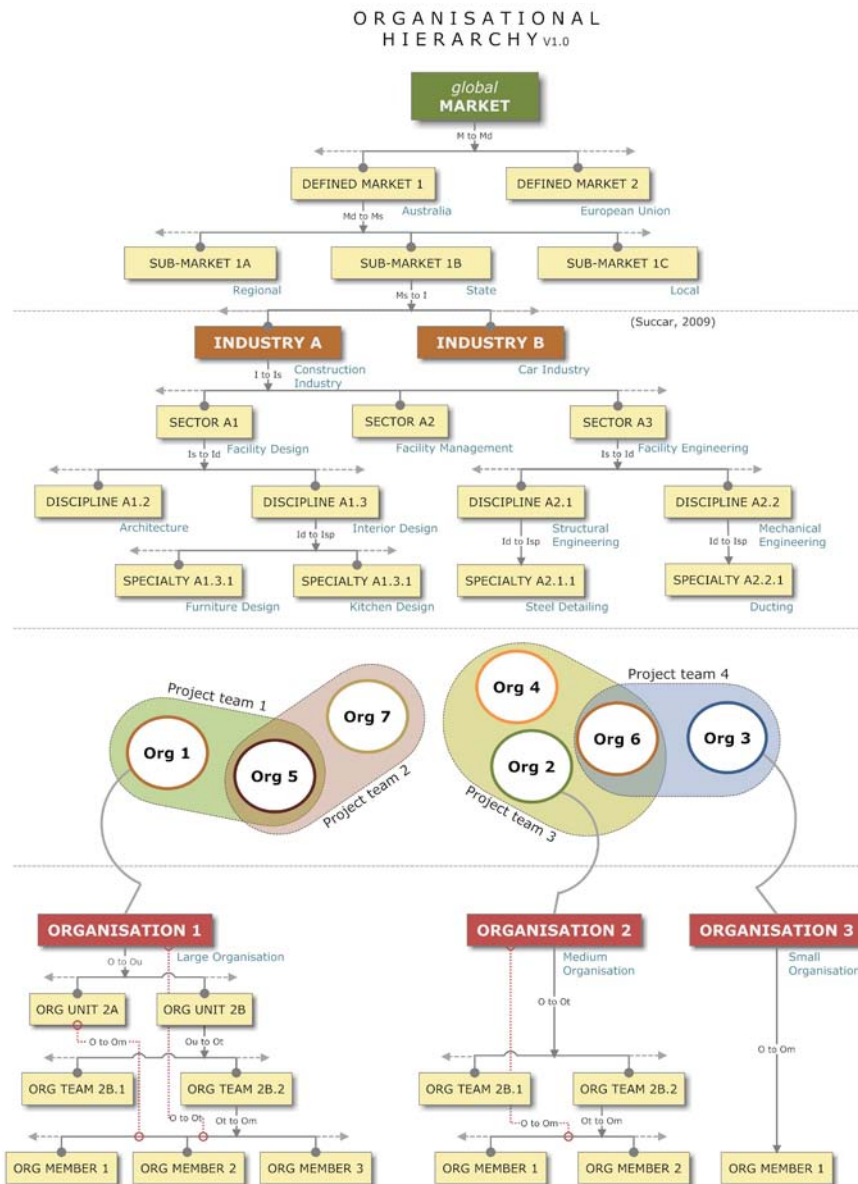
- **Flexibility (of application)**: BIM Capability and Maturity assessments can apply irrespective of organisational size, project type or how a project team is configured.
- **Uniformity (of measurement)**: BIM Capability and Maturity assessments can be based on a set of standardised organisational subdivisions. Assessment results pertaining to an organisational unit, an organisation or a project team can be uniformly and respectively compared to another same-scale unit, organisation or project team.

Figure 8 elaborates on the Organisational Hierarchy and introduces a granular scale. Acting as a BIM ‘scoping filter’ (Succar, 2009) the Organisational Scale (OScale) can be applied to BIM Players enabling a more-targeted approach to BIM implementation and assessment.

4 BIM MATURITY INDEX

The BIM Maturity Index³ (BIMMI) includes a set number of Maturity Levels which signify the evolutionary improvement of processes, technologies and policies within each BIM Stage. A maturity level is a “well-defined evolutionary plateau that institutionalizes new capabilities for developing the organization’s workforce” (SEI, 2008g).

Figure 7. Organisational Hierarchy used for BIM Maturity – Tree view v1.0



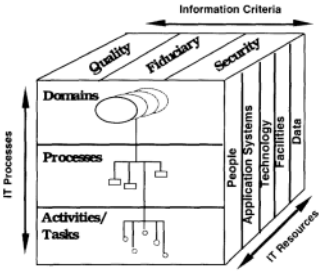
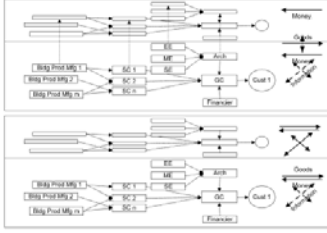
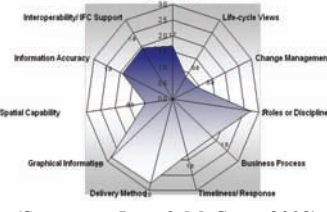
Maturity levels allow for a basic distinction between *immature* and *mature* entities in terms of “systematic approach[es] to business processes” (Sarshar et al., 2000). With the exception of articles jestingly advocating multiple immaturity levels (Anthony, 1992), ‘capability immaturity’ or lack of maturity is typically identified as a fixed starting point. A collation of process maturity levels

from ‘immature’ to ‘highly mature’ is typically referred to as a ‘Maturity Model’.

Capability Maturity Models

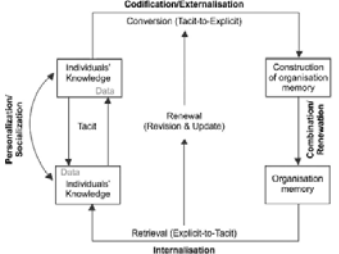
The Capability Maturity Model (CMM) is a process improvement framework originally intended as a tool to evaluate the ability of government

Table 3. Maturity Models influencing the BIM Maturity Index

Sample Representation	Abbreviation, Name – Organisation Description and Number of maturity levels
 Image from (Lainhart IV, 2000)	COBIT, Control Objects for Information and related Technology – <i>Information Systems Audit and Control Association (ISACA) and the IT Governance Institute (ITGI)</i> The main objective of COBIT is to “enable the development of clear policy and good practice for IT control throughout organizations” (Lainhart IV, 2000). The COBIT Maturity Model is “an IT governance tool used to measure how well developed the management processes are with respect to internal controls. The maturity model allows an organization to grade itself from nonexistent (0) to optimized (5)” (Pederiva, 2003). COBIT includes 6 Maturity Levels (Non-existent, Initial/ad hoc, Repeatable but Intuitive, Defined Process, Managed and Measurable and Optimised), 4 <i>Domains</i> and 34 <i>Control Objectives</i>. Note: There is some alignment between ITIL (OGC, 2009) and COBIT with respect to IT governance within organisations (Sahibudin, Sharifi, & Ayat, 2008) of value to BIM implementation efforts.
 Image Source: NASA, Software Engineering Process Group http://bit.ly/CMMI-NASA	CMMI, Capability Maturity Model Integration - <i>Software Engineering Institute / Carnegie Mellon</i> “Capability Maturity Model® Integration (CMMI) is a process improvement approach that (...) helps integrate traditionally separate organizational functions, set process improvement goals and priorities, provide guidance for quality processes, and provide a point of reference for appraising current processes” (SEI, 2006a) (SEI, 2006b) (SEI, 2008a) (SEI, 2008b) (SEI, 2008c). CMMI has 5 <i>Maturity Levels</i> (for Staged Representation, 6 Capability Levels for Continuous Representation), 16 core <i>Process Areas</i> (22 for CMMI-DEV and 24 for CMMI-SVC), 1 to 4 <i>Goals</i> for each Process Area, each goal is comprised of <i>Practices</i>... The 5 Maturity Levels are: Initial, Managed, Defined, Quantitatively Managed and Optimising.
 (Vaidyanathan & Howell, 2007)	CSCMM, Construction Supply Chain Maturity Model “Construction supply chain management (CSCM) refers to the management of information, flow, and money in the development of a construction project” as mentioned in (Vaidyanathan & Howell, 2007). CSCMM has 4 Maturity Stages: Ad-hoc, Defined, Managed and Controlled.
 (Suermann, Issa, & McCuen, 2008)	I-CMM, Interactive Capability Maturity Model - <i>National Institute for Building Sciences (NIBS) Facility Information Council (FIC)</i> This I-CMM is closely coupled with the NBIMS effort (Version1, Part 1) and establishes “a tool to determine the level of maturity of an individual BIM as measured against a set of weighted criteria agreed to be desirable in a Building Information Model” (Suermann et al., 2008) (NIST, 2007) (NIBS, 2007). A more detailed discussion of this maturity model is offered in Section 4. The ICMM has 11 ‘Areas of Interest’ measured against 10 Maturity Levels.

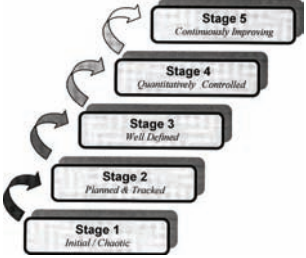
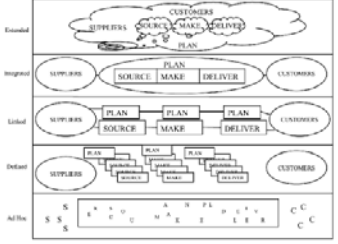
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Table 3. continued

 (Arif, Egbu, Alom, & Khalfan, 2009)	Knowledge Retention Maturity Levels Arif, Egbu, Alom and Khalfan (2009) introduced 4 levels of knowledge retention maturity. Knowledge management is an integral part of BIM capability and subsequent maturity. The Matrix thus incorporates these levels: (1) knowledge is shared between employees, (2) shared knowledge is documented (transferred from tacit to explicit), (3) documented knowledge is stored and (4) stored knowledge is accessible and easily retrievable (Arif et al., 2009).
 (Nightingale & Mize, 2002)	LESAT, Lean Enterprise Self-Assessment Tool - Lean Aerospace Initiative (LAI) at the Massachusetts Institute of Technology (MIT) LESAT is focused on “assessing the degree of maturity of an enterprise in its use of ‘lean’ principles and practices to achieve the best value for the enterprise and its stakeholders” (Nightingale & Mize, 2002). LESAT has 54 Lean Practices organised within three Assessment Sections: Lean Transformation/Leadership, Life Cycle Processes and Enabling Infrastructure and 5 Maturity Levels: Some Awareness/Sporadic, General Awareness/Informal, Systemic Approach, Ongoing Refinement and Exceptional/Innovative.
 (OGC, 2008)	P3M3, Portfolio, Programme and Project Management Maturity Model - Office of Government Commerce The P3M3 provides “a framework with which organizations can assess their current performance and put in place improvement plans with measurable outcomes based on industry best practice” (OGC, 2008). The P3M3 has 5 Maturity Levels: Awareness, Repeatable, Defined, Managed and Optimised.
 (SEI, 2008g)	P-CMM®, People Capability Maturity Model v2 – Software Engineering Institute / Carnegie Mellon P-CMM is an “organizational change model” and a “roadmap for implementing workforce practices that continuously improve the capability of an organization’s workforce” (SEI, 2008g). P-CMM has 5 Maturity Levels: Initial, Managed, Defined, Predictable and Optimising.
 (Kwak & Ibbs, 2002)	(PM)², Project Management Process Maturity Model The project management process maturity (PM)² model “determines and positions an organization’s relative project management level with other organizations”. It also aims to integrate PM “practices, processes, and maturity models to improve PM effectiveness in the organization” (Kwak & Ibbs, 2002). (PM)² has 5 Maturity Levels: Initial, Planned, Managed at Project Level, Managed at Corporate Level and Continuous Learning.

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Table 3. continued

 (Hutchinson & Finnemore, 1999)	SPICE, Standardised Process Improvement for Construction Enterprises - Research Centre for the Built and Human Environment, The University of Salford SPICE is a project which developed a framework for continuous process improvement for the construction industry. SPICE is an “evolutionary step-wise model utilizing experience from other sectors, such as manufacturing and IT” (Hutchinson & Finnemore, 1999), (Sarshar et al., 2000). SPICE has 5 Stages: Initial/Chaotic, Planned & Tracked, Well Defined, Quantitatively Controlled, and Continuously Improving.
 (Lockamy III & McCormack, 2004)	Supply Chain Management Process Maturity Model and Business Process Orientation (BPO) Maturity Model The model conceptualizes the relation between process maturity and supply chain operations as based on the Supply-chain Operations Reference Model4 (Stephens, 2001). The model’s maturity describes the “progression of activities toward effective SCM and process maturity. Each level contains characteristics associated with process maturity such as predictability, capability, control, effectiveness and efficiency” (Lockamy III & McCormack, 2004) (K. McCormack, 2001). The 5 Maturity Levels are: Ad-hoc, Defined, Linked, Integrated and Extended.
Other maturity models – or variation on listed maturity models - include those on Software Process Improvement (Hardgrave & Armstrong, 2005), IS/ICT Management Capability (Jaco, 2004), Project Management (Crawford, 2006), Competency (Gillies & Howard, 2003) and Financial Management (Doss, Chen, & Holland, 2008).	

contractors to perform a software project. It was developed in the late 80s for the benefit of the US Department of Defence (Hutchinson & Finnemore, 1999). It’s successor, the more comprehensive Capability Maturity Model Integration (CMMI), continues to be developed and extended by the Software Engineering Institute, Carnegie Mellon University. Below is a short historical synopsis of CMM, the basis for numerous maturity models across many industries:

“The U.S. Department of Defense (DoD) is the world’s largest software customer, spending over \$30 billion per year on software during the 1980s. At that time, software projects constantly seemed to be in crisis mode and were frequently responsible for large delays and overruns in defense systems. To address this software crisis on a national scale, the DoD funded the development of the Software Engineering Institute (SEI), a federally-funded research and development center (FFRDC), at Carnegie Mellon University in Pittsburgh, PA.

Humphrey brought his process maturity concepts to the SEI in 1986, where he founded its Software Process Program. Shortly after arriving, he received a request from the U.S. Air Force to develop a method for assessing the capability of its software contractors”(SEI, 2008f).

Capability Maturity Models originated in the field of quality management (Crosby, 1979) and are frameworks identifying a set of standardised process improvement levels which allow implementers to achieve significant business benefits. These include increased productivity and Return On Investment (ROI) as well as reduced costs and post-delivery defects (Hutchinson & Finnemore, 1999). Maturity models are typically made of multiple maturity levels; each level provides a layer in the foundation for continuous process improvement. Levels comprise of a set of process goals that, when satisfied, stabilise an important component in the ‘construction’ process. Achieving each level of the maturity framework

Figure 8. Granular Organisational Scale

Low Detail			High Detail			
Name	Sym	Granularity	Name	Sym	Granularity	Short Definition
MACRO Markets and Industries	M	Markets 1	(Macro M)	M	Market 1	Markets are the “world of commercial activity where goods and services are bought and sold” http://bit.ly/pjB3c
			(Meso M)	Md	Defined Market 2	Defined Markets can be geographical, geopolitical or resultant from multi-party agreements similar to NAFTA or ASIAN.
			(Micro M)	Ms	Sub-Market 3	Sub-markets can be local or regional.
	I	Industries 4	(Macro I)	I	Industry 4	Industries are ‘the organized action of making of goods and services for sale’. Industries can traverse markets and may be service, product or project-based. The AEC industry is mostly Project-Based. http://bit.ly/ieY3
			(Meso I)	Is	Sector 5	A sector is a “distinct subset of a market, society, industry, or economy whose components share similar characteristics” http://bit.ly/15UkZD
			(Micro I)	Id	Discipline 6	Disciplines are industry sectors, “branches of knowledge, systems of rules of conduct or methods of practice” http://bit.ly/7jT82
Isp				Specialty 7	Specialty is a focus area of knowledge, expertise, production or service within a sub-discipline.	
MESO Projects and their teams	P	Project Teams 8	n/a	P	Project Team 8	Project Teams are temporary groupings of organisations with the aim of fulfilling predefined objectives of a project - a planned endeavour, usually with a specific goal and accomplished in several steps or stages. http://bit.ly/dqMYg
MICRO Organisations, Units, their teams & members	O	Organisations 9	(Macro O)	O	Organisation 9	An organisation is a ‘social arrangement which pursues collective goals, which controls its own performance, and which has a boundary separating it from its environment’. http://bit.ly/v7p9N
			(Meso O)	Ou	Organisational Unit 10	Departments and Units are specialised divisions of an organisation. These can be co-located or distributed geographically.
				Ot	Organisational Team 11	Organisational Teams consist of a group of individuals (human resources) assigned to perform an activity or deliver a set of assigned objectives. Teams can be physically co-located or formed across geographical or departmental lines.
			(Micro O)	Om	Organisational Member 12	Organisational members can be part of multiple Organisational Teams.

establishes a different component" (Paulk, Weber, Garcia, Chrissis, & Bush, 1993).

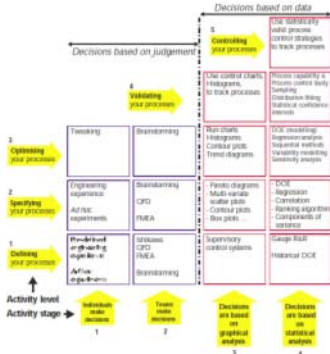
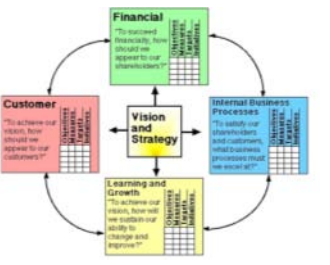
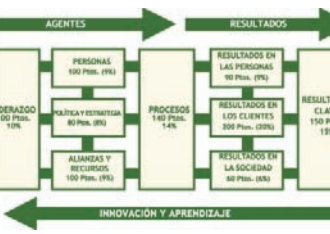
Although CMM is not without its detractors (Weinberg, 1993) (Jones, 1994) (Bach, 1994), research conducted within other industries have already identified the correlation between improving process maturity and business performance (Lockamy III & McCormack, 2004). Researchers have argued that

"to obtain consistently better results, it is (...) necessary to improve the process. For an organization to improve its capability, it is helpful to have a clear picture of the ultimate goal and a means to gauge progress along the way - hence the levels of the maturity model" (Jaco, 2004).

Currently available Capability Maturity Models are either specific to the software industry or focus mainly on the procedural aspects of an implementation process. The 'original' CMM is not applicable to the construction industry as it does not address supply chain issues and its maturity levels do not account for the different phases of a project lifecycle (Sarshar et al., 2000). Although there are a few (extensive) efforts which focus on the construction industry (refer to Table 4), there is no comprehensive maturity model/index that can be applied to BIM, its implementation stages, players, deliverables or its effect on project lifecycle phases.

Building Information Modelling Maturity Matrix

Table 4. Performance, Excellence and Quality Management frameworks influencing the BIM Maturity Matrix

Sample Representation	Abbreviation, Name – Organisation Description and specific influence on the BIM Maturity Matrix
 Image from (NIST, 2008)	Baldrige National Quality Program, 2008 Criteria for Performance Excellence - US Department of Commerce and National Institute of Standards and Technology (NIST) The Malcolm Baldrige Quality Award is an overall performance award conducted by evaluating/scoring organisations against 7 Categories of Performance (using a 1000 points scale): Leadership, Strategic Planning, Customer/Market Focus, Information & Analysis, Human Resource Focus, Process Management, and Business Results (NIST, 2008). <i>Note: BIM Capability and Maturity assessment tools partially introduced in this chapter are influenced by Baldrige's "quality of documented processes" as well as its scoring system.</i>
 Link: http://bit.ly/Scorecard	BSC, The Balanced Scorecard The Balanced Scorecard is a performance management tool (Kaplan & Norton, 1996a) and a strategic management system (Kaplan & Norton, 1996b). BSC has 4 Perspectives: Learning and Growth, Business Process, Customer and Financial Perspectives. Using the Balanced Scorecard within the industry has been discussed in the Conceptual Framework for Performance Management in Construction (Kagioglou, Cooper, & Aouad, 2001). <i>Note: Blm³ and other BIM performance measurement tools benefited from BSC's approach in clarifying how organisations align overall BIM strategy with other organisational objectives.</i>
 Link: http://bit.ly/EFQM	EFQM Excellence Model - European Foundation for Quality Management The EFQM (EFQM, 2008) Excellence Model is an annual award which includes 9 Concepts: Leadership, Policy & Strategy, People, Partnerships & Resources, Processes, Customer Results, People Results, Society Results and Key Performance Areas. Organisations may be assessed against, at least, 3 organisational maturity levels. <i>Note: BIM performance measurement tools can specifically benefit from EFQM and its applicability within the construction industry (Watson & Seng, 2001)</i>
 Link: http://bit.ly/IDEAL	IDEAL, Initiating, Diagnosing, Establishing, Acting & Learning Model – Software Engineering Institute / Carnegie Mellon "The IDEAL model is an organizational improvement model that serves as a roadmap for initiating, planning, and implementing improvement actions". It has 5 Phases: Initiating, Diagnosing, Establishing, Acting and Learning (SEI, 2008d). <i>Note: The Blm³ - which includes BIM Stages and Steps as two of its components – is indirectly influenced by the IDEAL model.</i>

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Table 4. continued

Link: <http://bit.ly/INTRO-SEI>

INTRo, IDEAL-based Based New Technology Rollout - Software Engineering Institute / Carnegie Mellon

INTRo embodies “detailed how-to information needed to manage the introduction of a new technology, organized into a work breakdown structure of stages, steps, and tasks. Tips, checklists, guidelines, and tutorials accompany process descriptions”. It has 7 Stages of new technology implementation: Project Initiation, Organizational Analysis, Technology-Based Solution Definition, Technology Selection and Testing, Whole Product Design, Breakthrough and Rollout (Levine, 2000) (SEI, 2008e).

Note: BIM Capability and Maturity assessments, introduced partially in this chapter, benefited from INTRo’s subdivisions. This is more apparent in low-granularity BIM Competency Areas.

© ISO 1999
© ISO 1999, (Russell, 2000)

ISO 9000 Quality Management System - The International Organization for Standardization

The basic model of ISO 9000 includes 8 Principles (ISO, 2008a) (ISO, 2008b) which align somewhat with EFQM (Russell, 2000). ISO 9001 includes 20 clauses meant for services organisations (Jalote, 2000) and can be mapped and compared against the CMM (Paulk, 1994).

Note: Blm³ did not directly borrow from ISO standards but attempted to avoid any irresolvable clashes with its principles and terminology.

PD Prime Designer DC Design Consultants PC Prime Constructor TC Trade Contractors S Suppliers					
Level of Detail (LOD) and Model Component Author (MCA)					
Conceptualization	Criteria	Design	Detailed Design	Implementation	Docs
LOD	MCA	LOD	MCA	LOD	MCA
100	PD	200	DC	300	TC
100	PD	100	DC	300	TC
100	PD	200	DC	300	TC

(AIA, 2008)

MPS, Model Progression Specification for Building Information, Integrated Project Delivery Models - American Institute of Architects

The MPS (AIA, 2008) is beneficial in establishing the optimum amount of details needed within a building information model at each project lifecycle phase and sub-phase. From a process improvement perspective, an organisation or a project team - implementing BIM with a degree of performance maturity - will need to establish its optimum Level of Detail to minimise *under* and/or *over* representation. The MPS has 5 Levels of Detail (LOD) measured against 4 Model Component Authors (MCA).

Note: Blm³ and other BIM Capability/Maturity tools incorporate LODs and MCAs as part of their assessments.

Other models of relevance and of potential benefit to Blm³ and other BIM Capability/Maturity assessment tools include: **ISO/IEC 15504, Information Technology - Process Assessment** Part 4: Guidance on use for process improvement and process capability determination - International Standards Organisation (ISO, 2004) and ITIL, Information Technology Infrastructure Library - Office of Government Commerce (OGC) in UK (OGC, 2009) (Cartlidge et al., 2007).

Other models of relevance and of potential benefit to Blm³ and other BIM Capability/Maturity assessment tools include: **ISO/IEC 15504, Information Technology - Process Assessment** Part 4: Guidance on use for process improvement and process capability determination - International Standards Organisation (ISO, 2004) and ITIL, Information Technology Infrastructure Library - Office of Government Commerce (OGC) in UK (OGC, 2009) (Cartlidge et al., 2007).

Influences Shaping the BIM Maturity Index

It is important to benefit from existing maturity models/indices including those not intended specifically for the AECO industry. Many lessons can be learned and much experience can be gained by analysing, testing and then adopting some of the widely-used maturity terms, performance targets and quality assurance measures. Below are some of the published efforts that

influenced the development of the BIM Maturity Index. Table 3 is a non-exhaustive list of source maturity models from different industries while Table 4 lists some of the widely adopted performance, excellence and quality management frameworks which influenced the BIM Maturity Matrix.

The above listed Capability Maturity Models are similar in structure and objectives but differ in conceptual depth, industrial focus, terminology and target audience. A common theme is how

Capability Maturity Models employ few simple experience-based classifications and benchmarks to facilitate continuous improvement within organisations.

In analysing their suitability for the development of a BIM-specific maturity index, most were broad in approach and can collectively form a basis for a range of BIM processes, technologies and policies. However, none of the models surveyed were easily scalable across the twelve organisational scales (identified in Figure 8). Also, from a terminology standpoint, there are not enough differentiation between the notion of *capability* (the ability to perform a task) and that of *maturity*⁵ (degrees of excellence in performing a task). This differentiation, in the author's view, is critical to cater for staged BIM implementation mandated by its disruptive and expansive nature.

It is also important to *not only* (i) identify BIM-specific maturity benchmarks, but to (ii) identify the detailed procedures to achieve these benchmarks and to (iii) develop a suitable scoring system for measuring teams and organisations against them. To attain all these objectives, the BIM Maturity Matrix – a performance improvement tool introduced in Section 5 – tries to learn from numerous Business Performance, Excellence and Quality Management models (Table 4).

The above frameworks form a good basis to generate a comprehensive scoring system for measuring BIM Capability and Maturity. They will also guide the preparation of multiple knowledge tools tailored to assist industry stakeholders in *implementing* and *assessing* BIM in a systematic and repeatable fashion.

Focus on NBIMS Capability Maturity Model

Before introducing a new maturity index, it is important to properly evaluate existing BIM-specific maturity models. At the time this chapter was readied for publication, two efforts were publicly available: the NBIMS' I-CMM and Indiana

University's BIM Proficiency Matrix⁶. Since not enough documentation - relating to Indiana University's effort - were located, this Section will exclusively focus on NBIMS' approach to BIM maturity assessment and reporting:

The U.S. National Building Information Model Standard™ “establishes standard definitions for building information exchanges to support critical business contexts using standard semantics and ontologies...[to be]...implemented in software”. NBIM Standard Version 1 – Part 1 proposes a Capability Maturity Model (CMM) for “users to evaluate their business practices along a continuum or spectrum of desired technical level functionality” and “for use in measuring the degree to which a building information model implements a mature BIM Standard” (NIST, 2007).

There are two versions of NBIMS' CMM. The first is a static tabular version identifying eleven ‘Areas of Interest’ measured against ten Levels of increasing maturity (Figure 9). The second is the Interactive Capability Maturity Model (I-CMM), a multi-tab Microsoft Excel® workbook based on the static tabular model (NIBS, 2007). The I-CMM is intended for use as an ‘internal tool’ (internal to organisations) deployed to “determine the level of maturity of an individual BIM [project] as measured against a set of weighted criteria agreed to be desirable in a Building Information Model” (NIST, 2007) (Suermann et al., 2008). I-CMM focuses primarily on measuring BIM information management and “should not be used as a benchmark for any other metrics” including those related to architectural, engineering, construction and management. It is also not intended as a “tool to compare BIMs or BIM implementations” (NIST, 2007).

NBIMS' I-CMM is based on the concept of Minimum BIM: achieving a minimum total score for maturity across ‘Areas of Interest’ beyond which a project is not considered ‘true BIM’.

NBIM Standard, version 1 states that “one should obtain a minimum score of 20.1 in order to consider true BIM maturity”. It is however noted

Figure 9. NBIMS CMM Chart (adopted from NIBS, 2007) – more readable MS Excel chart at <http://bit.ly/NBIMS>

Maturity Level	A Data Richness	B Life-cycle Views	C Roles Or Disciplines	G Change Management	D Business Process	F Timeliness/ Response	E Delivery Method	H Graphical Information	I Spatial Capability	J Information Accuracy	K nteroperability/ IFC Support
1	Basic Core Data	No Complete Project Phase	No Single Role Fully Supported	No CM Capability	Separate Processes Not Integrated	Most Response Info manually re-collected - Slow	Single Point Access No IA	Primarily Text - No Technical Graphics	Not Spatially Located	No Ground Truth	No Interoperability
2	Expanded Data Set	Planning & Design	Only One Role Supported	Aware of CM	Few Bus Processes Collect Info	Most Response Info manually re-collected	Single Point Access w/ Limited IA	2D Non-Intelligent As Designed	Basic Spatial Location	Initial Ground Truth	Forced Interoperability
3	Enhanced Data Set	Add Construction/ Supply	Two Roles Partially Supported	Aware of CM and Root Cause Analysis	Some Bus Process Collect Info	Data Calls Not In BIM But Most Other Data Is	Network Access w/ Basic IA	NCS 2D Non-Intelligent As Designed	Spatially Located	Limited Ground Truth - Int Spaces	Limited Interoperability
4	Data Plus Some Information	Includes Construction/ Supply	Two Roles Fully Supported	Aware CM, RCA and Feedback	Most Bus Processes Collect Info	Limited Response Info Available In BIM	Network Access w/ Full IA	NCS 2D Intelligent As Designed	Located w/ Limited Info Sharing	Full Ground Truth - Int Spaces	Limited Info Transfers Between COTS
5	Data Plus Expanded Information	Includes Constr/Supply & Fabrication	Partial Plan, Design&Constr Supported	Implementing CM	All Business Process(BP) Collect Info	Most Response Info Available In BIM	Limited Web Enabled Services	NCS 2D Intelligent As-Built	Spatially located w/Metadata	Limited Ground Truth - Int & Ext	Most Info Transfers Between COTS
6	Data w/Limited Authoritative Information	Add Limited Operations & Warranty	Plan, Design & Construction Supported	Initial CM process implemented	Few BP Collect & Maintain Info	All Response Info Available In BIM	Full Web Enabled Services	NCS 2D Intelligent And Current	Spatially located w/Full Info Share	Full Ground Truth - Int And Ext	Full Info Transfers Between COTS
7	Data w/ Mostly Authoritative Information	Includes Operations & Warranty	Partial Ops & Sustainment Supported	CM process in place and early implementation of root cause analysis	Some BP Collect & Maintain Info	All Response Info From BIM & Timely	Full Web Enabled Services w/IA	3D - Intelligent Graphics	Part of a limited GIS	Limited Comp Areas & Ground Truth	Limited Info Uses IFC's For Interoperability
8	Completely Authoritative Information	Add Financial	Operations & Sustainment Supported	CM and RCA capability implemented and being used	All BP Collect & Maintain Info	Limited Real Time Access From BIM	Web Enabled Services - Secure	3D - Current And Intelligent	Part of a more complete GIS	Full Computed Areas & Ground Truth	Expanded Info Uses IFC's For Interoperability
9	Limited Knowledge Management	Full Facility Life-cycle Collection	All Facility Life-Cycle Roles Supported	Business processes are sustained by CM using RCA and Feedback loops	Some BP Collect&Maint In Real Time	Full Real Time Access From BIM	Netcentric SOA Based CAC Access	4D - Add Time	Integrated into a complete GIS	Comp GT w/Limited Metrics	Most Info Uses IFC's For Interoperability
10	Full Knowledge Management	Supports External Efforts	Internal and External Roles Supported	Business processes are routinely sustained by CM, RCA and Feedback loops	All BP Collect&Maint In Real Time	Real Time Access w/ Live Feeds	Netcentric SOA Role Based CAC	nD - Time & Cost	Integrated into GIS w/ Full Info Flow	Computed Ground Truth w/Full Metrics	All Info Uses IFC's For Interoperability

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that the minimum score for the distinction of a ‘Minimum BIM’ is not fixed but is “dependent on the date the interface [the I-CMM tool] is used”. The minimum score thus changes⁷ yearly or “as the rhetorical bar is raised and owners demand more from the models being delivered” (NIST, 2007). Also, each of the 11 Areas of Interest used in NBIMS’ CMM are weighted. This weighting scheme is not conceptually fixed but can be preferentially altered by organisations as they see fit.

NBIMS’ CMM is still in its early days of development (NIST, 2007) and may yet change significantly. However, in its current form, NBIMS’s CMM and the I-CMM tool suffer from structural limitations that may restrict its usefulness and usability:

- NBIMS’ CMM employs ten maturity levels with minimal distinction between them.

Most capability maturity models surveyed - from within and outside the AECO industry - include only four, five or six distinctive levels (refer to Table 5).

- The Areas of Interest used are not easily understood and may significantly overlap (Suermann et al., 2008) (McCuen, 2007). This may still be true even with the additional explanatory tab available within the I-CMM tool.
- The variability of the ‘minimum score for the Minimum BIM’ will cause scoring inconsistencies. Pre-assigning the minimum score according to calendar year *and* allowing it to be changed ‘according to demands by owners’ are in sharp contrast. Also, it is difficult to imagine that industry’s BIM maturity will increase (or can be encouraged to increase) in a pre-defined linear fashion or that owners’ BIM requirements

Table 5. A non-exhaustive list of terminology used by CMMs to denote maturity levels including those used by the BIM Maturity Index

MATURITY LEVELS						
Maturity Models	0	1 _{ora}	2 _{orb}	3 _{orc}	4 _{ord}	5 _{ore}
BIM Maturity Index		Initial/ Ad-hoc	Defined	Managed	Integrated	Optimised
COBIT, Control Objects for Information and related Technology	Non-existent	Initial/ Ad- hoc	Repeatable but Intuitive	Defined Process	Managed & Measurable	Optimised
CMMI, Capability Maturity Model Integration (Staged Representation)		Initial	Managed	Defined	Quantitatively Managed	Optimising
CMMI (Continuous Representation)	Incomplete	Performed	Managed	Defined	Quantitatively Managed	Optimising
CSCMM, Construction Supply Chain Maturity Model		Ad-hoc	Defined	Managed	Controlled	N/A
LESAT, Lean Enterprise Self-Assessment Tool		Awareness/ Sporadic	General Awareness/ Informal	Systemic Approach	Ongoing Refinement	Exceptional/ Innovative
P-CMM®, People Capability Maturity Model		Initial	Managed	Defined	Predictable	Optimising
P3M3, Portfolio, Programme and Project Management Maturity Model		Awareness	Repeatable	Defined	Managed	Optimised
(PM) ² , Project Management Process Maturity Model		Ad-hoc	Planned	Managed at Project Level	Managed at Corporate Level	Continuous Learning
SPICE, Standardised Process Improvement for Construction Enterprises		Initial/ Chaotic	Planned & Tracked	Well Defined	Quantitatively Controlled	Continuously Improving
Supply Chain Management Process Maturity Model		Ad-hoc	Defined	Linked	Integrated	Extended

- can be established/ represented through a generic minimum score.
- The variability of scoring-weights assigned to Areas of Interest in accordance to organisational preference (or the elusive ‘national consensus’) – as encouraged within the NBIM Standard - will minimise the usefulness of the I-CMM tool and neutralise the ‘certification’ process.
- The current configuration of the I-CMM tool allows organisations/projects to accumulate high total scores even if they achieved very low scores on a number of Areas of Interest (‘platinum’ certification can be achieved even when a project has no Change Management or Spatial Capability).
- The NBIM’s CMM Areas of Interest are only useful in assessing Models and not the teams, organisations or project-teams which generate them.
- The NBIM’s CMM in both its static and dynamic versions can only be applied ‘internally’ through self-assessment or peer-revision.
- Most importantly, the inability of the NBIM’s CMM – in its current form - to assess any BIM metric beyond ‘information management’ (NIST, 2007) severely limits its applicability and usefulness.

The AECO industry, challenged by the widely-reported capabilities and requirements of Building Information Modelling, will benefit from the availability of a maturity index that can assess a host of metrics across many organisational scales. The availability of such a BIM-specific maturity index will assist individuals, organisations and industry bodies to (a) justify investment in BIM competency development and productivity enhancement, (b) assess their BIM performance, strengths and weaknesses and (c) potentially gain market recognition for their BIM products and service quality.

BIM-Specific Maturity Index

ABIM-specific maturity index has been developed by analysing then integrating several models from different industries. Its Maturity Levels reflect the *extent* of BIM abilities, deliverables and their requirements as opposed to *minimum* abilities reflected through Capability Stages. The BIM Maturity Index has five distinct levels: (a) Initial/Ad-hoc, (b) Defined, (c) Managed, (d) Integrated and (e) Optimised. Level names have been chosen through comparing terminology used by many maturity models (Table 5) followed by selecting those easily understandable by AECO stakeholders and able to reflect the increasing BIM maturity from ad-hoc to continuous improvement.

In general, the progression from low to higher levels of maturity indicate (i) better control through minimising variations between targets and actual results, (ii) better predictability and forecasting by lowering variability in competency, performance and costs *and* (iii) greater effectiveness in reaching defined goals and setting new more ambitious ones (Lockamy III & McCormack, 2004) (Kevin McCormack, Ladeira, & Oliveira, 2008). In this chapter, it will be difficult to discuss all maturity levels pertaining to all capability stages at all organisational scales. Only one sample capability/maturity/scale combination will be generically described below.

The following is a hypothetical assessment report for an Organisation (organisational scale 9) discovered to be at Capability Stage 1 (object-based modelling) and Maturity Level a (initial/ad-hoc):

- *Summary:* the organisation is at Capability Stage 1 with Maturity Level 'a'. BIM implementation is characterised by *the absence of* an overall strategy and *a significant shortage of* defined processes and policies. BIM software tools are deployed in a non-systematic fashion and without adequate prior investigations and preparations. BIM adoption is only partially achieved through the 'heroic' efforts of individual champions – a process that lacks the active and consistent support of middle and senior management.
- *Technology:* Usage of software applications is unmonitored and unregulated. Software licence numbers are typically misaligned to staff requirements. 3D Models are relied upon to mainly generate accurate 2D representations/deliverables. Data usage and storage are not well defined and data exchanges suffer from a severe lack of interoperability.

Hardware specifications are non-uniform and fall well below staff skills and expected BIM deliverables. Equipment replacement and upgrades are treated as cost items, postponed whenever possible and committed to only when unavoidable.

Network solutions are non-existent or ad-hoc. Individuals and teams use whatever tools available to communicate and share data. Stakeholders lack the network infrastructure necessary to harvest, store and share knowledge.

- *Process:* Senior leaders/managers have varied visions about BIM and its implementation is conducted without an overall strategy. As typical at this maturity level,

BIM is treated as a technology stream without much consideration for its process and policy implications. Change resistance is evident among staff and possibly widespread amongst middle management.

The workplace environment is not recognised as a factor in staff satisfaction/motivation and is not conducive to productivity. Knowledge is not recognised as an organisational asset and is mainly shared informally between staff - through tips, techniques and lessons learned.

Business opportunities arising from BIM are not acknowledged. BIM objects (components, parts or families) are not consistently available in adequate numbers or quality. 3D models deliverables (as BIM products) suffer from too high, too low or inconsistent levels of detail. More importance is given to visual quality of 2D representations than is given to 3D model accuracy.

Products and services offered by the organisation represent a fraction of the capabilities inherent within the software tools employed. There are no modelling quality checks or formal audit procedures.

BIM Projects are conducted using inconsistent practices and there are no project initiation or closure protocols. Staff competency levels are unknown to management, roles are ambiguous and team structures pre-date BIM. Staff are neither structurally trained nor inducted into BIM processes; are generally confused about workflows and 'who to go to' for technical and procedural assistance.

- Performance is unpredictable and productivity depends on champions' efforts within teams. A mentality of 'shortcuts' and 'working around the system' flourishes. Performance is inconsistent and is neither monitored nor reported in any systematic fashion. In general, islands of concentrated BIM productivity are separated by seas of BIM idleness/confusion.

- *Policy:* The organisation does not document or adopt BIM-specific guidelines and standards. There are minor or inconsistent quality controls for 3D models and 2D representation. There are no training policies, and educational mediums – when available - are not suitable or accessible to staff. Contractually, there is a dependence on pre-BIM arrangements with no BIM-specific risk identification and mitigation policies.

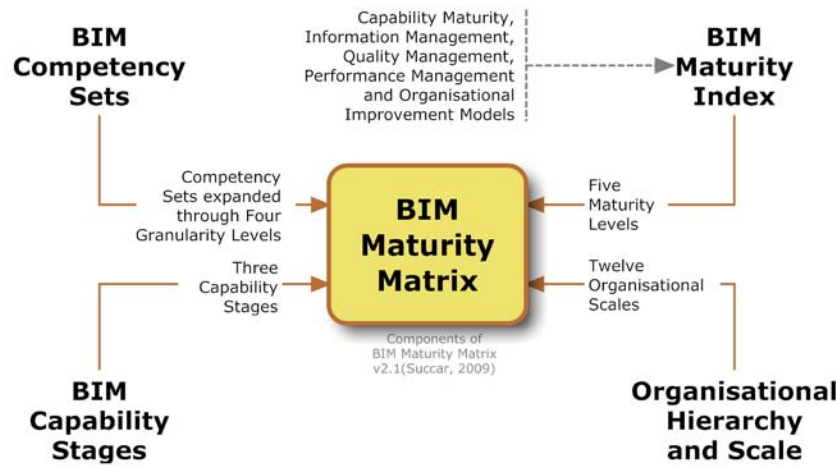
The above is a generic summary-description of a hypothetical organisation grappling with low BIM maturity while implementing object-based modelling. The BIM Maturity Matrix (BIM³), introduced in the next section, is a comprehensive knowledge tool that assists individuals, organisations and other organisational scales in planning, achieving and assessing BIM performance milestones.

5 THE BIM MATURITY MATRIX

The BIM Maturity Matrix (BIM³) is a knowledge tool which incorporates many BIM Framework components for the purpose of performance measurement and improvement. Both its structure and content have benefited from time-tested maturity (Table 3) and excellence models (Table 4). To enable its wide applicability across the AECO industry, the BIM Maturity Matrix follows a set of guiding principles. BIM³ has been developed to be:

- **Specific:** the Matrix is composed of a set of interlocking BIM capability stages, steps, organisational scales, maturity areas and levels. All components are well defined, complementary and serve specific purposes in assessing BIM capability and maturity.
- **Attainable:** all BIM capability stages and maturity levels can be achieved through an accumulation of defined actions.

Figure 10. Components of the BIM Maturity Matrix v2.2



- **Applicable:** the Maturity Matrix can be equally utilised by all AECO stakeholders across all Project Lifecycle Phases.
- **Flexible:** capability and maturity assessments can be performed across organisational scales.
- **Gradual:** the Matrix reflects and encourages smooth progression to increasingly higher capability and/or maturity.
- **Cumulative:** BIM capability stages and maturity levels, the two main components of the Matrix, are logical progressions. Deliverables from one capability stage or maturity level are prerequisites for the next stage or level.
- **Current:** the Matrix is designed around current and emerging technologies. Also, its format, dependencies and terminology have been selected to minimise the need for frequent structural changes.
- **Informative:** The Matrix provides “feedback for improvement” as well as “guidance for next steps” (Nightingale & Mize, 2002).
- **Measurable:** maturity assessments are linked to capability stages and organisational scales. This allows like-to-like comparisons without compromising units of measurement.
- **Granular:** maturity assessments can be conducted at multiple granularity levels, delivering a stepped-range of scores and reports.
- **Neutral:** the BIM Maturity Matrix does not prejudice proprietary, non-proprietary, closed, open, free or commercial solutions/schemas. It can be employed by stakeholders irrespective of their technical persuasion.
- **Relevant:** the Matrix and its underlying concepts are relevant to both industry and academia; this should encourage its adoption and development respectively.

To meet the above guiding principles, the BIM Maturity Matrix combines several BIM Framework components represented in Figure 10.

Sample Static Tabular Form

The BIM Maturity Matrix incorporates a set of concepts whose interactions can be represented through many static and dynamic mediums. The Matrix, in its expanded database-driven form, includes all Capability Stages, Maturity Levels and Organisational Scales. Table 6 introduces a static representation of the Matrix at a sample Granularity Level.

6 GRANULARITY OF COMPETENCY SETS AND AREAS

Competency Sets include a large number of individual competencies grouped under numerous competency headings (refer to Figure 5). To enhance capability and maturity assessments and to increase their flexibility, a Granularity ‘Filter’ (Succar, 2009) with four Granularity Levels (GLevels) has been developed. Progression from low to higher levels of granularity indicate an increase in (i) assessment breadth, (ii) scoring detail, (iv) formality and (iv) assessor specialisation.

Using high-granularity levels (GLevels 3 or 4) exposes more detailed Competency Areas than low-granularity levels (GLevels 1 or 2). This variability in breadth, detail, formality and specialisation enables the preparation of several BIM performance measurement tools ranging from low-detail, informal and self-administered assessments to high-detail, formal and specialist-led appraisals. Table 7 provides more information about the four Granularity Levels.

The mind map depicted in Section 2 identifies thirty-four Competency Areas available at GLevel 2 (Evaluation) as compared to only ten areas available at GLevel 1 (Discovery). Figure 11 explores BIM Competencies at GLevel 3 (Certification) and GLevel 4 (Auditing).

As depicted above, the number and specificity of BIM Competencies increase dramatically at higher GLevels unveiling granular Areas like Data Storage, Data Exchange and Semantic Connectivity (at GLevel 3) and Structured and Unstructured Data (at GLevel 4). Additional more-specific competencies (not shown) include metadata, analytical models and other computable and non-computable formats (Kong et al., 2005) (Mathes, 2004) (Fallon & Palmer, 2007).

In addition to granularity, the number of Competency Areas applicable to teams and organisations varies according to Organisational Scale and Capability Stage. For example, the number of

Competency Areas an ‘Organisational Member’ is evaluated against are less than that of a ‘Project Team’. Similarly, the number of Competency Areas available for assessment within a Collaborative BIM project (BIM Stage 2) is less than that available within an Integrated one (BIM Stage 3). This variability is represented in Figure 12.

Assessment Workflow and Reporting

BIM Capability and Maturity assessments can be employed at either one of three Capability Stages (Table 2), one of twelve Organisational Scales (Table 3) and at one of four Competency Granularity Levels (Table 7). To manage all these assessment and reporting configurations, a simple assessment and reporting workflow has been developed (Figure 13).

Workflow Diagram - v2.0

Expanding on the above diagram, a total of five workflow steps is needed to conduct a BIM Capability and Maturity Assessment. Starting with an extensive pool of generic BIM Competencies - applicable across AECO disciplines and organisational sizes – assessors first filter out non-applicable Competency Sets, conduct a series of assessments based on remaining Competency Areas and then generate a suitable Assessment Report:

- *Workflow Step 1:* The assessor establishes the Organisational Scale (OScale) of the assessed. For example, an organisation with multiple offices across different cities may decide to assess BIM Capability and Maturity across the whole Organisation or within one specific Organisational Unit. To a varying degree (refer to Table 7), assessments can be conducted at every one of the twelve OScales. This ranges from ‘Markets’ (e.g. evaluating international standards and

Table 6. Building Information Modelling Maturity Matrix – static tabular guide at sample granularity, v1.1

BIM MATURITY MATRIX					
BIM Competency Areas at Granularity level 1	a	b	c	d	e
	INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED
TECHNOLOGY	Usage of software applications is unmonitored and unregulated. 3D Models are relied on to mainly generate accurate 2D representations/deliverables. Data usage, storage and exchanges are not defined within organisations or project teams. Exchanges suffer from a severe lack of interoperability.	Software usage/introduction is unified within an organisation or project teams (multiple organisations). 3D Models are relied upon to generate 2D as well as 3D deliverables. Data usage, storage and exchange are well defined within organisations and project teams. Interoperable data exchanges are defined and prioritised.	Software selection and usage is controlled and managed according to defined deliverables. Models are the basis for 3D views, 2D representations, quantification, specification and analytical studies. Data usage, storage and exchanges are monitored and controlled. Data flow is documented and well-managed. Interoperable data exchanges are mandated and closely monitored.	Software selection and deployment follows strategic objectives, not just operational requirements. Modelling deliverables are well synchronised across projects and tightly integrated with business processes. Interoperable data usage, storage and exchange are regulated and performed as part of an overall organisational or project-team strategy.	Selection/use of software tools is continuously revisited to enhance productivity and align with strategic objectives. Modelling deliverables are cyclically being revised/optimised to benefit from new software functionalities and available extensions. All matters related to interoperable data usage storage and exchange are documented, controlled, reflected upon and proactively enhanced.
	BIM equipment is inadequate; specifications are too low or inconsistent across the organisation. Equipment replacement or upgrades are treated as cost items and performed only when unavoidable.	Equipment specifications – suitable for the delivery of BIM products and services – are defined, budgeted-for and standardised across the organisation. Hardware replacements and upgrades are well-defined cost items.	A strategy is in place to transparently document, manage and maintain BIM equipment. Investment in hardware is well-targeted to enhance staff mobility (where needed) and extend BIM productivity.	Equipment deployments are treated as BIM enablers. Investment in equipment is tightly integrated with financial plans, business strategies and performance objectives.	Existing equipment and innovative solutions are continuously tested, upgraded and deployed. BIM hardware become part of organisation's or project team's competitive advantage.
	Network solutions are non-existent or ad-hoc. Individuals, organisations (single location/dispersed) and project teams use whatever tools found to communicate and share data. Stakeholders lack the network infrastructure necessary to harvest, store and share knowledge.	Network solutions for sharing information and controlling access are identified within and between organisations. At project level, stakeholders identify their requirements for sharing data/information. Dispersed organisations and project teams are connected through relatively low-bandwidth connections.	Network solutions for harvesting, storing and sharing knowledge within and between organisations are well managed through common platforms (e.g. intranets or extranets). Content and asset management tools are deployed to regulate structured and unstructured data shared across high-bandwidth connections.	Network solutions enable multiple facets of the BIM process to be integrated through seamless real-time sharing of data, information and knowledge. Solutions include project-specific networks/portals which enable data-intensive interchange (interoperable exchange) between stakeholders.	Network solutions are continuously assessed and replaced by the latest tested innovations. Networks facilitate knowledge acquisition, storing and sharing between all stakeholders. Optimisation of integrated data, process and communication channels is relentless.

BIM COMPETENCY SETS

continued on the following page

Table 6. continued

BIM Competency Areas at Granularity level 1	PROCESS				
	a	b	c	d	e
	INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED
Infrastructure: physical and knowledge-related	The work environment is either not recognised as a factor in staff satisfaction or may not be conducive to productivity. Knowledge is not recognised as an asset; BIM knowledge is typically shared informally between staff (through tips, techniques and lessons learned).	The work environment and workplace tools are identified as factors affecting motivation and productivity. Similarly, knowledge is recognised as an asset; shared knowledge is harvested, documented and thus transferred from tacit to explicit.	The work environment is controlled, modified and it's criteria managed to enhance staff motivation, satisfaction and productivity. Also, documented knowledge is adequately stored.	Environmental factors are integrated into performance strategies. Knowledge is integrated into organisational systems; stored knowledge is made accessible and easily retrievable [refer to the 4 levels of knowledge retention (Arif et al., 2009)].	Physical workplace factors are reviewed constantly to insure staff satisfaction and an environment conducive to productivity. Similarly, knowledge structures responsible for acquisition, representation and dissemination are systematically reviewed and enhanced.
Products & Services specification, differentiation, project delivery approach and R&D	3D models deliverables (a BIM product) suffer from too high, too low or inconsistent levels of detail.	A "statement defining the object breakdown of the 3D model" (Bouygues, 2007) is available.	Adoption of product/ service specifications similar to Model Progression Specifications (AIA, 2008), BIPS 'information levels' (BIPS, 2008) or similar.	Products and services are specified and differentiated according to Model Progression Specifications or similar.	BIM products and services are constantly evaluated; feedback loops promote continuous improvement.
Human Resources: competencies, roles, experience and dynamics	There is an absence of defined processes; roles are ambiguous and team structures/dynamics are inconsistent. Performance is unpredictable and productivity depends on individual heroics. A mentality of 'working 'around the system' flourishes.	BIM roles are informally defined and teams are formed accordingly. Each BIM project is planned independently. BIM competency is identified and targeted; BIM heroism fades as competency increases but productivity is still unpredictable.	Cooperation within organisations increases as tools for cross-project communication are made available. Flow of information steadies; BIM roles are visible and targets are achieved more consistently.	BIM roles and competency targets are imbedded within the organisation. Traditional teams are replaced by BIM-oriented ones as new processes become part of organisation's / project team's culture. Productivity is now consistent and predictable.	BIM competency targets are continuously upgraded to match technological advances and align with organisational objectives. Human resource practices are proactively reviewed to insure intellectual capital matches process needs.
Leadership: innovation and renewal, strategic, organisational, communicative and managerial attributes	Senior leaders/ managers have varied visions about BIM. BIM implementation (according to BIM Stage requirements) is conducted without a guiding strategy. At this maturity level, BIM is treated as a technology stream; innovation is not recognised as a independent value and business opportunities arising from BIM are not acknowledged.	Senior leaders/managers adopt a common vision about BIM. BIM implementation strategy lacks actionable details. BIM is treated as a process-changing, technology stream. Product and process innovations are recognised; business opportunities arising from BIM are identified but not exploited.	The vision to implement BIM is communicated and understood by most staff. BIM implementation strategy is coupled with detailed action plans and a monitoring regime. BIM is acknowledged as a series of technology, process and policy changes which need to be managed without hampering innovation. Business opportunities arising from BIM are acknowledged and used in marketing efforts.	The vision is shared by staff across the organisation and/or project partners. BIM implementation, its requirements and process/ product innovation are integrated into organisational, strategic, managerial and communicative channels. Business opportunities arising from BIM are part of team, organisation or project-team's competitive advantage and are used to attract and keep clients.	Stakeholders have internalised the BIM vision and are actively achieving it (Nightingale & Mize, 2002). BIM implementation strategy and its effects on organisational models are continuously revisited and realigned with other strategies. If alterations are needed, they are proactively implemented. Innovative product/ process solutions and business opportunities are sought-after and followed through relentlessly.

BIM COMPETENCY SETS

continued on the following page

Table 6. continued

BIM Competency Areas at Granularity level 1	a	b	c	d	e
	INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED
Regulatory: rules/ directives, standards/ classifications, guidelines/ benchmarks and codes/ regulations	There are no BIM guidelines, documentation protocols or modelling standards. There is an absence of documentation and modelling standards. There is informal or no quality control plans; neither for 3D models nor for documentation. There are no performance benchmarks for processes, products or services.	Basic BIM guidelines are available (e.g. training manual and BIM delivery standards). Modelling and documentation standards are well defined according to market-accepted standards. Quality targets and performance benchmarks are set.	Detailed BIM guidelines are available (training, standards, workflow, exceptions...). Modelling, representation, quantification, specifications and analytical properties of 3D models are managed through detailed modelling standards and quality plans. Performance against benchmarks is tightly monitored and controlled.	BIM guidelines are integrated into overall policies and business strategies. BIM standards and performance benchmarks are incorporated into quality management and performance improvement systems.	BIM guidelines are continuously and proactively refined to reflect lessons learned and industry best practices. Quality improvement and adherence to regulations and codes are continuously aligned and refined. Benchmarks are repetitively revisited to insure highest possible quality in processes, products and services
Contractual: responsibilities, rewards and risks	Dependence on pre-BIM contractual arrangements. BIM risks related to model-based collaboration (differ in each market) are not recognised or are ignored.	BIM requirements are recognised. "Statements defining the responsibility of each stakeholder regarding information management" (Bouygues, 2007) are now available.	There is a mechanism to manage shared BIM intellectual property, confidentiality, liability and a system for BIM conflict resolution.	Organisation are aligned through trust and mutual dependency beyond contractual barriers.	Responsibilities, risks and rewards are continuously revisited and realigned to effort. Contractual model are modified to achieve best practices and highest value for all stakeholders.
Preparatory: research efforts/ deliverables, educational programmes/ deliverables and training programmes	Very little or no training available to BIM staff. Educational/ training mediums are not suitable to achieve the results sought.	Training requirements are defined and are typically provided only when needed. Training mediums are varied allowing flexibility in content delivery.	Training requirements are managed to adheres to pre-set broad competency and performance objectives. Training mediums are tailored to suit trainees and reach learning objectives in a cost-effective manner.	Training is integrated into organisational strategies and performance targets. Training is typically based on staff roles and respective competency objectives. Training mediums are incorporated into knowledge and communication channels.	Training is continuously evaluated and improved upon. Training availability and delivery methods are tailored to allow multi-modal continuous learning.
POLICY					
BIM COMPETENCY SETS					

continued on the following page

Building Information Modelling Maturity Matrix

Table 6. continued

	a	b	c	d	e
	INITIAL	DEFINED	MANAGED	INTEGRATED	OPTIMISED
Object-based Modelling: single-disciplinary use within a Project Lifecycle Phase	Implementation of an object-based tool. No process or policy changes identified to accompany this implementation.	Pilot projects are concluded. BIM process and policy requirements are identified. Implementation strategy and detailed plans are prepared.	BIM processes and policies are instigated, standardised and controlled.	BIM technologies, processes and policies are integrated into organisational strategies and aligned with business objectives.	BIM technologies, processes and policies are continuously revisited to benefit from innovation and achieve higher performance targets.
Modelling-based Collaboration: multi-disciplinary, fast-tracked interchange of models	Ad-hoc BIM collaboration; in-house collaboration capabilities incompatible with project partners. Trust and respect between project participants may be lacking.	Single-thread, well-defined yet reactive BIM collaboration. There are identifiable signs of mutual trust and respect among project participants.	Multi-thread proactive collaboration; protocols are well documented and managed. There are mutual trust, respect and sharing of risks and rewards among project participants.	Multi-thread collaboration includes downstream players. This is characterised by the involvement of key participants during projects' early lifecycle phases.	Multi-thread team included all key players in an environment characterised by goodwill, trust and respect.
Network-based Integration: concurrent interdisciplinary interchange of nD models across Project Lifecycle Phases	Integrated models are generated by a limited set of project stakeholders - possibly behind corporate firewalls. Integration occurs with little or no pre-defined process guides, standards or interchange protocols. There is no formal resolution of stakeholders' roles and responsibilities.	Integrated models are generated by a large subset of project stakeholders. Integration follows predefined process guides, standards and interchange protocols. Responsibilities are distributed and risks are mitigated through contractual means.	Integrated models (or parts of) are generated and managed by most project stakeholders. Responsibilities are clear within temporary project alliances or longer-term partnerships. Risks and rewards are actively managed and distributed.	Integrated models are generated and managed by all key project stakeholders. Network-based integration is the norm and focus is no longer on <i>how</i> to integrate models/ workflows but on proactively detecting and resolving technology, process and policy misalignments.	Integration of models and workflows are continuously revisited and optimised. New efficiencies, deliverables and alignments are actively pursued by a tightly-knit interdisciplinary project team. Integrated models are contributed to by many stakeholders along the construction supply chain.
Organisations: dynamics and BIM deliverables	BIM leadership is non-existent; implementation depends on technology champions.	BIM leadership is formalised; different roles within the implementation process are defined.	Pre-defined BIM roles complement each other in managing the implementation process.	BIM roles are integrated into organisation's leadership structures.	BIM leadership continuously mutates to allow for new technologies, processes and deliverables.
Project Teams (multiple organisations); inter-organisational dynamics and BIM deliverables	Each project is run independently. There is no agreement between stakeholders to collaborate beyond their current common project.	Stakeholders think beyond a single project. Collaboration protocols between project stakeholders are defined and documented.	Collaboration between multiple organisations over several projects is managed through temporary alliances between stakeholders.	Collaborative projects are undertaken by interdisciplinary organisations or multidisciplinary project teams: an alliance of many key stakeholders.	Collaborative projects are undertaken by self-optimising interdisciplinary project teams which include most stakeholders.
Markets: dynamics and BIM deliverables	Very few supplier-generated BIM components (virtual products and materials representing physical ones). Most components are prepared by software developers and end-users.	Supplier-generated BIM components are increasingly available as manufacturers/ suppliers identify the business benefits.	BIM Components are available through highly accessible/searchable central repositories. Components are not interactively connected to suppliers' databases.	Access to component repositories are integrated into BIM software. Components are interactively linked to source databases (for price, availability, etc...).	Dynamic, multi-way generation and interchange of BIM components (virtual products and materials) between all project stakeholders through central or meshed repositories.

BIM CAPABILITY STAGES

ORGANISATIONAL SCALES

Table 7. BIM Competency Granularity Filter

COMPETENCY GRANULARITY FILTER					
	GLevel Number, GLevel Name, Description and Scoring System (Numerical and/or Named)		OScale applicability	Assessment By, Report Type and <i>Guide Name</i>	
1	Discovery	A low detail assessment used for basic and semi-formal discovery of BIM Capability and Maturity. Discovery assessments yield a basic numerical score.	All Scales	Self	Discovery Notes <i>BIMC&M Discovery Guide</i>
2	Evaluation	A more detailed assessment of BIM Capability and Maturity. Evaluation assessments yield a detailed numerical score.	All Scales	Self and Peer	Evaluation Sheets <i>BIMC&M Evaluation Guide</i>
3	Certification	A highly-detailed appraisal of those Competency Areas applicable across disciplines, markets and sectors. Certification appraisal is used for Structured (Staged) Capability and Maturity and yields a formal, Named Maturity Level.	8 and 9	External Consultant	Certificate <i>BIMC&M Certification Guide</i>
4	Auditing	The most comprehensive appraisal...In addition to competencies covered under Certification, Auditing appraises detailed Competency Areas including those specific to a market, discipline or a sector. Audits are highly customisable, suitable for Non-structured (Continuous) Capability and Maturity and yield a Named Maturity Level plus a Numerical Maturity Score for each Competency Area audited.	8, 9, 10 & 11	Self, Peer and External Consultant	Audit Report <i>BIMC&M Auditing Guide</i>

the availability of supplier-generated BIM components), through ‘Project Teams’ (e.g. assessing collaboration dynamics and risk-mitigation protocols within a team) to ‘Organisational Members’ (e.g. assessing BIM competencies of an individual architect or engineer). In this first workflow step, the selection/application of an OScale filter considerably reduces the number of applicable competencies.

- *Workflow Step 2:* The assessor establishes assessment’ Granularity Level (GLevel). There are up to four GLevels which can apply according to established OScale (refer to Table 8). Once a GLevel is set, non-applicable and more granular Competency Areas are removed from the assessment pool.
- *Workflow Step 3:* After the number of applicable BIM Competencies has been

significantly reduced by OScale and GLevel filters, the assessor establishes the ‘actual’ and the ‘target’ BIM Capability Stages. For example, if the assessed organisation – an architectural firm - has object-based modelling capability and aims to start collaborating with a structural engineer *then* BIM Stage 1 is the ‘actual stage’ while BIM Stage 2 is the ‘target stage’. Armed with this knowledge, the assessor isolates Capability Sets A and B (refer to Figure 6) for focused capability assessment. The assessor then establishes whether each of the remaining applicable competencies has reached ‘minimum capability’.

- *Workflow Step 4:* The assessor isolates the BIM Competencies which reached ‘minimum capability’ and then assesses their maturity. Using the same example from workflow step 2, the assessor focuses his/

Figure 11. Competency Areas at Granularity Level 4 – partial mind map v1.1

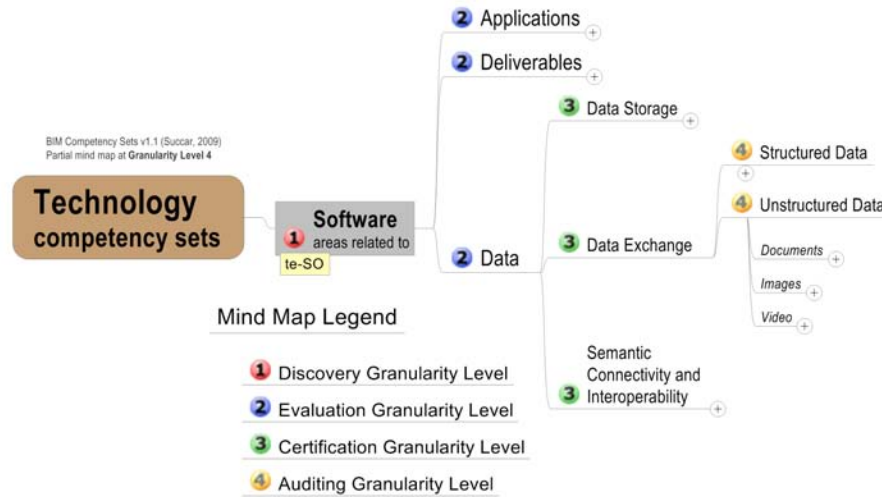
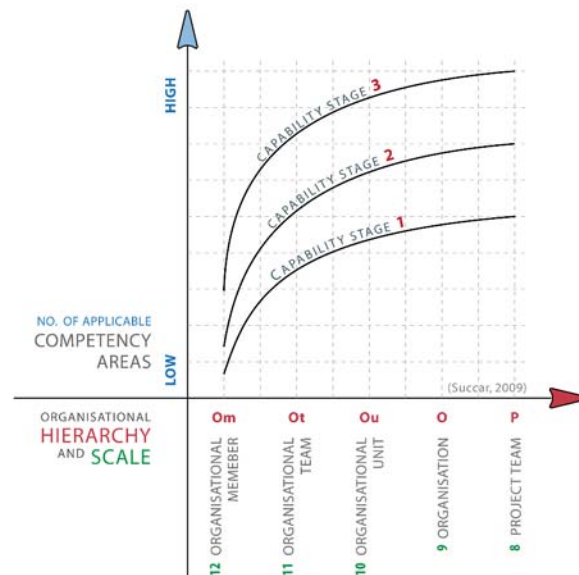


Figure 12. Applicability of Competency Areas relative to Organisational Scale and Capability Stage – diagram covering MICRO and MESO Organisational Scales v1.1

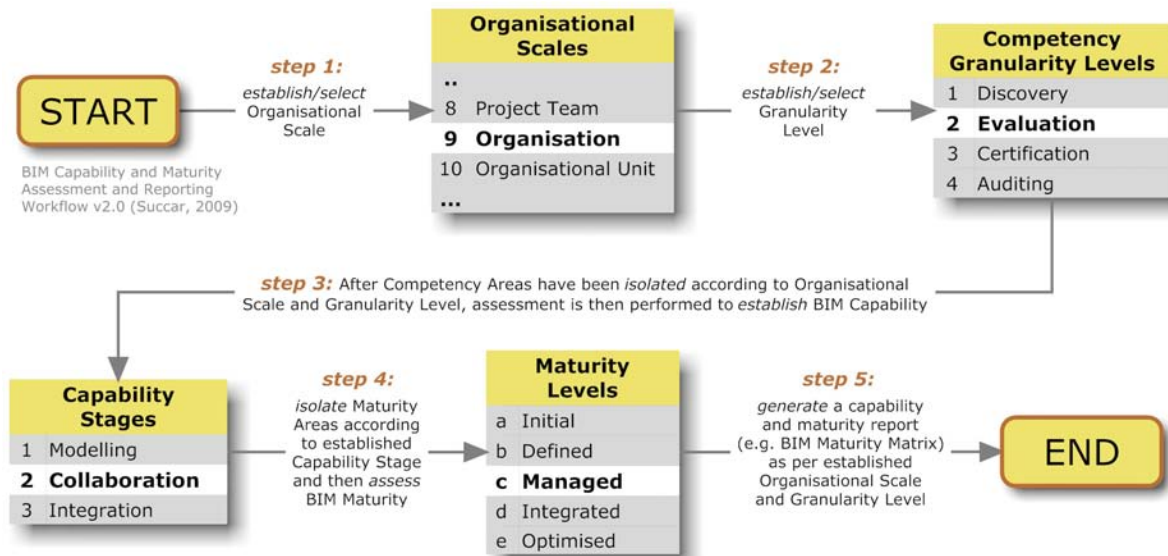


her attention on Competency Sets A and B and then assess them individually against the five Maturity Levels.

- *Workflow Step 5:* In the last workflow step, assessment results are reported using a template matching previously established

OScale and GLevel. As per table 8, there are four types of assessment reports which vary in formality, coverage, detail and the provision of a named or numerical score.

Figure 13. BIM Capability and Maturity Assessment and Reporting



Assessment Representation

Maturity assessments can be extensive in nature and may generate a significant amount of information that needs to be understood and acted upon. Knowledge visualisations can be employed to ‘abstract’ the BIM assessment deliverables and control their complexity by removing unnecessary detail (Kao & Archer, 1997). They are also instrumental in facilitating knowledge transfer to others (Eppler & Burkhard, 2005) as well as measuring BIM capability/ maturity against set visual benchmarks.

In addition to textual (e.g. the static BIM Maturity Matrix depicted in Section 4), assessments can be delivered in graphical (e.g. data-driven charts), multimedia (e.g. scenario-based online assessments) or through other types of knowledge visualisations (See example - Figure 14). These graphical representations allow visual comparisons between organisations or against an industry-wide average. They can also be used to help explain seemingly complex assessment results and promote action by teams and organisations.

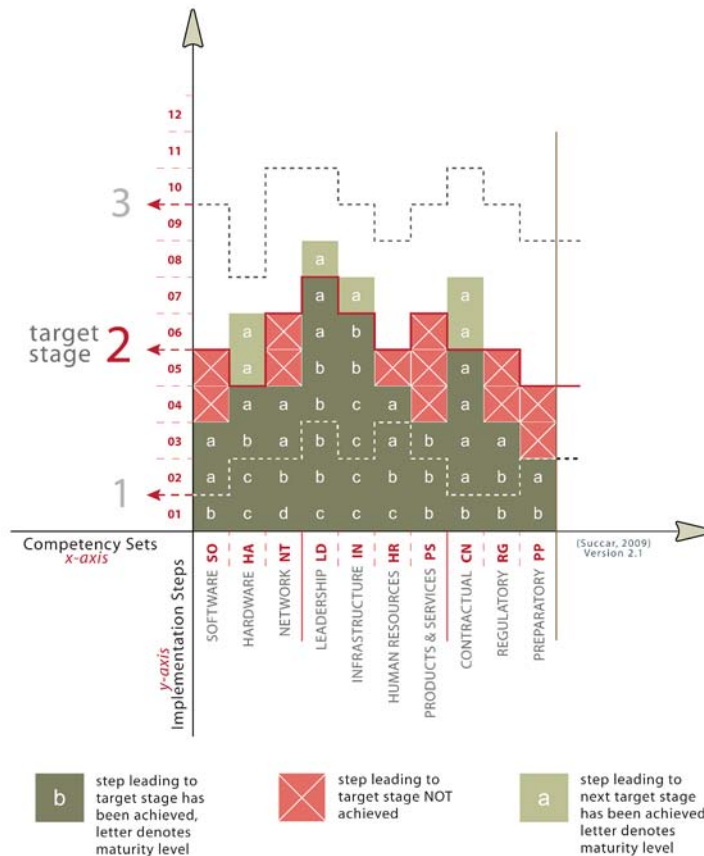
Sample Maturity Scoring System

Measuring BIM Capability and Maturity across markets, disciplines and organisational sizes requires an extensive, consistent yet flexible scoring system. Below is an exploration of the simplest form of scoring – called Maturity Discovery Score – to be used for informal, self-administered assessments at any Organisational Scale. The Discovery scoring system follows a simple arithmetic model:

- There are twelve individual scores relating to ten Competency Areas, one Capability Stage and one Organisational Scale.
- Maturity Levels are assigned a fixed number of maturity points: Level a (10 points), Level b (20 points), Level c (30 points), Level d (40 points) and Level e (50 points).
- The Maturity Discovery Score is the *average* of total points subdivided by twelve.

Table 8 provides a hypothetical Maturity Discovery Score of an assessed organisation at BIM Capability Stage 2.

Figure 14. Visual Report of a hypothetical BIM Capability and Maturity assessment – v2.0



7 A FINAL NOTE

The BIM Maturity Matrix builds upon the BIM Framework (Succar, 2009) which identifies BIM Fields, Stages, Lenses, Steps, Project Lifecycle Phases and a specialised conceptual Ontology. This chapter further extends the Framework by developing a BIM Maturity Index, an Organisational Hierarchy/Scale and a Competency Granularity Filter. It also introduces the BIM Maturity Matrix, a Capability and Maturity assessment and reporting tool that utilizes all the above components.

The availability of an extended BIM Maturity Matrix (especially in a database-driven web format) will be beneficial to construction industry stakeholders irrespective of their Design, Con-

struction or Operations' role. Industry practitioners can employ the Matrix and its underlying BIM Framework to:

- Increase their capability across a pre-identified range of technology, process and policy steps. As these competencies mature, they typically “meet an organisation’s functional and quality expectations” (Jaco, 2004), get ‘institutionalised’ through standards, and organisational structures (McCormack and Johnson 2000) and help teams and organisations achieve *consistency in capability* (Vaidyanathan & Howell, 2007).
- Accurately assess their own, their peers’ and potential project-partners’ capability

Table 8. Maturity Discovery Score - hypothetical maturity assessment at Granularity Level 1

MATURITY DISCOVERY SCORE						
BIM Maturity Matrix Assessment at Granularity Level 1		a	b	c	d	e
		10 Pts	20 Pts	30 Pts	40 Pts	50 Pts
Technology	Software			●		
	Hardware	●				
	Network		●			
Process	Leadership				●	
	Human Resources			●		
	Infrastructure		●			
	Products & Services		●			
Policy	Contractual		●			
	Regulatory			●		
	Preparatory				●	
Stage	Collaboration [2]			●		
Scale	Organisation [9]		●			
Subtotal		10	100	120	80	0
Total Points					310	
Maturity Score					25.83	
NOT SUITABLE FOR CERTIFICATION						

and maturity at selective organisational scales and granularity levels.

- Work towards a BIM ‘performance excellence award’, a BIM ‘maturity certificate’ or similar. Such awards are potentially beneficial for product/service differentiation as well as market positioning.
- Continuously assess and improve their BIM performance.

The BIM Maturity Matrix and its underlying BIM Framework are still being developed and extended. Future deliverables include a web-based interactive tool suitable for low-granularity, self-administered maturity assessment. Capability and maturity templates, questionnaires, guides, knowledge models and granular scoring systems are also being researched, developed and tested.

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KEY TERMS AND DEFINITIONS

BIM Fields: BIM Fields are conceptual clusters of domain players interacting and overlapping within the AECO industry. There are three BIM Field Types (Technology, Process and Policy) and three Field Components (Players, Requirements and Deliverables).

BIM Capability Stages: BIM Capability is the basic ability to perform a task, deliver a service or generate a product. BIM Capability Stages define the major milestones to be achieved by teams and organisations as they adopt BIM technologies and concepts. BIM Stages are defined by their *minimum requirements*.

BIM Lenses: BIM Lenses are distinctive layers of analysis which allow the researchers to selectively focus on any aspect of the AECO industry and generate knowledge views that either (a) highlight observables which meet the research criteria or (b) filter out those that do not.

BIM Steps: BIM Steps are the evolutionary or incremental steps that need to be completed to reach or progress within a BIM Stage (also see BIM Competency Sets below).

BIM Competency Sets: A BIM Competency Set is a hierarchical collection of individual competencies identified for the purposes of BIM implementation and assessment. If BIM Competencies are used for the purposes of active implementation, they are referred to as BIM Steps. However, if used for assessing existing implementations, they are referred to as BIM Areas.

BIM Organisational Scales: The BIM Organisational Scale is a hierarchical subdivision of markets, industries, project teams and organisations for the purpose of BIM capability and maturity measurement.

BIM Maturity Index: The term ‘BIM maturity’ refers to the *quality, repeatability and degrees of excellence* within a BIM capability. As opposed to ‘capability’ which denotes a *minimum ability*, maturity denotes the *extent of that ability*. The BIM Maturity Index (BIMMI) is a process improvement framework – with five distinct levels - developed to assess the maturity of BIM players, their requirements and deliverables across organisational scales.

BIM Maturity Matrix: The BIM Maturity Matrix (BIM³) is a performance assessment and improvement tool which incorporates BIM Stages, Competency Sets, Organisational Scales and Granularity Levels.

ENDNOTES

- ¹ The term *capability* in this chapter refers to the ‘basic ability to perform a task’ while the term *maturity* refers to the ‘degrees of excellence in performing that task’ (refer to Section 4).
- ² This chapter uses an expanded definition of the term ‘implementation’. Throughout this chapter, BIM implementation *does not only reflect the act of deploying* software, schema and their related processes but *represents all actions necessary to achieve, maintain and increase* BIM Capability and Maturity.
- ³ The author prefers to use the term BIM Maturity Index instead of BIM Maturity Model to minimise semantic confusion every time the word ‘model’ is invoked.
- ⁴ For an overview of the latest Supply-chain Operations Reference Model (SCOR), version 9, please refer to <http://bit.ly/SCORv9>.
- ⁵ Please note that the terms Capability and Maturity are used differently by the Software Engineering Institute – Carnegie Mellon, to denote CMMI “Continued Representation” and “Staged Representation” respectively.
- ⁶ Indiana University BIM Proficiency Matrix includes eight categories measured against four maturity/proficiency levels. The matrix focuses on the accuracy and richness of the digital model (as an end-product) and has less focus on the process of creating that digital model. More information is available at <http://bit.ly/iuBIM> (last updated 28.10.2009, last checked 04.11.2009).
- ⁷ The minimum score changed to 30 in June, 2009 and then became 40 soon after that (last I-CMM tool checked was v1.9 - August 24, 2009).

Section 3

Standards

Chapter 5

Product Modelling in the Building and Construction Industry: A History and Perspectives

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ABSTRACT

This chapter provides an overview of product modelling in the Building and Construction (BC) industry based on authors' experiences gained from various conducted research projects and also taking into account results of other research projects. This chapter starts with an introduction and background of the subject area in terms of motivation, industrial needs and requirements. This is followed by an overview of a historical background of the subject area. In this historical background we distinguish five generations of product modelling developments. The first generation of product modelling developments is characterized by the influence of previous expert and database developments and by the constituting high-level constructs (e.g. EDM, BSM, RATAS and GARM). The second generation of product modelling developments can be characterized by the development of detailed aspect systems and supporting frameworks for data exchange and integration (e.g. IRMA, ATLAS, COMBINE, PISA and IMPACT). The third generation product modelling developments can be characterized by its focus on collaborative engineering support by means of the application of middleware and client/server technology (e.g. SPACE, CONCUR, BCCM, VEGA and ToCEE) and the development of the IFC. The fourth generation of product modelling developments is heavily influenced by the Internet and Web Services standards such as XML, SOAP and UDDI and related business models such as eBusiness and eWork (e.g. bcXML, ifcXML and eConstruct). The next (fifth) generation of product modelling developments will be based on the emerging semantic web standards such as OWL and RDF, and based on the concepts of ontology

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modelling as experienced in ongoing (European) projects such as SWOP. After this historical overview, an analysis of the characteristics of interesting conceptual product approaches is presented. Here we discuss the Standardisation, Minimal Model, Core Model, NOT, Vocabulary and Ontology product modelling approaches. Followed by an analysis of a number of specific conceptual product models and how the basic product modelling constructs (i.e. semantics, lifecycle modifiers and multiple project views) are implemented. This chapter ends with a discussion about some ongoing projects (COINS, CHEOPS and SWOP) in the context of future trends.

1 INTRODUCTION

A number of research and development activities have been carried out during the last few decades in order to pave the way towards a complete so-called CIC (Computer Integrated Construction) environment. The development and use of national or more importantly international standards for exchanging and sharing electronic information have become an important issue regarding the technical integration aspects of CIC. Since the late 1960's a number of standards for electronic data exchange have been developed including IGES (Initial Graphics Exchange Specification), DXF (Drawing eXchange Format) and much more. Although some of these standards are still in use and also supported by most CAD (Computer Aided Design) systems, they are not suitable for CIC. Although IGES provided a very practical solution for CAD data exchange, it was not capable of capturing the complete product data in order to enable more sophisticated automation of building products and processes. In order to overcome the weakness of IGES, the US Air Force ICAM (Integrated Computer-Aided Manufacturing) program developed a new product data exchange format standard, called the PDDI (Product Definition Data Interface). The purpose of PDDI was to develop a mechanism that supports the direct and complete exchange or sharing of a product model amongst computer applications, without human intervention. Although PDDI was a research exercise, it contributed greatly to the understanding, mechanisms and models for the standardisation efforts within ISO 10303-STEP (STandard for the Exchange of Product model data).

The development of product model standards for the Building and Construction (BC) industry started around 1986 within the STEP AEC (Architecture, Engineering and Construction) group. Since 1986, a number of research have been carried out (mostly under the umbrella of STEP AEC) to develop the required standards and supporting technologies for the BC industry. What all these projects experienced is that modelling approaches used in other industry sectors are often not suitable for the BC industry. They also learned that large models are as vulnerable as dinosaurs to unexpected changes of time, conditions and circumstances. Another conclusion is that current efforts to produce standards for the BC industry were not very successful. One of the main reasons for this lack of success is that STEP AEC proved to be the wrong platform for the development of standards for the BC industry that was unable to agree with and to make a fist within ISO. These led to a number of other initiatives taking over the developments. Each of these efforts was characterized by its unique modelling approach and the implementation of supporting (and emerging) technologies. Concerning supporting technologies, many efforts have been spent since the mid 1980's to allow CADxx to interoperate through an IPDB (Integrated Project Database). In the BC research community several views exist on what constitutes an IPDB, which has resulted in a number of different conceptual approaches in the development of IPDBs. Despite ongoing research in this field and the fact that still a number of problems are not solved, some consensus has been reached about what constitutes an IPDB. It is generally agreed that (preferable internation-

ally standardized) product models should form the core for communication. However, in the current practice, IPDBs are delivered by CAD vendors, each of them applying its own formats for storing, exchanging and sharing of product model information.

This chapter provides an overview of product modelling in the BC industry based on authors' experiences gained from various conducted research projects and also taking into account results of other research projects. This chapter will give an introduction of subject area in terms of motivation, industrial needs and requirements. Also a historical overview of the subject area will be provided. In this historical background we will distinguish five generations of product modelling developments each with its own conceptual approaches and supporting technologies. After this historical overview, an analysis of the characteristics of interesting conceptual product approaches is presented. Followed by an analysis of a number of specific conceptual product models and how the basic product modelling constructs are implemented. This chapter ends with a discussion about some ongoing projects in the context of future trends.

2 BACKGROUND

Traditionally, the subject area of developing product models and supporting technologies is referred to as PDT (Product Data Technology). The scope of PDT is briefly summarised in the following statement: *Product Data Technology includes all aspects of the definition and methods of processing of information pertinent to a product throughout its development and operational life-cycle. A product is producible, produced or natural object, system of objects or substance. The product may consist of any combination of physical and conceptual objects (like software or algorithms)* (Owen et al. 1995). Furthermore, the

following statements can be made to characterise PDT in more detail (Nowacki 1995):

- PDT encompasses in particular the life-cycle stages of the design process, production planning process, production process and the operational process. Each process adds and transforms information about the product.
- PDT includes the technical methods and systems required for the definition, exchange, archiving and retrieval of product information.
- PDT deals with the sharing and exchange of product information with and between enterprises.
- Product information can be related to the shape, material, physical properties, visual appearance and other characteristics of the product.
- Product data is an integral part of all business data needed by an enterprise. It must be closely linked with other types of business data.

A product model holds the information and data about a product in an integrated way over the product life-cycle. Product models are based on conceptual models describing the real world as a collection of objects by using a formal modelling language. The modelling language is used to describe object and its properties as well as the associations between objects. The result of the conceptual modelling (or *product modelling*) activity is the conceptual scheme in which classes and attributes with their internal relations are defined. This conceptual scheme refers to class of objects sharing the attributes and internal relations which in the past often were referred to as "type" models. In ICT terms, an "instance" of a scheme represents the actual data of one specific example in the class of objects. In fact, this "instance" is the information that is shared and exchanged

between CADxx systems or stored in an IPDB. In the BC industry, however, most efforts have been put into the development of type models that represent a class of “buildings”. In this respect, the term BIM (Building Information Model) has become very popular recently. It is agreed upon that the term was popularized by Jerry Laiserin as a common name for a digital representation of the building (process) to facilitate exchange and interoperability of information in a digital format (Wikipedia, 2009). Although other definitions of BIM (as found in recent literature) more focus on BIM as a way of managing or organizing the process of information exchange and sharing within BC organizations and projects, the authors opt for the definition of Laiserin with the addition that BIM (or building product model) contains information regarding form, function and behaviour of a building and is able to describe the building throughout the building life-cycle. This extended definition does not say that all the different behaviours of a building have to be captured explicitly, only that all the information required for establishing form, function and behaviour is available. The role of the BIM or building product model is, in this context, equivalent to the role of the technical documentation in the current paper-based design and construction process. This set of drawings and related documents contains the information required to establish form, function and behaviour of a product.

With the definition of BIM or building product model offered above, the product model standards that are required for the BC industry are neither standards for the exchange of electronic versions of traditional technical drawings, nor standards for the exchange of geometric data. The form is only one of the relevant aspects. Standards that capture the product information are needed in a semantically meaningful way, in the same notions as used in practice. From such a semantically rich product model, other models, like a geometrical model, or a FEM (Finite Element Model) can be derived automatically. Additionally, 2D-drawings

or 3D models and other documents could be generated from the same building product model. For instance Graphisoft, since its debut in 1987, implemented this concept into their product ArchiCAD. This concept became known as the Virtual Building concept and has been followed by a number of other CAD vendors like Autodesk/Revit, Bentley and Nemetschek. Although these products do indeed provide the BC industry with some degree of interoperability, vendor-specific product model standards and supporting technologies are not the right solution. What is needed are neutral and open product model standards that form a technical basis for a future CIC. Due to the ad hoc nature of the BC industry and the lack of rich and dedicated market leaders, it is extremely difficult to come up with something useful for BC. As mentioned before, even ISO STEP AEC proved to be the wrong platform to accomplish this task while vendor supported IFC (Industry Foundation Classes) developments seem to offer acceptable interoperability solutions. This is an assurance that has started to be creating more questions and doubts since the publication of some white papers (Bentley, 2003; Bentley, 2007; Bentley, 2008; Graphisoft, 2006). In particular the white paper of Autodesk strongly suggests the need for new platforms rather than the IFC from IAI/BuildingSmart (International Alliance of Interoperability) (Autodesk, 2003). On the other hand IFC compliant platforms are becoming increasingly popular due to the strong market push for the implementation of BIM that is mainly initiated by the demand of clients of large BC projects.

3 MAIN FOCUS

3.1 Brief Overview of the History of Product Modelling Developments

Here we can distinguish five generations of product modelling developments:

1. The first generation of product modelling is characterized by the influence of previous expert and database developments and by the constituting high-level definitions of building systems and system elements and their interrelationships. There are many examples of the first generation product modelling developments including EDM (Engineering Data Model), BSM (Building System Model, STEP AEC activity), RATAS and GARM (General AEC Reference Model). The GARM model was proposed for inclusion in the STEP AEC standard. Even though it was never accepted, it has had a tremendous influence on the product modelling research community (Eir, 2004).
2. The second generation of product modelling developments can be characterized by the development of detailed aspect systems and supporting frameworks for data exchange and integration. There are many examples of the second generation product modelling developments including IRMA (Information Reference Model for AEC), ATLAS (Architecture, Methodology and Tools for Computer Integrated Large-Scale Engineering), COMBINE (Computer Models for the Building Industry in Europe), IMPACT (Integrated Modelling of Products and Processes using Advanced Computer Technologies) and PISA (Platform for Information Sharing by CIME Applications). The aim of the PISA project was to provide an approach to better capitalize on the potential of STEP and CORBA (Common Object Request Broker Architecture, Object Management Group). While most STEP developments concentrated on product information, CORBA provided a framework for the integration of applications. The PISA development effort supported the potential to integrate and leverage these technologies. The project was influential on its successors in the third generation of product modelling efforts (Eastman & Augenbroe, 1998).
3. The third generation of product modelling developments can be characterized by its focus on collaborative engineering support by means of the application of middleware and client/server technology and the development of the IFC. There are many examples of the third generation product modelling developments including SPACE (Simultaneous Prototyping in an integrated Construction Environment), VEGA (Virtual Enterprise using Groupware Tools and Distributed Architecture) and ToCEE (Towards a Concurrent Engineering Environment in the Building and Engineering Structures Industry), CONCUR (Concurrent Design and Engineering in Building and Civil Engineering) and BCCM (Building Construction Core Model). The development of the BCCM has been a product modelling development within the STEP AEC group and has provided the basis for the development of the initial IFC Object Model.
4. The fourth generation of product modelling developments is heavily influenced by the information modelling standards derived from Internet and WS (Web Services) developments such as XML (eXtensible Markup Language), SOAP (Simple Object Access Protocol) and UDDI (Universal Description, Discovery and Integration) protocol and related business models such as E-Business and E-Work. There are many examples of the fourth generation product modelling developments including eConstruct/bcXML, IAI/aecXML and IAI/ifcXML. The IAI/ifcXML uses XML schema language to specify the IFC conceptual model in order to provide information exchange and sharing in XML format. Information exchange sharing by WS can be done two ways by giving access to the IPDB where the product model is stored,

or by giving access to an API (Application Programming Interface) which provides access to a product model physical file or a specific domain view (Cruz, 2008).

5. The next (fifth) generation of product modelling developments is/will be based the emerging Semantic Web standards such as Web Ontology Language (OWL) and Resource Description Framework (RDF) and based on the concepts of ontology modelling. Formally, ontology can be defined as “an explicit specification of a conceptualization of a domain” (Davids et al, 2002). Informally and in PDT terms, we can say that ontology is a conceptual model that describes the classes (and objects) in a specific domain by using OWL. A number of approaches are trying to develop detailed ontologies for particular domains while other approaches are developing high-level ontologies that support the exchange of detailed (end-user) ontologies at a lower level. The chief example of the first is the Product Modelling Ontology which is the main result of SWOP (Semantic Web-based Open engineering Platform) project.

3.2 Overview of Conceptual Product Modelling Approaches

Similarities and differences between existing conceptual product modelling approaches have been the subject of a number of research projects during the last two decades (Dado, 2002). This overview will not explore all existing approaches, but will only concentrate on the most interesting approaches and their main characteristics.

1. Standardisation Approach

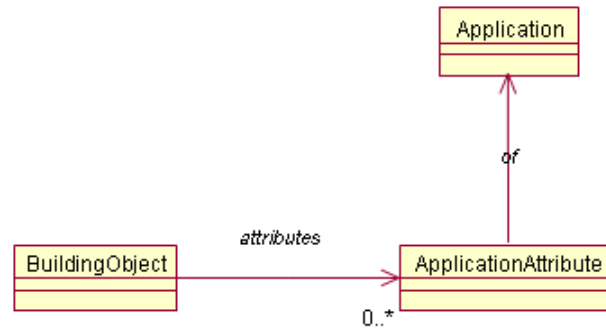
It is generally agreed that an international standard for the exchange and sharing of product data will benefit the BC industry dramatically. As discussed earlier there are traditionally two main efforts in developing international standards

for conceptual schemas for product information in the BC industry: (1) ISO STEP AEC, and (2) IAI/IFC.

In the STEP architecture, conceptual product models are developed either as an IR (Integrated Resource) or as an AP (Application Protocol). An IR is divided into two categories. The first category, referred to as GR (Generic Resources), includes models of general applicability, which do not have an application context. The second category, referred to as AR (Application Resources), include models related to an application or a class of applications in a given industry sector. Together with the AIC (Application Interpreted Constructs), IR represents the building blocks for an AP. An AP can be seen as the end product of the STEP design methodology. An AP is written using the EXPRESS language (ISO, 1994b) and provides verifiable schemas, which specify the functionality for an application requirement, like its information needs and information exchange means. The exchange and sharing of product information between two or more different application domains must be accomplished by the AP-interopability.

The industry, organised within the IAI organisation, started with the development of the IFC around 1994. The IFC are conceptual models of a building that support information exchange and sharing among different computer applications used in the project. The IFC architecture is based on several schema layers including: a resource layer that describes distinct underlying concepts, a core layer that defines a kernel meta-model and core extensions to define the basic objects, an interoperability layer that defines data that is used across multiple domain areas and domain layer that defines detailed data used within specific application areas. A number of STEP technologies have been used to develop the IFC, including the EXPRESS language, portions of the STEP IR, STEP Physical File Format (ISO, 1994c) and the Standard Data Access Interface (SDAI) (ISO, 1995). As mentioned earlier the

Figure 1. The main idea of de Vries. Applications hold the attributes of BuildingObjects, which are not described in the conceptual model.



STEP BCCM (ISO, 1994d) has been used as a basis for the development of the IFC Object Model. While most IFC developers are involved in both standardisation efforts, IAI and STEP, the IFC standard has been endorsed by the ISO as a Publicly Available Specification (PAS) under the ISO label ISO/PAS 16739.

2. Minimal Model approach

The standardization approach results in highly complex and detailed conceptual product models with hundreds of objects, which are very difficult to manage and maintain. In order to avoid complexity in models, proposals for “small and manageable models” using a minimal model approach have been proposed in the past. The first idea of the minimal approach was presented in 1991 by de Vries (de Vries, 1991). He suggested elaborating a model at meta-level that can be used to exchange data between application schemas, which hold the more detailed semantics of the objects. Figure 1 illustrates his main idea.

Exchanging information between two different applications is carried out by two mappings, one of each from the conceptual application schema to the minimal schema. Because the minimal schema only holds the references from BuildingObjects to certain ApplicationAttributes that are described in the application conceptual schema in more detail, the amount of data in the exchange file is reduced.

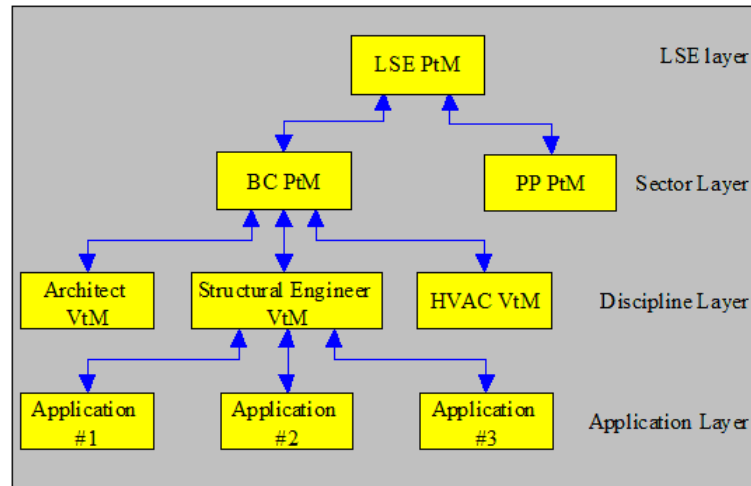
One of the main problems of this approach is that BuildingObjects have to be specialised in the application conceptual schema. However, most conceptual application schemas of existing computer applications do not include semantic notions like wall, floor, beam, etc. Therefore, exchange based on this approach is often strictly limited to the exchange of geometrical information.

Tarandi suggested a quite similar approach in 1998 (Tarandi, 1998). He proposed to delegate semantics to classification and coding systems like SfB (Samarsbetskommitten for Byggnadsfragor) or BSAB (Byggandets Samordning AB). Although Tarandi showed that such an approach could be very successful on a national level, it is not possible to follow his approach on an international scale. One of the main reasons is that most classifications have been developed on a national basis. Therefore mapping between classification systems of different countries is extremely difficult, because classifications are view-dependant. Also different classification systems often use incompatible definitions.

3. Core Model Approach

There are many different types of conceptual product models and the intended role of any specific model is not always clear. As discussed earlier, conceptual (or “type”) models are created using a formal modelling language and are used as the

Figure 2. ATLAS model architecture. The LSE layer consists of a core model (i.e. LSE Project type Model) which supports inter-sector communication. The Sector Layer consists of two core models: BC PtM and PP PtM, which support interdisciplinary communication. The Discipline Layer consists of a number of core models (referred to as View type Models), which each of them support communication within one specific discipline (e.g. architecture, structural engineering and HVAC engineering). The Application Layer consists of large number of application models, which represents the information for specific applications.



data type declarations by systems that store actual product models (or “instance” models). In addition, “application” models are conceptual models that an application is built upon. Core models are neither type models nor application models. Core models are intended to be high-level models that provide a unifying reference for more detailed application models, which will be constructed on top of them. Unlike application models, core models are generally not intended to be instantiated for representing actual data (though they can be used for exchanging information between different application areas) (Froese, 1995).

One good example of a core model is the BCCM. At the ISOTC184/SC4/WG3/T12 meeting in Berlin (1993), the BC Working Group (WG3) commenced an APPP (Application Protocol Planning Project). Main objective of this initiative was to define a framework for the development of APs and to determine the priority areas for initial AP development. The WG3 recognised that the BC

industry is made up of a number of disciplines that each have their own application requirements. It was also recognised that there is a set of common information to be exchanged between these disciplines. This set of information is less detailed as required for an AP. This kind of information is referred to as the core data and from this the concept the BBCM has been developed. The BBCM does not include fully elaborated objects, but provides only a set of objects from which application-specific objects can be specialised.

In the European ATLAS project a hierarchy of core models was proposed. ATLAS aimed at the development of standards and tools for interdisciplinary communication and inter-sector communication (Tolman et al, 1994). The sectors involved were the PP (Process Plant) and the BC sectors. The ATLAS model architecture was based on four layers, as shown in Figure 2.

The ATLAS project showed that interdisciplinary and inter-sector communication can be

developed based on an approach of layered core models. On the other hand the amount of effort needed to develop and maintain translators (i.e. mappers) is extremely large. The ATLAS project showed that mapping between different product models is highly complicated. One of the reasons is that in relational (database) systems, bi-directional mapping can only be done by two different one-way mappings under tightly constraint conditions. The best solution would be if the same mapping code could be used for both directions by using object-oriented databases and programming languages.

The model architecture of the IFC is also based on layers. The core layer of the IFC provides the basic structure (and objects) of the IFC object model, which can be used and redefined by various interoperability and domain models. Although the IFC model architecture is influenced by the ATLAS project, it is not as complicated as the ATLAS model architecture. The IFC are more like the BCCM, which was the starting point for the development of the IFC as discussed earlier.

4. Neutral Object Tree Approach

Van Nederveen has suggested the idea of Neutral Object Trees (NOT) as part of his PhD thesis in 2000 (van Nederveen, 2000). Figure 3 shows a part of the NOT meta-model.

The idea is to leave the standardisation approach for what it is and directly build an “instance” model. Van Nederveen and partners were involved in the design stage of the HSL (Dutch High Speed Railroad Link). Their role was to provide the project management with a tool for interface management (each object that involves several companies over time, is a potential bottleneck). What they did was to collect all the objects of interest for all involved parties and devised collections of small “neutral” decomposition hierarchies using acceptable neutral object names. Then they divided the track of the HSL into a number of sectors with each again divided into

a number of sub-sectors. A bridge for example was about the lowest node in the NOT. Then they integrated the model pieces in each sector and sub-sector using cut and paste, hence creating the first NOT of a large-scale construction project. Finally they added functionality to the nodes of the NOT such as the expected start end end-dates, document control data and data about the parties involved. NOT can be elaborated as towards a type model to support other more traditional PDT developments.

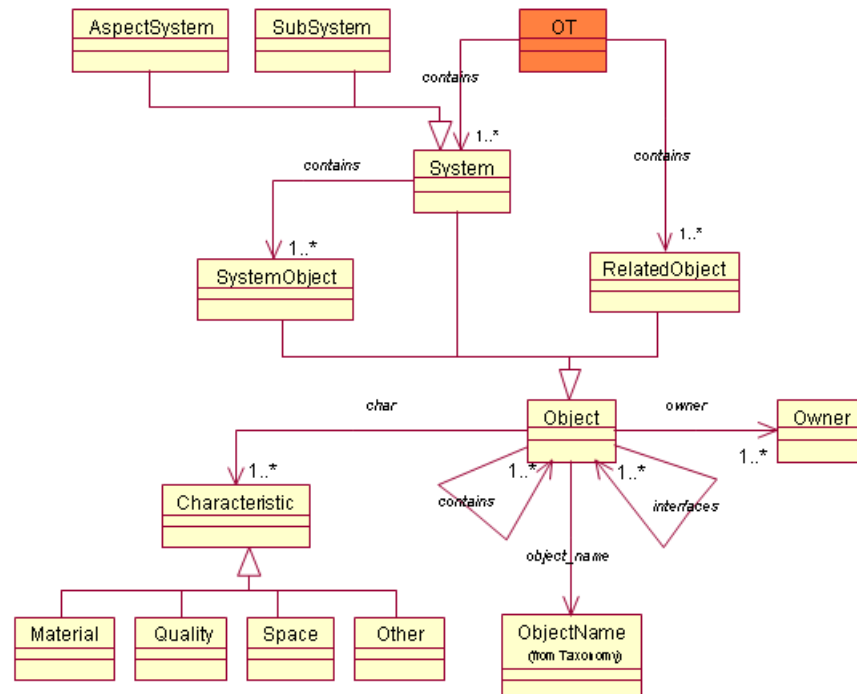
5. Vocabulary Approach

Communication between humans is done by natural language that is based on some language rules (i.e. syntax) and a vocabulary which contains the total number of words known in that particular language. In a vocabulary, words are accompanied with a definition (i.e. semantics). However, computers are not (yet) able to understand the natural language (i.e. semantics of words) and therefore communication cannot be based on natural languages. In order to overcome this problem, most electronic vocabularies are “controlled vocabularies”. A controlled vocabulary is restricted to a set of words used within an organisation for a given purpose in a specific domain. Vocabulary designers do not need to provide all the definitions, only those related to their local uses and it is not required that they search for agreement on a larger scale.

The idea of developing controlled vocabularies for improved communication based on XML technology has been the subject of two major international projects in the past:

- (a) **The US-oriented aecXML project:** The aecXML vocabulary has been proposed by Bentley Systems in 1999. Initially it was not clear whether this was going to be a rival or a complementary system to the IAI/IFC. The IAI/IFC provides a conceptual model of building systems and system elements

Figure 3. Part of the NOT meta-model. An OT contains one or more Systems and RelatedObjects. A System contains one or more SystemObjects and can be AspectSystem or SubSystem. SystemObject, System and RelatedObject are subtypes of Object. An Object can have one or more Characteristics (Material, Quality, Space and others), has at least one Owner and has an ObjectName, which is stored in Taxonomy. An Object contains and interfaces one or more other Objects.



and their interrelationships in a single conceptual model, whereas aecXML shares limited common building elements and commercial information between disparate software packages used by AEC professionals for specific commercial transactions. Nowadays, aecXML is merged with the IFC the US Chapter of the IAI at the NIBS (National Institute of Building Sciences).

- (b) **The European eConstruct project:** In 2000, the pan-European project eConstruct announced their initiative to create an XML vocabulary for the European BC industry, called bcXML. eConstruct's main objective is to contribute to the development of an information infrastructure for the European BC industry. This objective was realised

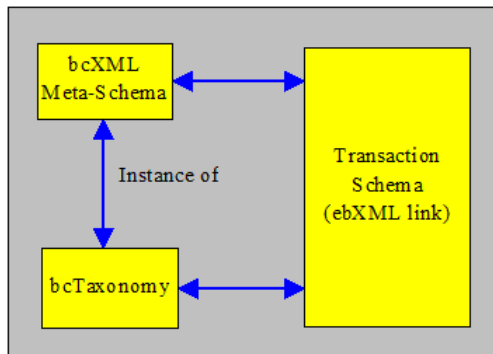
by the development of a XML vocabulary, which not only supports meaningful communication between European BC partners, but also supports national languages and classification systems. Figure 4 shows the bcXML architecture.

As shown in Figure 4, the bcXML architecture contains three components:

- bcXML Meta-Schema
- Transaction Schema
- bcTaxonomy

The bcXML Meta-Schema holds the generic language information upon which the bcXML DTD/XSD is built. The Transaction Schema

Figure 4. The bcXML architecture



defines how information is communicated and is partly based on ebXML. EbXML is an international initiative established by UN/CEFACT (United Nations Centre for Trade Facilitation and Electronic Business) and OASIS (Organization for the Advancement of Structured Information Standards), which provides a XML-based infrastructure for E-Business communication. The bcTaxonomy holds the objects (as instance of the bcXML Meta-Schema), such as a door, wall, etc., which provide the required semantics for meaningful communication. In eConstruct, a bcTaxonomy, referred to as bcBuildingDefinitions, has been developed.

Another vocabulary approach is the LexiCon which is a development by STABU (Research and Standardisation Institute) from the Netherlands (STABU, 2006) as part of the CONCUR project in 1998 (CONCUR, 1998). Basically, the LexiCon tries to bridge the gap between the traditional classification world and the PDT world. The LexiCon contains a structured set of objects, properties and units, each with a lexical description following the common practice. The structure is mainly a decomposition tree, but augmented with specialisation. To some extent the structure looks like an implementation of the FU-TS (Functional Unit - Technical Solution) tree used in the GARM. Also the LexiCon aims at providing a structuring mechanism for the exchange of building objects as defined in different classification and cod-

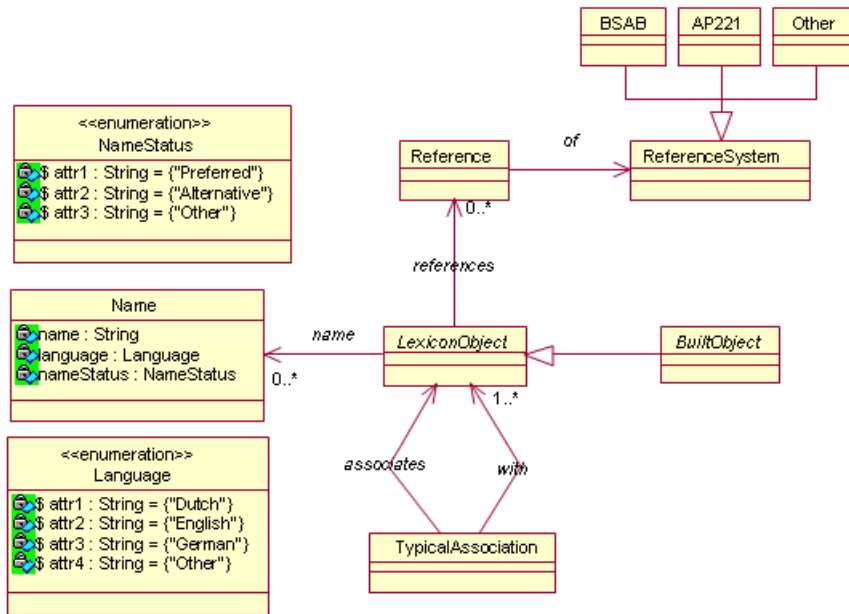
ing systems including multi-language support. Figure 5 shows this structuring mechanism of the LexiCon.

STABU started the work on the creation of the Lexicon in line with the eConstruct proposal for bcTaxonomy (i.e. bcBuildingDefinitions). Initially, this was in a Dutch context, authorised by the Dutch BAS (Bouw Afspraken Stelsel) organisation. There was/is a close co-operation with the similar initiatives from the Norwegian Building Standards and the German GAEB (Gemeinsame Ausschuss Elektronik im Bauwesen). In 2006, these organizations signed an agreement that they would combine their separate efforts into the International Framework for Dictionaries (IFD) Library (under the umbrella of the IAI) to produce a single object library / ontology that they would share between themselves for mutual benefit.

6. Ontology Approach

Although XML indeed solved a number of the communication bottlenecks in the BC industry and its application can be found in a number of eBusiness developments today, it has also manifested some of its limitations. One of the main complains is that XML only provides simple taxonomic relations for structuring vocabularies. Each term (or object) within a vocabulary can inherit from or be nested in another object. These simple modelling mechanisms are ideal for creating catalogues as such and therefore very suitable for eCommerce developments, but not for “real” meaningful communication between CAxx systems. This problem is solved by the recent rise of the Semantic Web, which adds new capabilities to XML vocabularies. As discussed earlier, driving the Semantic Web is the organization of a number of detailed domain ontologies which are supported by reference and/or high-level ontologies. The basic idea is that a number of interlinked (shared) reference ontologies exist, each addressing a certain problem domain. An ontology

Figure 5. Part of the initial LexiCon meta-model. Each *LexiconObject* has zero or more *References*, zero or more *Names* and can have a *TypicalAssociation* with one or more other *LexiconObjects*. All kinds of *ReferenceSystems* can be included: from a classification system, such as BSAB or SfB, to a STEP AP, such as AP221, and many others. Object naming include features such multiple-language support and name preferences.



developer can use these reference ontologies for (1) creating additional reference ontologies, or (2) creating specific company ontologies, or (3) creating specific application ontologies. From a modelling point of view, each specific ontology is an extension of one or more reference ontologies (including additional objects and attributes), while each specific application ontology is an extension of one or more reference ontologies. This provides the necessary interoperability between computer applications. An MSc thesis at Delft University of Technology showed the advantages of such an approach (Dierckxsens, 2003). In this study, the concept of “ontology networks” has been further detailed and as proof of concept, a number of ontology-driven CAXx systems have been built. A second MSc project showed the advantage of developing an object-based library as the semantic basis for developing Ontology Networks (Hellemans, 2005). This object library contains the neutral definitions of building objects

which have been structured according the GARM methodology. Built upon this object library, a BC Ontology Network (bcoWeb), including some example CAXx applications that make use of the bcoWeb were developed.

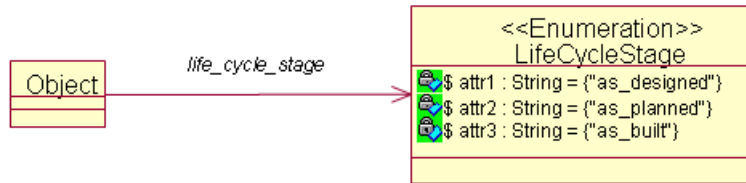
3.3 Basic Conceptual Product Modelling Concepts

In this paragraph the most important conceptual product modelling concepts which can be found in the conceptual product models developed in R&D projects as discussed above.

1. Semantic Modelling

The primary goal of information modelling techniques is to secure that both humans and computers understand the diagrams and the information they contain. As discussed earlier communication between humans is often done by

Figure 6. An Object can for example exist in one or more of the three different LifeCycleStages: *as_designed*, *as_planned* and *as_built*. Following this construct, objects can co-exist as three instances, each instance representing the information of the object in one specific life-cycle stage.



natural language, based on some language rules (i.e. syntax) and a vocabulary, which contains the words (i.e. semantics). Most modelling languages use a syntax that supports binary sentences only. An example of a binary sentence is: a “Building” contains one or more “Storeys”. “Building” and “Storey” are both nouns, while “contains” is a verb and “one or more” is used to express cardinality. In product modelling “words” (i.e. the nouns) are often referred to as entities or objects and represented graphically by a simple box. A line between two boxes indicates a binary association and holds an association name (i.e. the verbs). All words in a diagram together form the dictionary, and all verbs the syntax of the language thus created.

For information modelling in BC, there are at this time two obvious candidates: Express-G and UML. The first, Express-G, has been the default standard for (STEP-based) product modelling over the years. However, STEP was defined specifically to deal with the information consumed or generated during the life-cycle of a product (i.e. a building). For this purpose, ISO STEP included the information specification language Express and its graphical notation Express-G in their standards. However the software industry adopted UML (Unified Modelling Language) as a standard for OO (Object-Orientated) software modelling. Current available UML modelling tools have advanced support for software development, and often include features such as code generation and reverse engineering.

2. Life-Cycle Modelling

Objects can exist within one or more life-cycle stages. In product modelling, life-cycle qualifiers are used to express the existence of an object in a certain life-cycle stage. The life-cycle dimension is an important one in product modelling, because information about building products is in most cases time-dependent. In order to model buildings over their life-cycle, qualifiers like “as_designed”, “as_planned” and “as_built” can be added to the objects. The life-cycle dimension can be implemented in different ways, depending on the purpose and scope of the model and on the personal flavour of the information specialist. Figure 6 shows the basic idea.

3. Project Modelling

While the STEP AEC was mainly concentrating on design and shape aspects, other researchers started to work on models that involved planning and realisation of projects. It was generally agreed that product modelling should be extended to project modelling, including entities such as processes, resources and control. Process objects represent the processes or actual construction efforts on the project. Resource objects represent the resources, such as equipment, temporary construction works, etc., which are used in the project. Control objects represent items that control or constrain other objects, such as contracts, budgets, and standards. The concept of product-process-resources-control

is often referred to as the "project view", in which product objects represent the design/engineering view. In fact, this model approach was up to a certain level the objectification of the IDEF0 (Integration DEFinition for Function) process systematic as shown in Figure 7.

3.4. Overview of Applied Modelling Concepts in Existing Conceptual Product Models

Extending product modelling to building project modelling, has been subject of many academic research projects in the last two decades. In the past, most conceptual project models are developed as core models where entities are not expected to be instantiated, but only serve as high-level models, upon which more detailed application models can be built. In the next section, we will discuss five building project models which have been developed within R&D projects in the past:

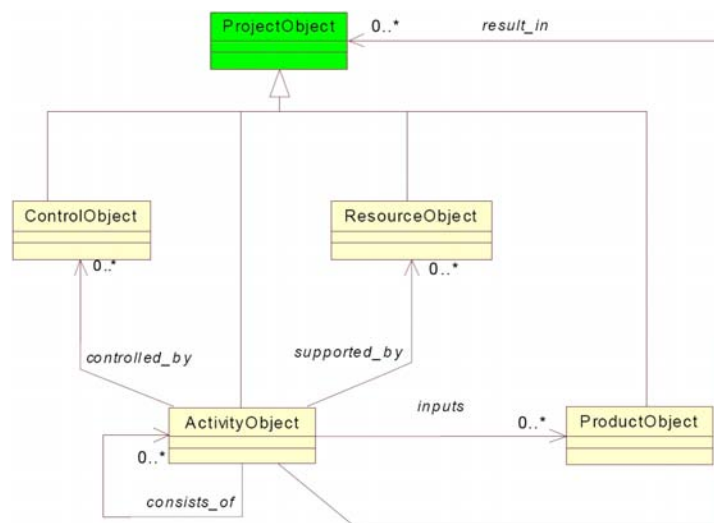
1. Unified Approach Model

The UAM (Unified Approach Model) was an early academic exercise, suggesting how the use of a single conceptual modelling technique for modelling all kinds of construction information would facilitate the integration of different computer applications from very diverse domains, such as CAD, project management and EDI procurement (Bjork, 1992a). An exercise showed how the model could be used for structuring information concerning the erection of partition walls.

Another goal of the UAM was to provide a framework, which would help explain the relationship between current classification systems and product models. The research also highlighted the differences between activity models, which usually are formalised using techniques such as IDEF0 and conceptual models, including object classes for activities (Froese, 1992).

The UAM already supported the idea of project modelling. However, the control part is ignored

Figure 7. Objectification of the IDEF0 paradigm. ActivityObjects are the central objects. Because in IDEF-0, model decomposition goes through the activities, ActivityObjects may consist of one or more other ActivityObjects. ActivityObjects may have one or more ProductObjects as input, and may result in one or more ProjectObjects (each of the basic objects). ActivityObjects may be controlled_by one-to-many ControlObjects, and may be supported_by one to many Resource-Objects.



and there is no support for life-cycle integration. Only a few semantic entities are included. Figure 8 shows a slightly modified version of the original UAM.

2. *ATLAS Large-Scale Engineering Project Type Model*

As discussed earlier, the ATLAS project aimed at the realisation of a hierarchical core model architecture that provides meaningful electronic communication between computer applications of (1) one discipline, (2) disciplines of one sector and (3) disciplines of different sectors (i.e. BC and PP) (Tolman et al, 1994). The ATLAS LSE PtM (Large-Scale Engineering Project Type Model) supports a project view and has a life-cycle dimension. It does have specialised entities for on-site construction, because the model was intended to be a high-level model upon which more detailed discipline models and application

models can be built. Figure 9 shows a part of the ATLAS LSE PtM.

Though the aim of ATLAS was primarily concentrating on design/engineering of buildings and process plants, it was also one of the first projects that tried to bridge the gap between design/engineering and planning/realisation. The triple: Actor-Activity-Result and the distinction between ResourceResult (used in subsequent stages) and ControlResult (like drawings or plans) follows the basic project modelling concepts. The ATLAS LSE PtM provided an abstracted set of semantical entities that were common for BC and PP. Using these abstracted objects, computer applications of both worlds could communicate. For example a PP application for piping could communicate with a BC floor design application to guarantee that its load could be carried.

In the final demo of the ATLAS-project more than 20 applications from both BC and PP worked together in close harmony in the design

Figure 8. UAM (slightly modified). Following the core construct of ATLAS, UAM states that Activities performed by Agents produce Results. Results are defined in Contracts and sometimes later on function again as Resources (subtyped by Durable, Consumable and Factory). Activity necessitates ResourceUse, which causes Cost. Results can be Physical, Information or Service. An Agent is an abstract super type of Organisation and MicroLevelAgent. MicroLevelAgent is an abstract supertype of Person, Application and Machine and is used by Organisation and sometimes functions as Durable Resource.

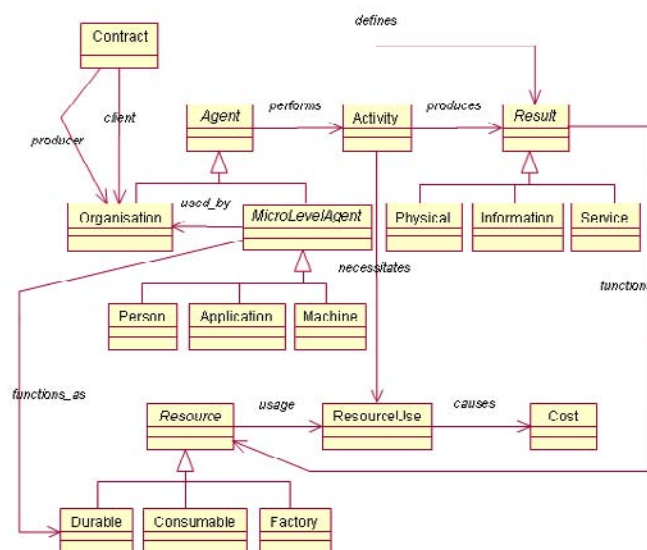
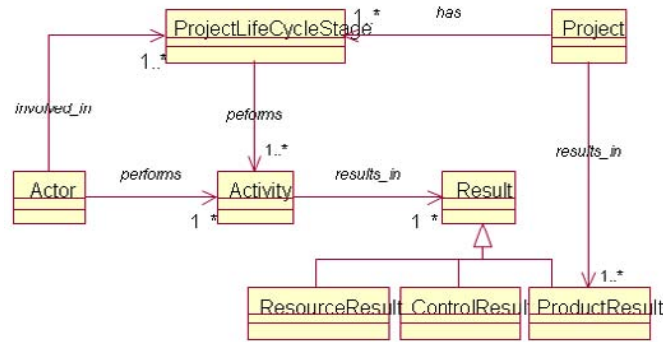


Figure 9. Part of the ATLAS LSE PtM (free interpretation). The model describes the Results that each actor (e.g. Architect, Planner etceteras) produces in a particular LifeCycleStage of a Project (i.e. an Actor performs one or more Activities which result in Results and are performed in a particular LifeCycleStage of a Project). Results can be ControlResult, ResourceResult or ProductResult.



of a brewery. The applications relevant for planning/realisation were related to project management and control. The overall conclusion of the ATLAS project was that it is indeed possible to develop a hierarchical model structure that supports meaningful communications between (applications of) different actors and disciplines, but that it is extremely difficult and really requires too much effort in order to be seriously applied in practise.

3. Building Construction Core Model

After the completion of the ATLAS project, the WG3 group initiated the APPP project as discussed earlier. The core model hierarchy researched in ATLAS formed the basis of the plan. The BCCM was the first of five sector core models as proposed in the project. An early version of the BCCM (ISO, 1994d) supported the idea of project modelling. Also the idea of life-cycle integration is supported (i.e. required, designed, planned, realised and maintained). The model also included a large number of specialised entities and attributes like Cost, Performance, and Quality. Figure 10 shows a part of the core of the BCCM.

The BCCM differs from the ATLAS in the way it handles properties of objects. Each property or

characteristic can be described in different states, which seems to follow the real world where often the design of top floors has to be done while the bottom floors are already erected. The same construct can be found in other models like for example the BPM (Building Project Model). As to the division between product-related objects and process-related objects (activities), the BCCM has the same pitfalls as the ATLAS models.

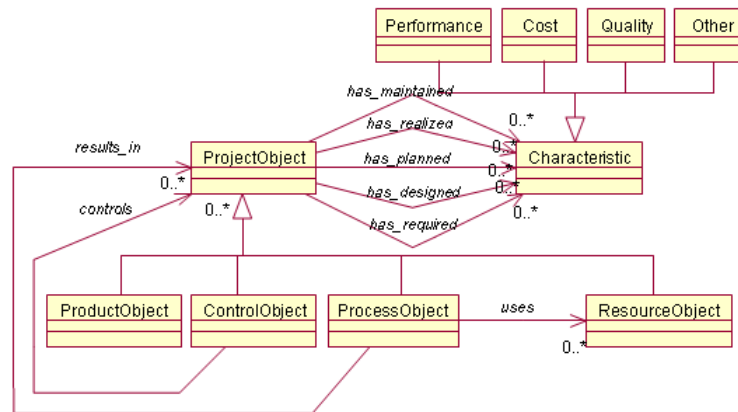
4. Building Project Model

The BPM has been developed by Bart Luiten, as part of his PhD research, and was published in 1994 (Luiten, 1994). The core of the BPM resembled the core of the early BCCM. A project view is supported (product, process, resource, not control). Also the idea of life-cycle integration (as_required, as_designed, as_planned, as_realized) is supported. The life-cycle dimension is implemented through a “state” parameter. Figure 11 shows a part of the BPM.

5. Industry Foundation Classes

While the ISO organisation was developing the BCCM, the IAI was developing similar standards in the form of the IFCs. While the development of

Figure 10. Part of the BCCM. Four types of objects are supported: Product, Process, Resource and Control (each is a subtype of ProjectObject). Each type of object can have a set of characteristics, like Cost, Performance, Quality, etc. Each characteristic can be described in different life-cycle stages: *has_required*, *has_designed*, *has_planned*, *has_built*, and *as_maintained*. ProcessObjects use zero or more ResourceObjects and result in zero or more ProjectObjects, which are controlled by zero or more ControlObjects.



the BCCM had to stop due to lack of funding, the IAI/IFC, financially supported by rich industrial partners, is still an ongoing development. Although the IFC supports a project view, it does not seem to support a real life-cycle concept, because the main objective of the model is to support the design/engineering stage. Semantics are (1) provided as specialised entities, or (2) hidden in enumeration types and (3) provided by references to external classification tables. Figure 12 shows a part of the initial IFC class hierarchy.

The *IfcRoot* is the most abstract object, and forms the root class for all IFC entity definitions of the IFC kernel or subsequent layers of the IFC object model. It is therefore the common supertype of all IFC entities, besides those defined in an IFC resource schema. In the second object-level, the notation of *IfcObject* is used. *IfcObject* is the generalisation of any semantically threaded thing or process within IFC. *IfcRelationship* is the supertype of all objectified relationships in the IFC. *IfcPropertyDefinition* defines the gen-

eralisation of all characteristics (i.e. a grouping of individual properties) that may be assigned to objects. *IfcModelingAid* provides the general concept for constructs that support the creation of a design artefact, in particular its geometric form. They are part of the project information set, but not part of the artefact itself. *IfcObject* is supertype for entities at the third object level, such as *IfcProduct*, *IfcProcess*, *IfcResource* and *IfcControl*, which are again abstract supertypes for entities at fourth object level.

While a number of researchers were developing (mostly) high-level project models, (i.e. following a core model approach, mainly was focussing on providing mechanisms for life-cycle support) another group of researchers started to develop highly detailed semantic application models capable of supporting meaningful communication between computer applications. In the next section, we will discuss some detailed application models which have been developed within R&D projects in the past:

Figure 11. Part of the BPM (free interpretation). Four types of objects: Product, Activity, Resource and Actor (each is subtype of ProjectObject). ProjectObject can have Characteristics (Cost, Performance, Quality etc.). The implementation of the life-cycle dimension is done through an enumeration type State. An Activity uses one or more Resources and is performed by one or more Actors, which has a disposal of one or more Resources.

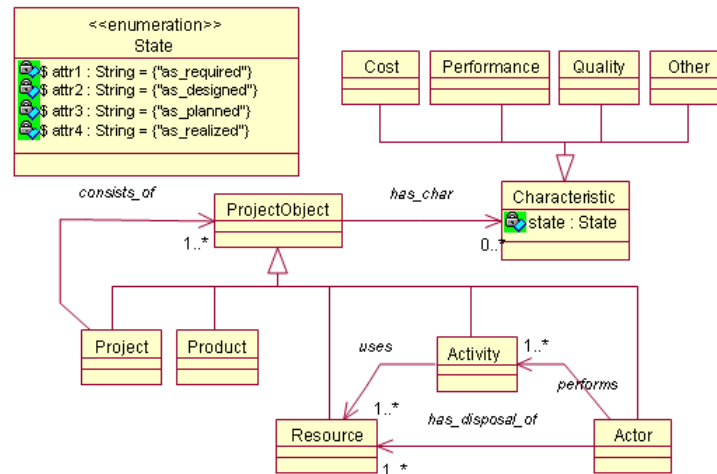
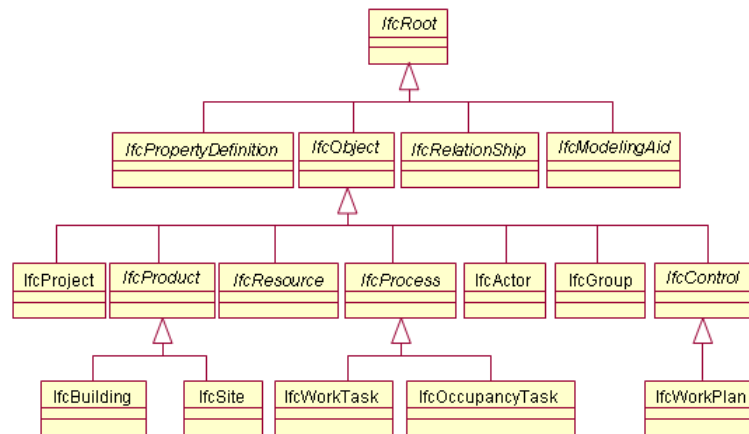


Figure 12. Part of the initial object class hierarchy in the IFC model



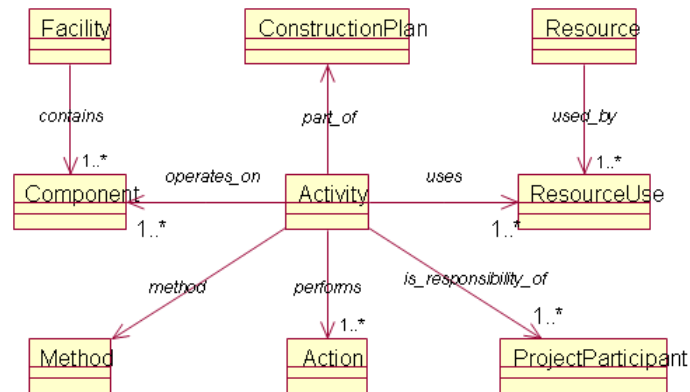
1. General Construction Object Model

The GenCOM (General Construction Object Model) was part of a project carried out from 1989 to 1992 at Stanford University to improve the integration of project management software using standard object-oriented models of construction

projects and was published by Thomas Froese as part of his PhD thesis (Froese, 1992).

The GenCOM model (consisting of 36 fully elaborated object classes) was implemented in an integrated project planning application called the Object-model-based Project Information System, OPIS. Figure 13 shows a part of the GenCOM.

Figure 13. Part of the GenCOM. Activity is the core entity. Activities are the responsibility of one or more ProjectParticipants, operate on one or more Components (that together form a Facility), use one or more Resources and perform one or more Actions and follow certain Methods. Activities are part of a ConstructionPlan



2. Simultaneous Prototyping in an integrated Construction Environment

The SPACE project was a project carried out by the University of Salford. The main goal of SPACE was to provide users with a multi-disciplinary computer environment where project information can be exchanged between the various construction professionals, including clients, designers, contractors, etc. (Underwood & Alshawi, 1997).

Within the SPACE project a number of conceptual product models have been developed, including a high-level project model for information life-cycle exchange. In addition, a number of highly detailed application models, which support specific activities, have been developed. The EVALUATOR (project Estimate And interim VALuations monthly generATiOn in an integRated environment) model has been developed as blueprint for a prototype computer application, which is capable of supporting project estimates and monthly interim valuation certificates within the SPACE framework. Figure 14 shows a part of the EVALUATOR model.

3. Synthesis Model for Construction Planning

The SMCP (Synthesis Model for Construction Planning) was part of the PreFacto project and was published by Jagbeck as part of her PhD thesis (Jagbeck, 1998). The main goal of the PreFacto project was to develop a prototype system for a future construction planning system. The central concepts and functions were investigated in an earlier R&D project, the MDA planner project. Based on the results of the MDA Planner, the PreFacto system was developed and tested in SMCP. Figure 15 shows a part of this model.

In both GenCOM and the SMCP, an association is used to connect an Activity with a certain construction method. In some existing scheduling and cost-estimating systems, implementing the idea of computer-interpretable construction methods, have been based on the concept of breakdown of projects into activities. In this case, construction methods can be defined as a systematic way of grouping activities together as high-level activities to support the selection of activities at various levels of detail. According to this approach, a construction method model has been defined by

Figure 14. Part of the EVALUATOR model. *ConstructionActivity* is the core entity. A *ConstructionActivity* is determined by and *ConstructionPlan* and determines a *ProjectEstimateItem* (which part of a *ProjectEstimate*). *ConstructionActivities* use one or more *ConstructionResources* to construct a *BuildingElement* and are subjected to a *RateVariation*.

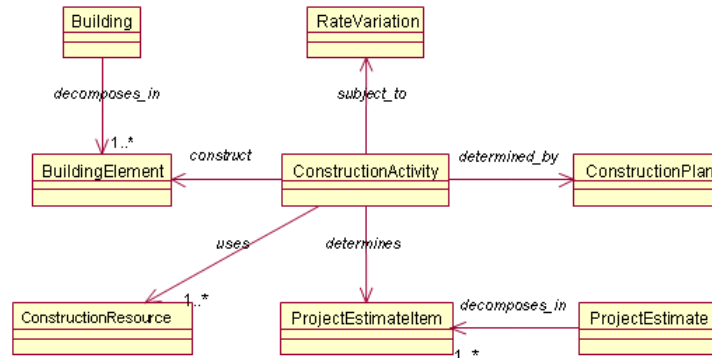
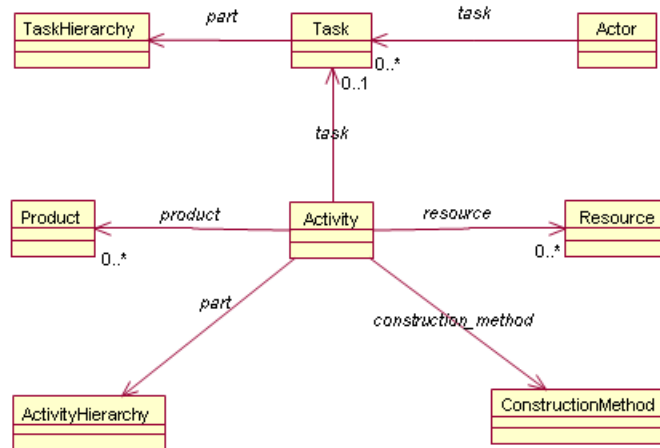


Figure 15. Part of the Synthesis Model for Construction Planning. *Activity* is the core entity. An *Activity* is part of an *ActivityHierarchy* and is associated with a certain *ConstructionMethod*, zero or more *Products*, zero or more *Resources* and zero or one *Task*, which is part of a *TaskHierarchy* and associated with an *Actor*.



a hierarchical breakdown of its constituting lower level activities. This brings us to the problem as discussed in the PhD of Dado, i.e. the fact that it is not possible to specialise Activity and Result independently (Dado, 2002). In this respect Activity and Result are like Siamese twins, inseparably attached to each other. This togetherness is the

commonly used root statement. The consequence are (1) that each specialised Activity-Result pair has to be tied together through a Redefine Type (RT) attribute, or (2) that specialised pairs are delegated to other models that are, in some way or the another, related to the core model (mostly though mapping), or (3) that no further speciali-

sation is provided. None of these “solutions” is really satisfactory, because project communication requires clear and common definitions of all the relevant entities that play a role (details of pairs of Activities and Results) in one project model. In order to overcome the problems with existing conceptual project and applications models, Dado developed a conceptual project model that is based on a matrix, which is referred to as the RAM (Responsibility Assignment Matrix). Each intersection point (referred to as WorkObject) on the RAM represents the scope of work that has been contractually agreed and which organisation is responsible, i.e. the extension of the WBS (Work Breakdown Structure) with the OBS (Organisation Breakdown Structure). A WBS in this thesis is not defined as a strictly product- or process-related decomposition, but allows decomposition in both directions, which overcomes one of the biggest problems of the existing building product models namely the idea that product and process should be decomposed independent. Figure 16 shows basic idea of this approach.

4 FUTURE TRENDS

In this section we briefly introduce some ongoing initiatives in the Netherlands. These initiatives are supported by the Dutch BC Industry and may play a significant role in the future development of BIM and its widespread implementation throughout the Dutch BC industry.

4.1 COINS

“COINS” (Constructive Objects and the Integration of Systems) is an initiative by the CUR (a non-profit organization in the Netherlands that is occupied with the development, acquisition and transfer of knowledge and experience in the field of civil engineering). “COINS” is also attached to the BuildingSmart-programme of the IAI. Its main goal is to provide sector-wide agreements

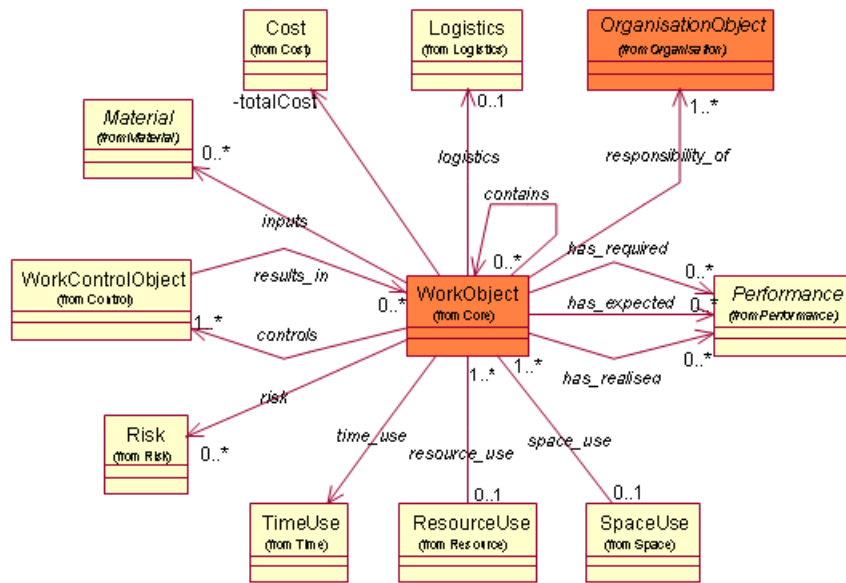
about information exchange both for objects and systems since IFC, according to COINS, does not sufficiently cover the BC industry spectrum. Currently most of the large Dutch BC companies are committed to the developments within COINS and there several ongoing experiments including the first testing tools developed by TNO (the Netherlands Organization for Applied Scientific Research).

“COINS” uses the OWL format to allow for semantic information exchange. The exact definitions are laid down in a publication by Schaap et al (2008). The core model defines physical objects, their relations with spaces and finally the topology (Figure 17). It does not explicitly define geometrical representation but rather references to standards such as IFC. Add-ons can be built on top of the core model. Currently the official add-ons are definitions for Functional Specifications and Quantity Estimations. This rudimentary COINS model is sufficient to represent the basics in a systems engineering context. It can represent Functions with their associated requirements and Function-fulfillers (physical objects and spaces) with their associated performances in a layered hierarchical structure separated by baselines.

Actors in the BC industry can work independently or distributed on the same base model. Therefore COINS introduced a “Coins Container” for information exchange and change management within a formal VISI (communication standard for management information in the Netherlands) framework. This allows actors to manipulate, independently, relevant parts of the total CBIM (COINS-BIM) model. A CBIM manager and a standard database tools check for conflicts before merging the manipulated data into the BIM (Figure 18).

TNO has built a test tool (available on <http://www.coinsweb.nl/>) by which an actor can define or decompose functions and their function-fulfillers as well as visualizing them with an integrated IFC viewer. The tool can be used both as a central BIM server and as a client application. Itannex

Figure 16. WorkObject is/are the responsibility_of one or more Organisation Object(s) is the core construct of the integrated model. Together they form each intersection point of the RAM. The construct WorkObject contains zero or more other WorkObjects, results in a simple decomposition structure, which represents the WBS of the project. The relation between WorkObject and the different project views, which are defined in other diagrams, are modelled through association relations. The modelling construct WorkObject resource_use ResourceUse represents the traditional “project view” as seen in existing project models. Life-cycle modifiers have been added to the different classes in the different packages. The required semantics for meaning communication between the different participants have been delegated to the different view diagrams



(Dutch Autodesk reseller) introduced a COINS-integration for Revit at the end of 2008 that allows a 3D-modeller to explicitly link drawn objects with function-fulfillers. In the near future the integration will produce an IFC file for every function-fulfiller and will allow all actors to visualize the objects within an IFC viewer without needing Revit.

In theory, all COINS-compatible products are compatible through the CBIM. It is expected that more market parties will make their products COINS-compatible once the standard gains momentum. At the moment, the Nemetschek Scia has taken up the challenge of supporting calculation models in addition to purely geometric models for

any arbitrary construction as well as exposing it through a COINS plug-in similar to Revit.

The benefits of using COINS are the same as for BIM in general: it allows multiple distributed users to work on a project asynchronously with a variety of applications that support the standard. The central model guarantees that no information is redundant and that all actors have the certainty of using the latest up-to-date information. Pre-requisite is that all actors use the same standard and therefore the COINS group urges clients of large and complex projects to make the use of COINS obligatory for all actors working on their projects.

Figure 17. A basic COINS core model allows defining objects, spaces, topology and references to geometric representations (IFC). With this rudimentary model it is possible to define a hierarchical breakdown of an object. The core model can be extended with Functional specifications, Cost estimations and such (Adapted from Schaap et al, 2008).

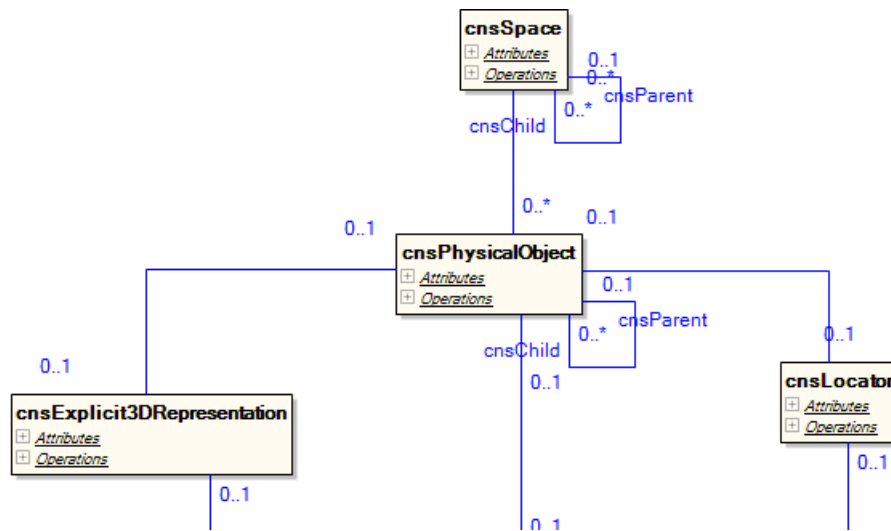
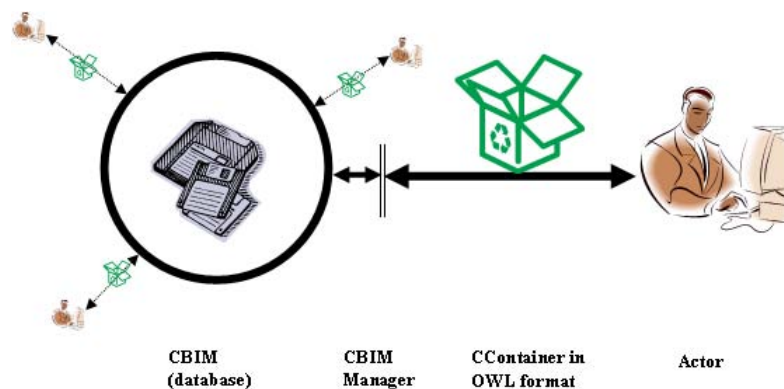


Figure 18. The basic COINS mechanism allows actors to manipulate small portions of the CBIM database. A CContainer transports this information in the OWL format within a formal VISI transaction. Before merging the modified information back into the CBIM a CBIM manager and the database itself check for inconsistencies / conflicts (Adapted from Schaap et al, 2008).



Despite the first promising results that have been achieved in real life experiments, COINS is still far from supporting complex large-scale projects for several reasons. The first reason is that the formal descriptions only address rather static issues such as topology, geometry, change management, planning and such for a rather small

amount of properties since CBIM only stores information that is strictly needed for the further stages of a project. However, it is rather difficult to define relevant information beforehand and it is even more difficult to provide a standard for it (unless it allows storing any type of information in addition to the predefined information). A

good example of this situation is input files for specific applications such as Revit. These files represent a mixture of significant (and therefore they are explicitly represented in CBIM) and insignificant project details (and therefore they are not supported by CBIM). In a complete COINS environment one may expect a Revit modeller to export the model to CBIM where an AutoCAD modeller or another Revit modeller can continue working on the information. In reality CBIM fails because a major amount of critical application-specific settings are needed (line thicknesses, scales, building codes, links to object libraries and such), in order to produce the desired results. COINS has chosen to avoid these types of problems and stores in CBIM input files similar to VISI transaction attachments. This causes a major amount of information redundancy and a rather undefined location of input files and their associated information.

The second reason is that the information in COINS does not include semantics. The only level of semantics is that the model distinguishes the type of object (space, physical, etc). The standard does not hold the semantics of a space or object itself since it is stored as textual information only, without reference to any semantic model. Therefore it uses OWL as though it is a data format.

The third reason is that COINS only supports a single breakdown structure. It does not allow an actor to define multiple alternative solutions for a problem. It is unrealistic to assume that a large project has a unidirectional solution breakdown structure.

The fourth reason is that COINS has not addressed the heavily dynamic and cooperative nature of BC projects. It assumes that the BIM manager can interpret all changes in incoming containers. The BIM manager(s) are not designers and therefore it is perfectly possible to update CBIM with wrong information. Since CBIM is a static database it will not complain about the information. It is only after a while when other actors in the project discovering flaws in a portion of

information in their applications. “COINS” is not a dynamic system and is not able to immediately calculate the consequences of new information. It only stores information without putting any significance on its semantic details.

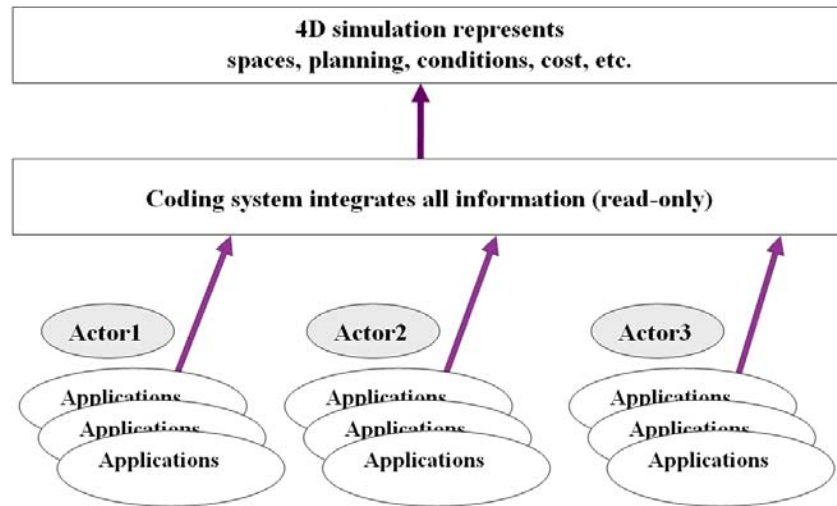
4.2 ABCybrics

ABCybrics (Association Based Communication - Cybrics) is a Dutch company that has chosen for a more dynamic, bottom-up approach in dealing with BIM. The basic idea is to allow for continuous trial and error during the entire project, which is a natural way of working. The results of all actions are immediately visualized in a 4D simulation.

The four cornerstones within ABCybrics are spaces, conditions, planning and costs that all actors understand despite of their own specific domains. A code language allows working of CAD-applications but also excel sheets, planning and cost estimation software, and a wide range of other applications to publish their object-oriented information in the 4D simulation. The latter can show both the building progress and the associated logistics. The method has been successfully applied on a number of architectural projects such as the Central Station in Amsterdam.

The benefit of this approach is that bottlenecks and inconsistencies in a project such as critical paths and clashes become quickly clear since all information is coupled to one of the four commonly understood cornerstones. The downside of this approach is that the 4D environment is not interactive and therefore it is impossible to make changes in the model because there is no central BIM. Modifications must originate from the individual actors and their applications. This limitation has been introduced on purpose. This way, the quality and responsibility for certain parts of the project are clearly delegated to specific actors. The experiences of previous projects have shown that unskilled actors do not survive the project.

Figure 19. ABCybrics visualizes information in various applications directly in a 4D environment. Project actors can immediately see the consequences of their modifications. ABCybrics allows actors to communicate about spaces, planning, conditions and costs without domain specifics.



4.3 CHEOBS

Within the COINS project it became clear that the information in the CBIM does not hold references to detailed semantics. This gap can be filled by object libraries, which are becoming increasingly important for reuse of knowledge. In this regard CHEOBS (Dutch object library for infrastructure projects) introduced a web service based on the Gellish format (object-relation-object definitions, which is very similar to the OWL format) that can be queried for functions, function fulfillers and their relations. This approach makes use with COINS interesting. Currently one of the COINS experiments attempts to provide a proof of concept for this type of integration. CHEOBS is also useful in other systems engineering tools and is currently being integrated in PKM (Personal Knowledge Management) tools.

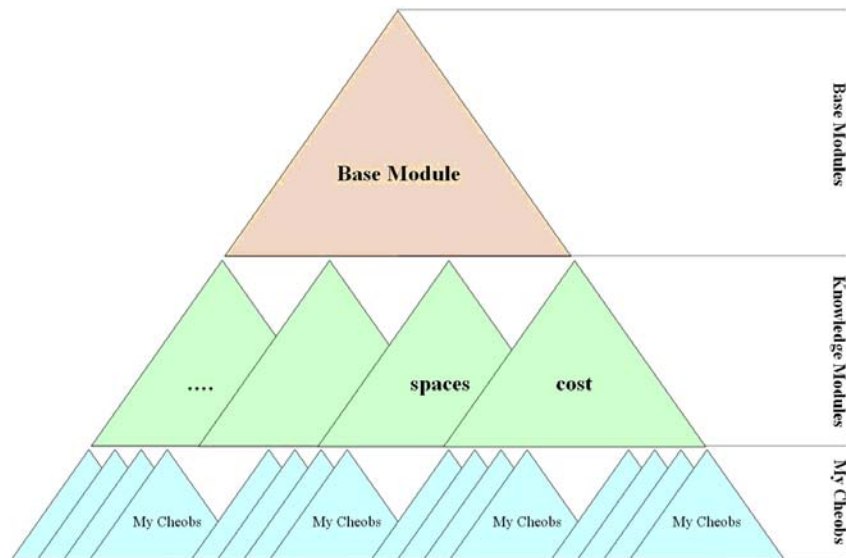
CHEOBS is an initiative by CROW, a platform that develops and manages practical knowledge in the Dutch BC industry and specifically for infrastructure projects, contract forms, public spaces, building processes and mobility. CHEOBS currently attempts to expose explicit knowledge

through web services. It uses a three-layer structure shown in Figure 20: (1) A basic module with common definitions, of which sewerage (in close cooperation with RIONED) is the first completed product (2) specific knowledge modules (Costs, functional specifications and such) and finally (3) My Cheobs that allows extending Cheobs with customized knowledge.

In the future all definitions will reference suppliers (more precisely, suppliers will subscribe to CHEOBS objects). For instance using Cheobs approach will allow searching for a door in general and a query for available suppliers. These suppliers may offer their specific doors through web services to allow for cost estimations and such.

The benefit of CHEOBS is that it may be used in a variety of applications, because extendable object definitions and their associated suppliers will always be one of the building blocks of a BIM. Furthermore, suppliers will subscribe to the service when the use of CHEOBS can become common for its users, making it a dynamic online market that can provide standard solutions that can also anticipate new design & construct contracts.

Figure 20. CHEOBS uses a three-layered structure to expose explicit knowledge. The base module and specific knowledge modules can be extended with protected MyCheobs modules (Adapted from CROW CHEOBS, 2009, www.crow.nl/cheobs).



4.4 SWOP

The SWOP (Böhms, 2008b) project aims to provide an open, semantic, standards-based, distributed production platform to allow for rapid production of flexible and configurable, but industrialized complex solutions. Production knowledge and expertise are represented in parametric catalogue items and reference design patterns. The Open Engineering Platform will be based on Semantic Web technologies and Genetic Algorithms. It focuses on using pre-defined and proven solutions in the early design stage (similar to CHEOBS). The research parties in the project consortium are CSTB, TNO, VTT, USTUTT and PARAGON. Also, four industries and some end users involved (ZUB, Blum, TRIMEK and SAT), as well as an ICT developer (Semantic), and a consultant (AEC3).

SWOP allows rapid development and modification of ontologies. One of the major SWOP products is PMO (Product Modelling Ontology), which is an extension to the OWL format that

facilitates product modelling. TNO developed the convenient PMO Editor that can visualize the result in 3D.

The PMO Configurator allows users to generate a configuration based on previously defined PMO ontologies. A useful extension is the IFC-PMO link, which can read an IFC file, match it with PMO ontologies and allow the end user to edit the IFC object in any way the PMO ontology permits. Finally the result can be exported back to IFC. This link may prove a major contribution in developing BIM environments.

Where COINS lacks a dynamic system, SWOP excels with Genetic Algorithms (GA) that optimizes configurations for competitive products. This task usually requires a significant amount of effort “by hand”. After the best design alternative has been found, the product moves towards production stage for which SWOP has developed a CRM (Customer Relationship Management)/ERP (Enterprise Resource Planning) integration and a Construction Workflow Configurator. There has been an attempt to integrate the editors,

configurators and genetic algorithms into one convenient application, but it has not been completed as yet.

SWOP does not mention any central storage system, but the nature of OWL allows to provide those capabilities; more likely the information will not reside on a central server but it will be available through a distributed network of resources (such as a CHEOBS server, suppliers web services and the like) to which actors can subscribe. A client must be aware of the possibilities but also of the risks of distributed storage of valuable data; for instance web services may disappear. Therefore it will always be necessary to identify baselines on which all information must be gathered and frozen to a specific location for archiving. The pruning question is how to access that information if the specific web services are not available anymore.

4.5 BIM Server

Since 2009, the BIM Server has been released by the non-profit organization BIMServer (www.bimserver.org). It is the implementation of the Building Information Exchange Protocol (BIEP) that is a new standard developed by the Open Source BIM foundation in a joint effort with TNO, the Eindhoven University of Technology and various commercial companies.

The core is open source software developed in Java and allows merging, versioning, querying, linking and 3D viewing of information based on the IFC standard. Additionally commercial plugins provide PMO (referring to the SWOP discussion) and COINS compatibility, CAD connectors (Revit), GIS (Geographic Information System) linking and more. Client applications can link to BIM Server using SOAP, that is accessible through a web site and finally third-party services can connect using REST (Representational State Transfer) web services in order to provide up-to-date information on their products.

Presently a preliminary version of BIMServer is functional that is not yet ready as a multi-user environment. However it is a major step in providing the architecture that is needed for COINS, SWOP and other initiatives. An online version BIM Server is available at <http://demo.bimserver.org/>.

4.6 Conclusion on Future Developments

This section described current developments that attempt to bring BIM a step closer its intended goal. “COINS” uses a static top-down approach and uses the OWL format to store data rather than semantic information. CHEOBS is a library that may complement COINS but also many other applications that need commonly agreed ontologies. ABCybrics demonstrates that a goal-based bottom-up approach using proven expertise and solutions is successful for its dynamic communicative nature. Finally SWOP seems to be the summation of the above mentioned initiatives because it is a complete dynamic design environment from design to manufacturing that allows semantic information manipulation and optimization, complete with explicit knowledge reuse capabilities. The SWOP publication mentions that the current “COINS configurator” may be integrated with SWOP. The newly released BIMServer provides a working platform for experiments with BIM initiatives.

None of the mentioned initiatives are completely suitable for market release as they do not provide a complete response to the market requirements for BIM. The systems still largely depend on human interference in order to produce the correct results. Fortunately most of the initiatives focus around the same promising OWL standard for information sharing and exchanging.

5 CONCLUSION

This chapter provided an overview of product modelling in the Building and Construction (BC) industry based on authors' experiences gained from conducted R&D research projects in the past coupled with results of other research projects in the last two decades. We started with an introduction and background of the subject area in terms of motivation, industrial needs and requirements. Then followed an overview of a historical background of the subject area in which we distinguished five generations of product modelling developments. The first generation of product modelling developments is characterized by the influence of previous expert and database developments and by the constituting high-level constructs (e.g. EDM, BSM, RATAS and GARM). The second generation of product modelling developments can be characterized by the development of detailed aspect systems and supporting frameworks for data exchange and integration (e.g. IRMA, ATLAS, COMBINE, PISA and IMPACT). The third generation product modelling developments can be characterized by its focus on collaborative engineering support by means of the application of middleware and client/server technology (e.g. SPACE, CONCUR, BCCM, VEGA and ToCEE) and the development of the IFC. The fourth generation of product modelling developments is heavily influenced by the Internet and Web Services standards such as XML, SOAP and UDDI and related business models such as eBusiness and eWork (e.g. bcXML, ifcXML and eConstruct). The fifth generation of product modelling developments will be based on the emerging semantic web standards such as OWL and RDF. It will be based on the concepts of ontology modelling as experienced in ongoing (European) projects such as SWOP. Following this historical overview, the chapter offered an analysis of the characteristics of some interesting conceptual product modelling approaches. In this chapter, we discussed the Standardisation,

Minimal Model, Core Model, NOT, Vocabulary and Ontology product modelling approaches. The chapter also provided an analysis of a number of specific conceptual product models and how the basic product modelling constructs (i.e. semantics, lifecycle modifiers and multiple project views) are implemented. Finally this chapter discussed some ongoing projects (COINS, CHEOBS and SWOP) in the context of future trends and market requirements.

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KEY TERMS AND DEFINITIONS

Product Data Technology (PDT): PDT includes all aspects of the definition and methods of

processing of information pertinent to a product throughout its development and operational life-cycle. A product is producible, produced or natural object, system of objects or substance. The product may consist of any combination of physical and conceptual (Owen et al. 1995).

Ontology: Ontology is a set of well-defined concepts describing a specific domain. The concepts are defined using a subclass hierarchy, by assigning and defining properties and by defining relationships between the concepts (van Rees, 2007).

Standardization: The main idea of standardization is to develop models that describe a whole class of Objects (e.g.) a whole class of buildings, which are often referred to as “type” models. These standardized type models provide software vendors a basis on which their applications can be built. Occurrence data (i.e. one particular building) can be instantiated by the end-users and exchanged and shared with other applications that are based on the same schema (i.e. same type model).

XML: eXtensible Mark-up Language (XML) is a universal data format for the Internet. XML is a general-purpose specification for creating custom mark-up languages. It is classified as an extensible language, because it allows the user to define the mark-up elements. It's a standard way for storing information (Wikipedia, <http://en.wikipedia.org/wiki/XML>, Accessed 7 July 2009).

eConstruct: eCommerce and eBusiness in the European Building and Construction Industry: Preparing for the Next Generation Internet (eConstruct) is an EU research project that ran from January 2000 till January 2002 (Project Number IST-1999-10303). TU Delft was one of the participants in this EU FP5 research project.

Project Modelling: The extension of design-oriented product models with entities related to the project realization, including entities such as processes, resources and control. “Process” objects represent the processes or actual construction efforts on the project. “Resource” objects represent the resources, such as equipment, temporary con-

struction works, etc., which are used in the project. “Control” objects represent items that control or constrain other objects, such as contracts, budgets, and standards (Dado, 2002).

Object Tree (OT): An OT is a simple hierarchical list of objects of a project for storing object names, identification, basic properties and decomposition structure (Nederveen, 2000).

Chapter 6

The US National Building Information Modeling Standard

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ABSTRACT

The publication of the National BIM Standard (NBIMS) at the end of 2007 after two years of work by the most highly diverse team ever assembled by the National Institute of Building Sciences brought a symbolic shift in the architecture, engineering, construction, and facility ownership (AECO) community. However, what impact did it have on the industry? This chapter looks at the strengths, weaknesses, opportunities, and impact of the NBIMS into 2009 and beyond. Specifically, this chapter will delve into some of the strengths of the NBIMS, such as promulgating a standardized approach for documenting information exchanges between stakeholders, and applying the NBIMS Interactive Capability Maturity Model (I-CMM) to evaluate a project or portfolio for BIM maturity. Opportunities exist in the areas of sustainability, modularity, and fabrication, as demonstrated in several industry projects to date. Weaknesses of the NBIMS are that it is not directly applicable yet at the technical level such as the National CAD Standard (NCS). Along with the NCS, the NBIMS and their umbrella parent organization, the Facility Information Council of the National Institute of Building Sciences are gradually being absorbed into the buildingSMART™ Alliance. Lastly, the primary impact of the NBIMS will be felt in terms of current and future projects promoting interoperable information exchange for specific stakeholders. These include multiple applications of interoperable-IFC-based approaches.

1 INTRODUCTION

In 2004, the National Institute of Standards and Technology (NIST) published a report stating that

poor interoperability and data management costs the construction industry approximately \$15.8 billion a year, or approximately 3-4% of the total industry (Gallaher, et al. 2004). Additionally, the buildingSMART™ Alliance is calling for a \$600B reduction in construction costs through productivity

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improvements by 2020, and they feel it is conservative. Since the NIST report, many have dubbed Building Information Modeling (BIM), as the answer to this problem. From the National BIM Standard (NBIMS) published December 27, 2007, a BIM (i.e. a single Building Information Model) is defined as “a digital representation of physical and functional characteristics of a facility” (Kennett 2006 and NBIMS 2007). Several reports have sought to assess the level of BIM diffusion in the industry. For instance, the Construction Management Association of America (CMAA) Survey of Owners (D’Agostino et al. 2007) reported on the state of Building Information Modeling in the American construction industry at the same time as the NBIMS publication at the end of 2007. In the joint publication of their eighth annual survey of owners, FMI, a construction-specific research, consulting, and investment banking firm partnered with the CMAA to determine the current state and future trends in the construction industry surrounding BIM. The subtitle, “The Perfect Storm—Construction Style” alludes to the current market forces that are driving technological adoption at a greater rate than in the previous seven years of the survey. Specifically, the authors state, “A fresh tool – Building Information Modeling (BIM) is enabling and supporting this change in philosophy, process, and approach, which will allow owner organizations, in turn, to weather the coming storm of construction industry challenges” (D’Agostino et al. 2007).

After NBIMS publication in December, 2007, many in the industry were disappointed that the standard did not provide a detailed “road map” for how to apply BIM to specific existing processes. However, as this chapter will discuss, the NBIMS represents a strategic departure from existing, traditional AECO business processes, and instead focuses on what information should flow from stakeholder to stakeholder in the future of the BIM-based facility industry. Instead of a technical how-to document, the NBIMS represents what could or should be accomplished, and leaves the

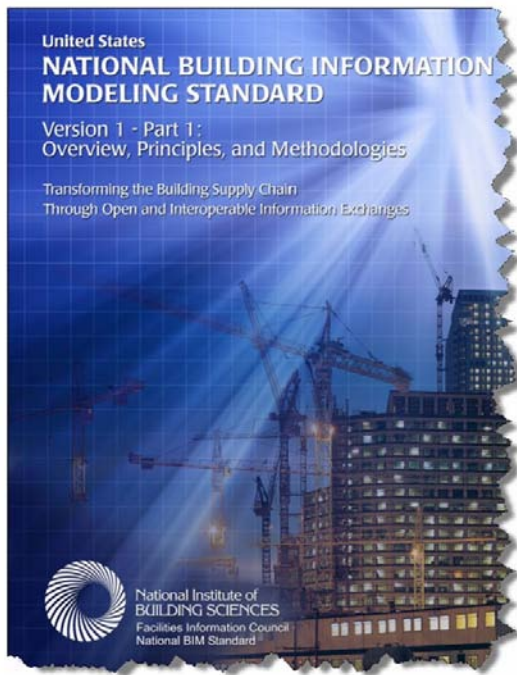
role of establishing best management practices (BMPs) to research entities like NIST or Universities, or industry entities like the American Institute of Architects, the Construction User’s Roundtable (CURT), the AGC BIMforum and others. The specific objectives of this chapter are to discuss the NBIMS in 2009 and beyond. This will be accomplished by discussing its existing and future strengths, weaknesses, opportunities, and impacts.

2 BACKGROUND

The NBIMS was published December 27, 2007 after approximately two years of effort starting in August of 2005 (See Fig. 1). The leader of the NBIMS Committee effort was Mr. Dana K. “Deke” Smith, FAIA of the National Institute of Building Sciences Facility Information Council (NIBS-FIC), the same entity responsible for producing the National CAD Standard (NCS) since the 1990s.

In retrospect, this association with the NCS could be considered a blessing as well as a curse. The blessing came in the form of an organization of diverse and respected professionals, proven processes, and technical knowledge. The curse came in the form of an industry that expected another NCS, *version 4.0* in NBIMS *version 1.0*. In other words, the NBIMS is much less technical than the NCS. Whereas the NCS discusses specifics like line weights and layering targeted for paper production of architectural drawings, the NBIMS is all-encompassing of the facility lifecycle and addresses how to view communication between all participants of the facility lifecycle. In all, this left the NBIMS – much like other standards or standards organizations, with strengths, weaknesses, opportunities, and possible challenges to overcome before accomplishing the greatest impact possible. This chapter will discuss specific facets of all of these.

Figure 1. The National Building Information Modeling Standard, Version 1, Part 1: Overview, Principles, and Methodologies (adapted from, Source: <http://www.buildingsmartalliance.org/nbims/>)



3 US NATIONAL BUILDING INFORMATION MODELING STANDARD

Strengths

As it is well known in the construction industry and corroborated by Adrian (1995) who noted that “the success or failure of every construction project can be measured in terms of four variables: cost, time, quality, and safety.” More specifically, in a landmark study started in 2006, Kunz and Fischer (2007) from Stanford University’s Center for Integrated Facility Engineering (CIFE) studied virtual design and construction (VDC) and concluded that “. . . VDC is being used and significantly growing. As this growth proceeds and advances, users become more proficient [mean-

ing] they are more likely to perceive value and thus make organizational and strategic shifts in their operations.” Later they noted that “advanced users report increased efficiency and indicate an important business opportunity for those who can provide VDC-based services early on.” In this light, the NBIMS hopes to transform the information supply chain for facility acquisition, rather than just optimize one part of the process, as was the case with its precursor, the NCS.

Historically, the AECO industry’s efforts to implement and support better information flow between stakeholders with existing CAD systems have focused primarily upon format and output versus open information and workflows (i.e. a paper centric versus a process centric viewpoint). The transition to BIM is different than the move to CAD because CAD did not significantly alter business processes, but simply increased the speed at which centuries-old traditional tasks were completed through electronic means. This was comprised of digitizing a well-known 2D-based design and paper-centric project delivery system (Livingston 2007).

The strength of the NBIMS was and is that it established a North American position congruent with the International Alliance for Interoperability (IAI) and their approach for standardizing interoperable solutions for routine tasks in the facility lifecycle. Along these lines, the NBIMS was intentionally generic, while still promulgating support for the IAI approach to standardize industry operations. This included support for the Information Delivery Manual (IDM), Model View Definition (MVD), and International Framework for Dictionaries (IFD) approaches. Of course, the most notable product from the IAI are their Industry Foundation Class (IFC) file type that is available as an export in all mainstream BIM authoring platforms. By establishing this precedent, the NBIMS has catalyzed many other projects. These include the Construction Operations Building Information Exchange (COBIE) (as described in Fig. 2) and other Industry foundation Class

(IFC) based, interoperable approaches aimed at sharing information that will be discussed more in the “Impact” section.

Another unique strength of the NBIMS is the Interactive Capability Maturity Model (I-CMM) included and discussed in NBIMS Chapter 4 in Sections 4.1 and 4.2. The I-CMM is a Microsoft Excel-based tool that users can download from the hyperlink within the document that allows scoring a BIM project’s maturity level. Based on the Carnegie Mellon University (CMU) model for monitoring software maturity, (the original CMM concept) the NBIMS I-CMM provides a way to turn subjective evaluations into objective analysis by assigning ratings on a 1-10 scale in eleven areas of information management maturity into a single score. Users who are unfamiliar with the interface can scroll through definition and description worksheets in a Microsoft Excel workbook to learn how to use the tool. Or, more experienced users may simply find that all they need are the user-friendly dropdown boxes on the main interface that allow users to rate information management maturity in all eleven areas with a maximum score of 100. Fig. 3 shows an example screen capture of the I-CMM. In order to account for varying levels of importance among the 11 criteria, and in order to make the objective scores easily understandable, each “score” is weighted by a percentage. This ranges from criteria of lesser importance at 84% or a .84 multiplication factor (e.g. data richness) to 96% or a .96 multiplication factor (e.g. interoperability). In this way, the static CMM has been supplemented to “reward” more accurate and interoperable BIMs over those that merely enhance visual architectural drawings. It is important to note that the I-CMM weights, while not empirically based on any statistical data, were reviewed and approved by the National BIM standard Committee and included in the publication of the NBIMS.

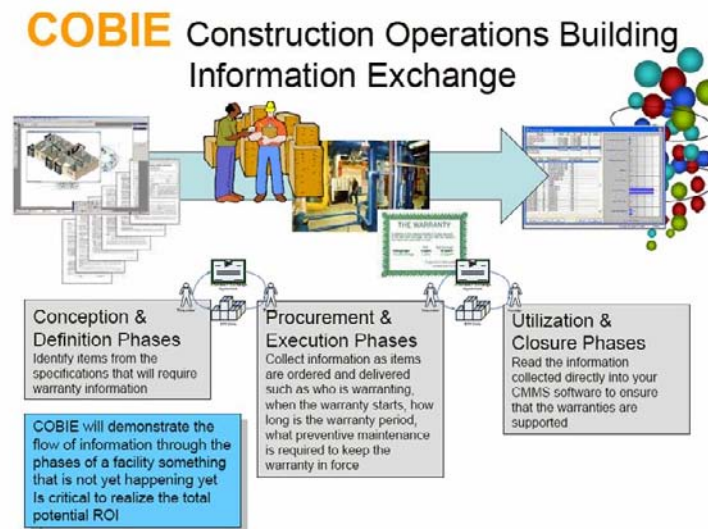
Additionally, the I-CMM is discussed in Smith and Tardif’s book, *Building Information Modeling: A Guide to Strategic Implementation* (2009)

and the I-CMM’s efficacy was validated in the summer of 2007 by the NBIMS testing team. In a test case project rating the American Institute of Architects (AIA) Technology in Architectural Practice (TAP) annual BIM award winners, NBIMS Testing Team members conducted single blind, subjective evaluations of the “best BIM projects in the world” and then compared their score with secondary evaluators. In most cases, team member scores only varied by 2-7%, emphasizing the validity of the tool’s ability to turn a nebulous and subjective process into a quantitative and objective one.

A second goal of the test case was to demonstrate that even “the best BIMs in the world” did not always score a proverbial “A+” on the I-CMM. Rather, the 2007 samples scored anywhere from “Minimum BIM” with a score of 20 or an average score of “Silver” near the high 70s or low 80s depending on the type of project. Only one project scored in the “Platinum” category, a test bed BIM project attempting to push the boundary of existing information management with BIM.

A follow-up evaluation of the 2008 AIA TAP Award winners yielded similarly promising results regarding the NBIMS I-CMM validity, but demonstrated that the scores of the BIM projects dropped considerably. The scores and surveys portrayed an industry with a growing capability maturity in the first stages of BIM use, visualization and prediction. But, the 2008 evaluation demonstrated lesser capability in the next stages of implementation, such as integration and automation. The “low hanging fruit” of visualization, clash detection techniques, collaboration, and models as the central focus of projects have largely been achieved by phases early in the lifecycle: plan and design. The next lifecycle phases are poised to incorporate BIM usage in a more mature capacity, especially the construction phase through the use of BIM in production and automation to support field activity. From the team’s perspective, it was also clear that the Operations and Maintenance phase of the building lifecycle was furthest behind

Figure 2. Construction Operations Building Information Exchange (COBIE) Overview (adapted from, Source: <http://www.wbdg.org/resources/cobie.php>)



in use of the technology, with implications for further model development and incorporation of other data requirements specific to that phase.

Fig. 4 shows an evaluation of the 2008 AIA TAP BIM Award winning submissions. The highest scoring area, “Graphical Information” shows that most of the award-winning BIM submissions focused on rich visual representations and have not yet achieved equivalent success in the areas emphasized in the NBIMS: interoperable file transfer.

Weaknesses

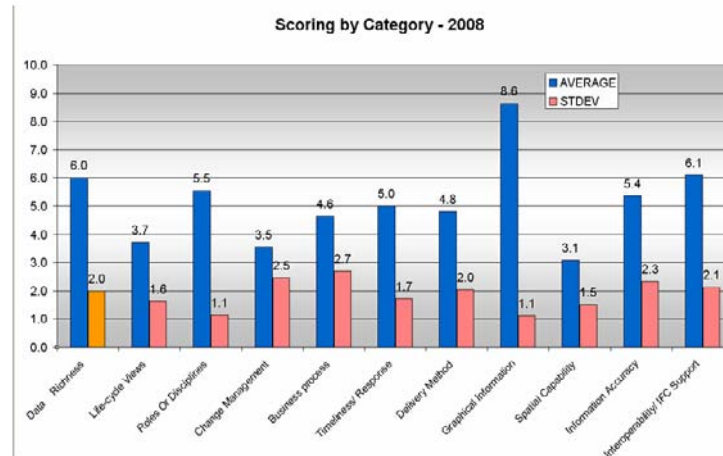
The primary weakness of the NBIMS is that it did not have enough technical information for immediate, mainstream industry relevance. Other than the I-CMM, most of the targeted audience for NBIMS (architects, engineers, constructors, owners, etc.) would most likely read the entire 400+ page document and think, “Now what?”

However, as the title implies, the NBIMS published in 2007 was only Version 1, Part 1 and

Figure 3. Screen Capture of the I-CMM (adapted from, Source: http://www.buildingsmartalliance.org/docs/BIM_CMM_v1.9.xls)

The Interactive BIM Capability Maturity Model			
Area of Interest	Weighted Importance	Choose your perceived maturity level	Credit
Data Richness	84%	Expanded Data Set	1.7
Life-cycle Views	84%	No Complete Project Phase	0.8
Change Management	90%	No ITL Implementation	0.9
Roles or Disciplines	90%	Two Roles Partially Supported	2.7
Business Process	91%	Two Roles Partially Supported	1.8
Timeliness/Response	91%	Two Roles Fully Supported	1.8
Delivery Method	97%	Partial Plan, Design&Constr Supported	2.8
Graphical Information	93%	Plan, Design & Construction Supported	2.8
Spatial Capability	94%	Partial Ops & Sustainment Supported	0.9
Information Accuracy	95%	Operations & Sustainment Supported	1.9
Interoperability/IFC Support	96%	All Facility Life Cycle Roles Supported	1.9
		Forced Interoperability	1.9
Credit Sum			20.1
Maturity Level			Minimum BIM

Figure 4. Scoring by Category from 2008 AIA TAP BIM Award Winners (adapted from, Courtesy: Mat Krogulecki, MACTEC)



was only meant to serve as an overview, as the subtitle “Overview, Principles, and Methodologies” implies. Furthermore, the NBIMS seeks to “Transform the Building Supply Chain.” Whereas the NCS was seeking to unify intradisciplinary architects and draftsman on a unified technical standard, the NBIMS seeks to unify interdisciplinary professionals in the world’s largest industry. Therefore, what is initially perceived as NBIMS’ greatest weakness will eventually be its greatest opportunity and (hopefully) accomplishment: unifying the facility lifecycle through the “open and interoperable exchange of information.”

Therefore, the answer to the “now what?” question is that stakeholders in the facility lifecycle need to accomplish the same types of business process mapping and enterprise resource planning to which they gave lip service in the Quality movement in the 1980s. While the Post World War II industrial manufacturing industry accomplished this and flourished, the 21st Century facility industry has demonstrated either too many reasons or excuses (depending on one’s perspective) for not standardizing their processes and information exchange (See Fig. 5).

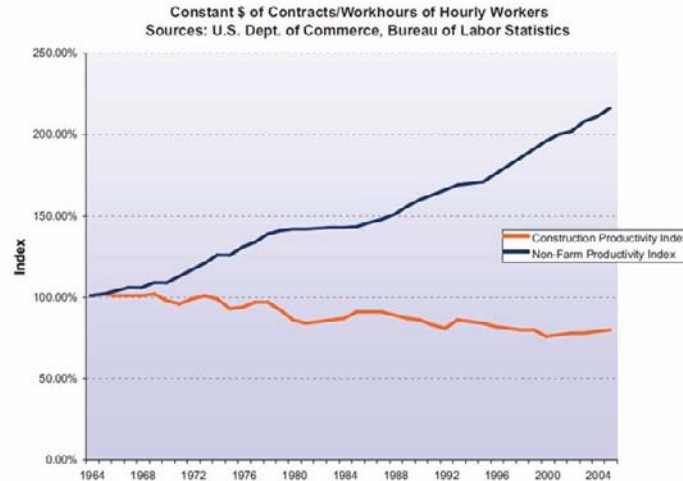
Therefore, moving forward (and in order to answer the “now what?” question), it is advisable

for design, engineering, or construction firms to sit down with the NBIMS and start by reading the most readily digestible portion, Chapter 4, Sections 1 and 2, regarding what constitutes a minimum BIM and the accompanying Capability Maturity Model. By using the CMM as a report card, firms can begin to assess their current capabilities, and attach dates to the greater levels of maturity for establishing goals of increased BIM competence. A simple four step plan for accomplishing this approach is outlined below:

Step 1

One of the most beneficial features of the NBIMS I-CMM is for those who have not begun to implement BIM. In this case, the recommended first step is to assess current operational capabilities by using either the static or interactive versions of the CMM. For example, even an architecture firm that uses the National CAD Standard (NCS) to produce its plans and elevations has a place in the NBIMS I-CMM. This would score a level three credit for the “Graphical Information” category in the NBIMS I-CMM. Firms should use the CMM to complete analysis of their current operations across the board.

Figure 5. Productivity Curve (adapted from, McGraw-Hill “Interoperability in the Construction Industry Report”)



Step 2

Next, firms should use the maturity levels beyond their existing maturity level as the basis for strategic roadmap planning. Carrying the “Graphical Information” category further, a firm should phase their software acquisitions, training, and skills to add 3-D, 4-D, and n-D capabilities to their offered services. Simply by attaching goal dates for attaining these skills to the added levels of maturity can aid firms begin their BIM journey.

Step 3

For firms who are already accomplishing BIM-based designs and construction planning, they should use the I-CMM as a menu for offering owners additional services with a pricing structure tied to the value added of their BIM information management services. Additionally, firms should track I-CMM scores for each individual BIM accomplished.

Step 4

Step 4 requires long term management of a database for past BIM-based designs and analysis of their I-CMM scores to find opportunities for improvement or added business in areas of under-utilized information management. For example, if a firm’s scores are climbing in every category but one, the firm could accurately infer that their BIM approach has stagnated in that area and more training or innovation in that area needs to be accomplished. Likewise, in a well-maintained BIM database, past geometry and information management techniques can be used again and again, with more rapid deployment and greater profit achieved after their initial learning curve has been overcome. Overall, the NBIMS I-CMM can be implemented in a variety of ways for strategic or operational BIM information management analysis. These four steps help users leverage the tool for possibly more successful BIM implementation or improvements.

Opportunities

Sustainability

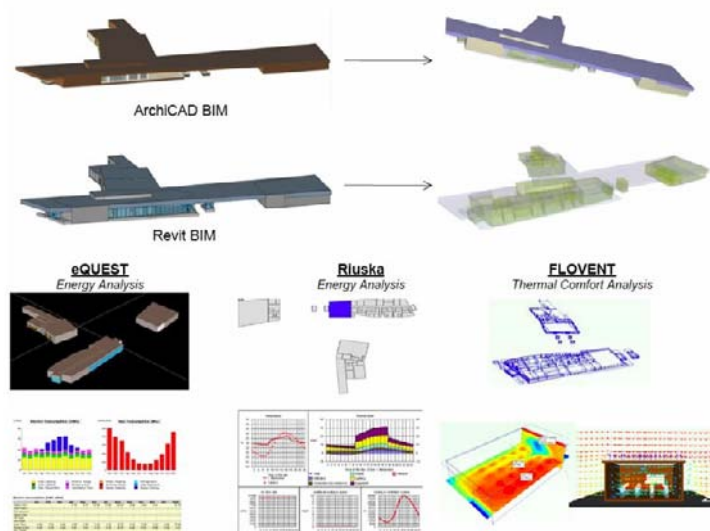
One of the primary opportunities for the NBIMS is that it was published 10 years after the formation of the United States Green Building Council (USGBC). While the USGBC was building its portfolio of Leadership in Energy and Environmental Design (LEED) certified projects, the methods required for LEED building certification showed more and more the need for the “digital representation of the physical and functional characteristics of facilities.” With each newly certified LEED Accredited Professional and the exponential growth in the number of LEED certified buildings since the turn of the 21st century, the need for reliable building data for sustainable analysis has become more pressing. Specifically, one of the largest real property owners in the world, the U.S. General Services Administration (GSA) won a 2008 AIA TAP BIM Award (Fig. 6) for their extensive work in the area of energy simulations, thermal analysis, daylighting and shading models. The GSA understands that their mission is not only to provide leasable space to US Government agencies, but to maximize their income stream from leasing spaces that are more energy efficient and pleasant, in turn rating the highest possible volumetric rental dollars.

In February of 2008, Alan Edgar, the Executive Director of the NBIMS Committee was asked about his feelings regarding BIM and the future of clean technology or sustainability. His answer follows here:

“The need for business efficiency is driving the need for transformation in both work methodologies and information standards. Collaborative project and operation methodologies are proving to be much more efficient and they produce higher quality results. Coordinated information standards developed using open and consensus-based methods produce a more generalizable and

sustainable standard when compared with de facto requirements based on a particular organization or vendor. Implementing open and consensus-based standards in software to support interoperable exchanges between many software applications is the responsibility of application developers in consultation with standards organizations. When this is done effectively, a very high rate of exchange with very high quality and reliability are achieved. Although much more work is needed, the first generation of these innovations is available and being implemented now in the plant, geospatial and the real property operation and commerce domains. In the building design and construction domain, the first generation is being developed and should be officially reviewed and approved soon. The buildingSMART alliance™ is the organization in North America that is coordinating these activities across all of these domains as well as others such as education, product manufacturing, security and environmental sensitivity. Also, the Alliance is affiliated with international coordinating and standards organizations. The National BIM Standard Project Committee (NBIMS Committee) is a buildingSMART alliance™ member and is responsible for developing, maintaining and supporting implementation of building information modeling standards in the US. Both buildingSMART alliance™ and the NBIMS Committee are organized under the National Institute of Building Sciences – a public/private organization authorized by the U.S. Congress in 1974. NIBS also supports the National CAD Standards Committee and the Whole Building Design Guide; which are Alliance members as well. That the businesses working in the context of ‘cleantech’ are being built on environmentally positive ideas is a bonus. The Alliance would like for these businesses to multiply their advantages by using open and interoperable project collaboration methodologies and building information management and modeling standards because they dramatically reduce the waste involved in producing and operating buildings and plants

Figure 6. GSA Submission and 2008 AIA TAP BIM Award Winner for Outstanding Sustainable Design Using BIM



as well as produce a higher quality product that is more long-lived and has less environmental impact during and after its useful life. Remember that a primary goal is for Cleantech companies to join the Alliance and participate on domain and standards development/management committees" (Source: Personal Email, February 16, 2008).

Clearly, according to Alan Edgar, BIM and sustainability will flourish symbiotically in the future.

Modularity

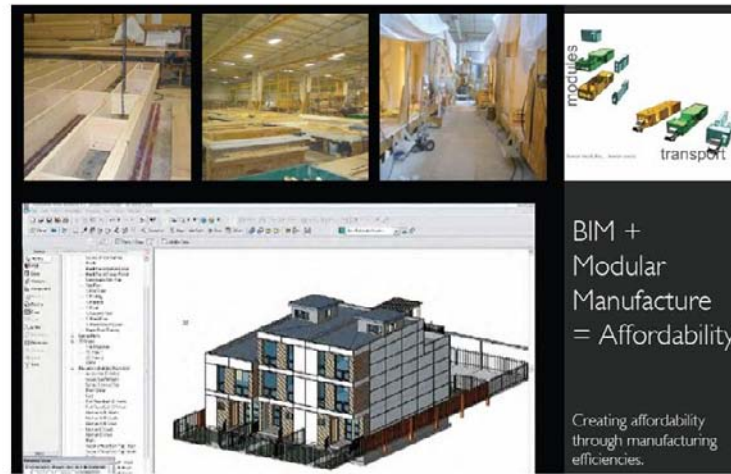
One of the award-winning academic curriculums in the 2008 AIA TAP BIM awards was the University of Illinois at Chicago, Studio 515 Graduate Studio. Their curriculum focused on modular approaches via BIM for downtown, modern Chicago living. Before marginalizing their project as an academic exercise, it should be noted that Toyota, the global-leading auto manufacturer,

has delved into the construction market with a similar approach. Work is also underway at the furniture giant, IKEA, to create not only easy to assemble furniture, but BIM-based, modular construction.

Fabrication

As evidenced by the CIS II file format used in the steel design, analysis, and manufacturing industries, the IFC approach hopes to accomplish similar successes by using "virtual mockups" or digital information to streamline the analysis, manufacturing, and assembly process. A good example of commercial-off-the-shelf (COTS) software being used for fabrication is the 2007 AIA TAP BIM award winning Loblolly house project which used Autodesk's Revit™ software to create a façade of specially designed timber on a computer numerically controlled (CNC) routing machine. Each piece's dimensions and features were read electronically from the BIM

Figure 7. “BIM + Modular Manufacturing = Affordability” (adapted from, Worn, 2008)



file export and its production was automated by the CNC machine's ability to read the file's data. In the future, as more projects start using standard design types, mass customization, or even custom projects like the Loblolly house project, electronic fabrication for construction or FM will become more commonplace.

Another project that demonstrated direct BIM-to-facility fabrication was the construction/renovation of the new Autodesk Headquarters facility in Waltham, Massachusetts. According to Laura Handler, BIM Manager for Tocci Building Corporation (as shown in Fig. 8), the “origami millwork” designed by Tocci in Revit was sent directly to the fabricator to create the one-of-a-kind effect seen in the model and accompanying pictures.

4 IMPACT

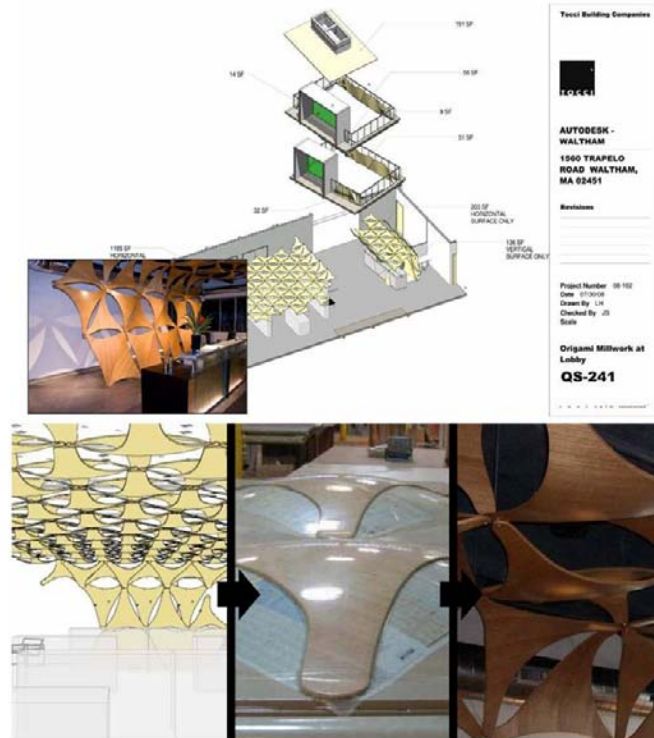
The NBIMS transitioned from creating the standard to sustaining the standard in 2008 and will continue in 2009 and beyond. The primary vehicle for broadening the NBIMS' impact will be to accomplish the vetting and approval of other candidate standards that follow the NBIMS ap-

proach. As of the fall of 2008, NBIMS has nine research projects in the works (East 2008):

AECOO Testbed

The Testbed is an international, hands-on, and collaborative rapid prototyping program designed to develop and deliver working commercial software that can frame candidate standards for OGC's, NBIMS, and buildingSMART™ International's specification and other standards programs where they may be formalized for release as open standards. The current phase of the Testbed is focusing on developing information interoperability using the IFC in two primary areas: quantity take-off and energy analysis. AECOO-1-Testbed is a joint buildingSMART Alliance™ (bSA)/ OGC Interoperability Initiative. It provides a global, industry wide effort to move our building industry forward in meeting a number of challenges. The AECOO-1 testbed culminated in March of 2009 with a live demonstration of their new proposed Model View Definition (MVD) for quantity takeoff (QTO) and building performance energy analysis (BPEA). (POC Louis Hecht, lhecht@opengeospatial.org).

Figure 8. a) Tocci BIM design for Autodesk HQ b) Direct to CNC Fabrication (adapted from, Handler, 2009)



Construction-Operations Building Information Exchange (COBIE)

According to the NBIM Project Fact Sheet, COBIE's objective is to "create both an IFC reference standard supporting the direct software information exchange and a spreadsheet that can be used to capture COBIE data for both renovation and capital projects" (Brodt and East, 2006). COBIE eliminates duplicative data entry, eliminates paper reproduction costs, and improves the quality construction handover information. A number of federal agencies are requiring the delivery of COBIE data during design and also during construction. These agencies include: the Department of State, the Corps of Engineers, and the General Services Agency. A live demonstration and automated testing of designer-side COBIE deliverables was conducted in July 2008. The following vendors

were successful in providing COBIE design data directly from their applications: Autodesk (Revit), Bentley (Architect), Nemetschek (VectorWorks), Onuma (Onuma Planning System), Project Work Bench (Room-Data). In March of 2009 at the National Facility Management and Technology Conference, three more applications were tested and passed for COBIE-compliance: Graphisoft (ArchiCAD), TOKMO, and MicroMain. (POC: Bill East, bill.east@us.army.mil)

Inter-Agency Federal Asset Classification (IFACT)

The IFACT project is designed to create a database to improve equipment asset identification and tracking, and asset information management. While this work is sponsored by several Federal agencies the holder of the classifications developed

through this work will be the Construction Specification Institute (CSI). To that end, the IFACT project resulted in a review of the OmniClass Table 23, “Products.” The team is also working to compile a new set of abbreviations in the NCS. (POC Greg Ceton, gceton@csinet.org)

Quantity Take-Off

The quantity take-off project aims to eliminate the time wasted in “counting door knobs and light bulbs.” The Association for the Advancement of Cost Engineering (AACE) and the American Society of Professional Estimators (ASPE) are leading this effort to identify design and estimating information exchanges required, not only to eliminate the “counting” activities, but also to eliminate the mapping of discipline oriented design views to system oriented construction processes. (POC: Peter Bredehoeft, pete.bredehoeft@ch2m.com)

SMARTCodes™

The objective of the SMARTCodes™ project is to support rapid completion of code compliant design and more timely permitting reviews using BIM-based submissions. Demonstrations of the automated code checking of BIM designs against the envelope and lighting provisions of the 2006 ICC International Energy Conservation Code have been completed. Current work is focused on egress and accessibility provisions of the 2006 ICC International Building Code. Development of formal BIM-based information exchange standards supporting these automated checks is underway. The team is currently working with BIM vendors to support their demonstrations of automated code checking. (POC: Dave Conover, dconover@iccsafe.org)

Spatial Compliance Information Exchange (SCie)

Ensuring compliance with spatial programming requirements is an important aspect of the overall project management goals of any project. SCIE enables the accounting of space by function and zoning using the recently harmonized International Facilities Management Association (IFMA)/ Building Owners and Managers Association (BOMA) space measurements standards. One of the key ideas behind the development process of Information Exchange formats is the re-use of previously created “model views” or extracted data sets. SCIE data is also needed for facility asset management and is already delivered through the COBIE format, described above. As a result, if one changes the space measurement and zoning requirements in the COBIE specification to be required data items, then the SCIE is delivered as a by-product of the COBIE deliverable. SCIE is a generic specification that fully reflects the requirements of the GSA BIM Guide for architectural programming, without using agency specific information classifications. (POC: Bill East, bill.east@us.army.mil)

Specifiers’ Properties Information Exchange (SPie)

The Specifiers of Construction in Independent Practice (SCIP) is leading an industry-wide initiative that includes CSI, product manufacturers, manufacturer’s association, specification software companies, product publisher organizations, and federal government agencies to prepare a minimum set of attributes that can be specified to be included on all manufactured products in a BIM. A complete set of properties across all UNIFORMAT and MASTERFORMAT sections have been completed. SPie provides templates that identify, for a given type of product, a standard set of properties that should be included in a BIM

object. These templates are maintained by manufacturer associations and their representatives. An initial set of templates was created by the professional association, Specifications Consultants in Independent Practice (SCIP). A set of “strawman” templates were publicly released in December 2009 at the AEC Ecobuild Conference. The initial set of completed templates was released April 2, 2009 on the Whole Building Design Guide website with an interactive search page for hundreds of possible items and can be accessed at: http://www.wbdg.org/references/pg_sptsearch.php. (POC: Bill East, bill.east@us.army.mil)

Structural Information Exchange

This project has brought together several structural engineering software manufacturers to develop an information exchange standard for structural member geometry. This was required since current BIM and structural engineering software do not provide common interchange formats for structural geometry. This project is sponsored by the Pankow Foundation and has been underway since September 2007. (POC: Thomas McLane tmclane@atcouncil.org)

UNIFORMAT Consolidation

The following represents information directly from Mr. Robert Johnson, UNIFORMAT consolidation coordinator (Source: personal email, April 2, 2009).

The goals of the current update effort include:

- Harmonizing the current CSI, GSA, and ASTM versions into one version.
- Make revisions to recognize all the various uses and users of UniFormat including cost control, preliminary project descriptions, BIM, facility management, and sustainable design.

The team held a series of workshops where all interested parties were invited and then publishing a draft for public review and comment. The workshops have included participation by representatives of the ASTM committee responsible for UniFormat, NAVFAC, GSA, AIA, CSC, RS Means, commercial master specification providers, and others. Achieving a consensus among all these stakeholders looking at UniFormat from a variety of viewpoints does not happen easily and so the progress has not been very fast. You can find the latest proposed draft on the CSI website under Standards and Formats. Making UniFormat usable for BIM is certainly one of the important considerations. We believe UniFormat will become a more commonly used and understood format because of BIM. One of the areas that we have not done any specific work on yet but see as a need is to provide a further breakdown of UniFormat to identify the various construction solutions to functional elements (systems and assemblies). Using exterior wall assemblies as an example, a system to classify masonry, precast concrete, metal stud framed, wood stud framed, etc. type exterior wall assembly solutions (POC: Robert Johnson rjohnson01@covad.net).

5 CONCLUSION

The largest threat to the NBIMS and BIM movement in general is that the spirited arguments that got it this far will turn into progress-stalling arguments and inactivity. To summarize the spectrum of people involved in the publication and future of NBIMS is to describe a range from “optimizers” to “utopians.” The optimizers think that the industry is turning out billions of dollars of work a year and just needs improvement through more standardized processes. The utopians think the current process is broken and want to start with a clean slate – writing a new road map for ultimate efficiency. Of course, future efforts can only be successful if they realize the old adage attributed

to General George S. Patton in World War II, “a good plan now is better than a perfect plan next week.” In other words, the NBIMS efforts need to focus on realistic, achievable goals with timelines for accomplishing those goals. The primary threat is not lethargy or inactivity, but instead lack of consensus in an organization chartered to create consensus-based standards.

To this end, the communication, processes, and organizational structure of the NBIMS body must be clear as they move from publication to sustaining their mission. This threat appears to have been overcome with the move of the NBIMS to the buildingSMART Alliance™.

In order to chip away at the billions of dollars lost annually due to redundant design and data losses, there is an urgent need to fund research regarding BIM return on investment (ROI) and streamlining BIM business processes for use by all. This includes addressing existing business practices and training methods and inserting a BIM-based approach (where appropriate) for the greatest productivity gains with the least economic investment.

The NBIMS was the first major standard of its kind in North America. While there are a myriad of informational resources on BIM from different industry or author perspectives, the NBIMS stands alone as the sole body dedicated to improving the building supply chain through open and interoperable information exchange. This chapter discussed the strengths, weaknesses, opportunities, and impacts that the NBIMS document and team of professionals face moving forward in a fragmented industry. By building on the strengths, ameliorating the weaknesses, capitalizing on the opportunities, and ensuring maximum impact, the NBIMS will mature and secure added value for all facility stakeholders in the new frontiers of sustainable design, modularity, and fabrication.

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KEY TERMS AND DEFINITIONS

Building Information Model/Modeling (BIM): Paraphrased from the National BIM Standard, A BIM is a virtual or digital representation of the physical and functional characteristics of a facility. As such, it serves as a shared knowledge repository for all stakeholders for a facility from inception onward. Physical characteristics could include architectural designs or construction drawings, while functional characteristics could

include structural analysis, sequencing, or a myriad of other simulations.

buildingSMART™ International: The North American Chapter of the International Alliance for Interoperability (IAI) coined the term the *buildingSMART Alliance* as a sort of “franchise” or branding approach. The name caught on and carried back over to the IAI for their outreach efforts. The mission of the IAI or buildingSMART organizations is to spearhead technical, political, and financial support for advanced digital technology in the real property industry—from concept, design and construction through operations and management.

Industry Foundation Class (IFC): In its most basic format, an IFC is a file extension that can be read by multiple software platforms. But, looking more in depth, the IFC movement represents nearly 20 years of work towards interoperable information sharing in the facility industry. Building on work of the International Standards Organization, the International Alliance for Interoperability (IAI) created IFCs to represent entities through an information-attributed, object-oriented approach. For more specific information, read this article by Paul Seletsky of SOM: <http://www.aecbytes.com/feature/2004/IFCmodel.html>

Interactive Capability Maturity Model (I-CMM): Discussed in Sections 4.1 and 4.2 of the NBIMS, the I-CMM is a tool that allows users to rate an individual project or a portfolio of skills along a continuum of information management maturity. Projects with lower levels of information management maturity receive lower scores and projects with more mature information management receive higher scores with a maximum score of 100/100. Currently, the tool is used merely for self evaluation, but can be used whenever multiple stakeholders want to define specific information management approaches.

Information Delivery Manual (IDM): The IDM process maps out common information exchanges between stakeholders in the construction

and defines the types of information that need to be exchanged.

Interoperability: There are many designs and components authored, viewed, and analyzed during the life of a facility. Interoperability means that each item authored could be viewed, analyzed, and edited in multiple software platforms, even those from different software vendors. The watershed study for interoperability is the 2004 study by the National Institute of Standards and Technology stating that the lack of interoperability cost the facilities industry an estimated \$15.8 Billion a year.

Model View Definition (MVD): An MVD is a diagram that is used for defining how and what components will be used for an information exchange. For example, the recent precast concrete MVD started with a Precast Structural connection. Further “drill downs” define how the element will be bounded and represented in software.

Section 4

Applications

Chapter 7

A CAD–Based Interface Management System using Building Information Modeling in Construction

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ABSTRACT

Many interface events and problems occur in Architecture/Engineering/Construction (A/E/C) projects during the construction phase. Identifying and controlling related interface events and problems are essential to construction management. Interface management (IM) has become the most important project-management strategy in construction management. Interface management is the systematic control of all communications that support an operational process. Construction IM affects cost, scheduling, and quality directly and indirectly. Despite many academic studies and considerable discussion regarding IM, information about systematic approaches for managing interface events and problems during the construction phase is lacking. Interface or changed events can be identified and traced in IM such that participants can improve construction processes, minimize mistaken rework, and reduce total duration. This study presents a novel practical methodology for tracking and managing interfaces using Building Information Modeling (BIM). When using BIM, users can obtain an overview of previous and current interfaces in a given project and implement appropriate advanced control strategies and manage interfaces and problems in A/E/C projects. This pilot study utilizes BIMs for IM to the construction/mechanical/electrical interfaces in a building project and develops a construction CAD-based Interface Management (CBIM) system for project participants. The CBIM system is applied to a case study of a construction building project in Taiwan to verify the proposed methodology and demonstrate the effectiveness of IM.

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1 INTRODUCTION

Architecture/Engineering/Construction (A/E/C) projects typically involve various participants. Information regarding the needs and process status of each project participant are typically not transmitted properly from one service provider to the next, or properly exchanged among service providers. Building Information Modeling (BIM) can be regarded as an effective information-sharing environment for information retrieval for all construction project participants (Gould and Joyce, 2008). BIM has been implemented by numerous A/E/C firms to increase productivity and acquire long-term benefits of current construction practices (Goedert and Meadati, 2008). Typical paper-based drawings generated by the architectural firm are only marginally useful for general contractors and subcontractors in terms of information sharing. Numerous interface problems usually exist in construction projects. Additionally, participants usually execute their own work and rarely share information with others especially in interfaces. However, no appropriate platforms that assist project participants in exchanging and sharing interface information during the construction phase. The primary purpose of this study is to develop a web-based platform for communicating interfaces among all project participants using BIMs during the construction phase. The general constructor and subcontractors can organize and manage the interface and change information in the central database. Furthermore, BIM can retrieve interface information established by the general constructor or subcontractors during the construction phase. The definition of “interface information” in the study refers to all information related people, events, time, location description of project interfaces during the construction process. Through the BIM central database, users can obtain an overview of previous and current interfaces for a given project and implement advanced control and management for changes in A/E/C projects. Furthermore, this study applies IM in construc-

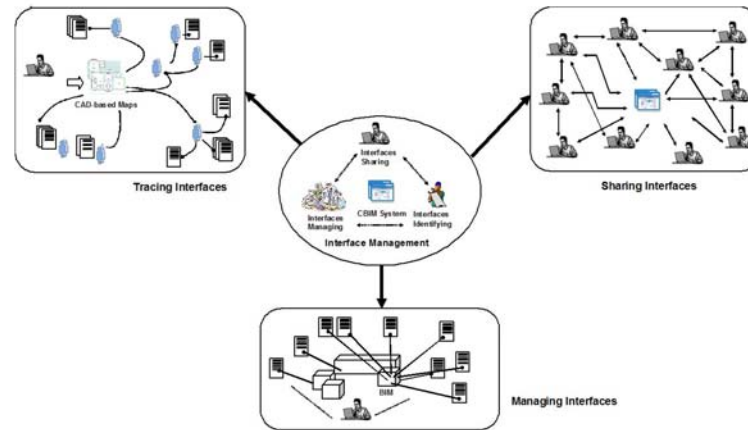
tion/mechanical/electrical interfaces in a building project and proposes a novel construction CAD-based Interface Management (CBIM) system integrated into BIM for project participants. The proposed CBIM system is applied to a case study of a construction building project in Taiwan to verify the efficacy of the proposed methodology and demonstrate IM effectiveness.

2 BACKGROUND

Construction projects are characterized by extreme complexity and non-standardized production. Unlike manufacturing, each project differs as it is designed and executed to meet owner needs. Thus, effectively managing project interfaces is essential to construction management. The complex nature of the construction industry makes it well suited to IM, particularly for interface information sharing among participants. Without IM, poorly coordinated and controlled boundary conditions among project participants can cause interface problems such as design errors, mismatched parts, system performance failures, coordination difficulties and construction conflicts (Chen et al., 2007). Effectively tracking and managing interfaces can improve construction IM during the construction phase, thereby avoiding unnecessary mistakes. Traditional interface communication methods include face-to-face meetings and telephone calls. Normal communication between participants helps prevent delays in the progress of solving interface among participants (Al-Hammand 1993, 2000). Effective information sharing for interfaces enables project participants to identify existing interfaces and solve interface problems. However, a typical problem in traditional communication is that discussions cannot be recorded and shared with others. In the construction management, interface information can serve as a reference for enhancing interface management.

According to questionnaire survey results from 16 senior managers and engineers specialized in

Figure 1. The concept and application of CBIM system in construction projects



construction management, the primary construction interface problems during the construction phase in Taiwan are as follows: (1) insufficient platforms/functions supporting IM for construction project management; (2) failure to properly manage conflicts during the construction phase; (3) complex interface conflicts related to time, space, issues and organizations; (4) a serious lack of communication and management of interface issues; (5) few suitable platforms available for assisting participants in sharing interface information when needed; and, (6) difficulty in tracking interface events and obtaining current information regarding identified interface issues.

During the construction phase, participants usually execute their own work and rarely share interface information with other participants. IM is an information-intensive task in which extremely useful information is available to related participants. Facilitating sharing and managing interface information in construction projects is the primary objective of this study. The one of characteristics for BIM approach is to enhance information sharing for collaborative work. The BIM approach is applied to keep building information in a digital format, and facilitate updating and transfer easily. Additionally, construction information can be modeled in real time with full consideration of

basic building information that increases project constructability and productivity. The main function of BIM in this study is information exchange and sharing. This pilot study applies BIMs for enhancing IM in a construction building project in Taiwan (see Fig. 1).

3 CAD BASED INTERFACE MANAGEMENT SYSTEM

Regarding interfaces, there are various studies in the literature. For instance, VDT (Virtual Design Team), CYCLONE (CYCLIC Operation Network), and STROBOSCOPE (State and Resource Based Simulation of Construction Processes) provide tools for tracking, identifying, and simulating bottlenecks related to organization level interfaces. However, those are simulation tools for decision making for managers and engineers. The approach and system what we proposed are different from the above approaches. They belong to a way of communication platform related the facing interfaces. This study develops the CBIM system to communicate and manage interfaces for all participants by integrating BIM in the construction phase. Identifying, tracking, controlling, and managing construction interface events and

problems are critical and necessary tasks. Additionally, engineers typically function as workers facilitating the identification and management of interface events and problems associated with project activities. The primary purposes of this study are as follows: (1) develop a web-based IM system for participants and integrate this system with BIMs; (2) integrate web technology with a central database, to improve the exchange of interface event information and tracing efficiency; and (3) support all project participants in dynamically monitoring and controlling construction processes using Really Simple Syndication (RSS) functionality.

Effective IM requires support from various participants, communications and tools. The BIM approach provides effective digital tools for IM in a graphical form. Although BIM can enhance the production of construction drawings, BIM also enhances information sharing in construction management and building lifecycle management. Notably, BIM can also be interpreted as the process of generating, storing, managing, exchanging, and sharing construction information in the reusable manner. In that sense, BIM is a good example of an effective interface management activity, with existing problem acquisition and illustration techniques at its foundation. Furthermore, BIM is a central system that facilitates the management of various information types, such as original plan data, change lists and descriptions, technical reports, and actual data. BIM keeps the information for all interface phases in the system, such that all project participants can view the latest information via their own organizational perspective. The general contractor and subcontractors can trace and control the most recent interface information for any interface, change, and conflict in the construction phase. Changes and interfaces for any interface phase can be updated quickly and made available to each participant.

Interface Management

Interface management is now recognized as the most critical strategy in process management. Interface management is the systematic control of communications that support process operations (Healy, 1997). As an outgrowth of the influences of system-based thinking in project management, IM addresses project complexity and allows for a dynamic and well-coordinated construction project system (Chen et al., 2007). Despite the many academic studies and extensive discussion in practice, construction professionals lack systematic approaches for managing interfaces during construction and assembly phases (Evans, 1997).

All interface events can be identified and tracked in construction projects to improve the construction process and minimize deleterious change. Only limited research has examined interface management issues in construction. (1) Chan (2005) suggested an interface management framework for China's BOT projects. (2) Chua (2006) proposed a work-breakdown structure (WBS) concept for improving work interface management. (3) Al-Hammand (2000) proposed 19 common interface problems identified based on four categories (financial problems, inadequate contract, specification, and environment problems). (4) Pavitt and Gibb (2003) used CladdISS tool to process maps, action plans, management strategy, and interface management. (5) Chen (2007) illustrated how IM can help application of agile project management and lean construction. (6) Chen (2008) presented a multi-perspective approach for systematically exploring comprehensive cause factors affecting various interface issues.

Morris (1983) argued that two interfaces exist, i.e. static interfaces and dynamic interfaces. Stuck-enbruck (1983) identified three main interfaces -personal interfaces, organizational interfaces and system interfaces. Pavitt and Gibb (2003) proposed three main interfaces -physical inter-

Table 1. Description of construction interface management phases

Phase	Description
Interface Finding	Interface finding is the checking for new or existing interface events related to projects.
Interface Identifying	Interface identifying ensures that the identified interfaces are consistent with all relational participants.
Interface Communicating	Interface communicating is the process of requesting, responding to and tracing processes among relational participants.
Interface Recording	Interface recording is all information recording processes related to the identified interface event
Interface Closing	Interface closing is the final closing action when the interface event is reconfirmed without further identification or tracing.

faces, contractual interfaces and organizational interfaces.

This study uses three main interfaces during the construction phase -connection interfaces, schedule interfaces and organizational interfaces. Connection interfaces are actual physical connections between two or more construction elements or components. The schedule interface comprises related time and sequencing notes for grouping work elements based on contractual requirements. Organizational interfaces consist of the interactions and responsibilities between various horizontal and vertical participants in a construction project. Moreover, this study proposes an IM procedure that includes interface finding, interface identification, interface communication, interface recording and interface closing, based on literature review findings and interviews with various construction experts. Each phase is briefly outlined in the following descriptions (see Table 1).

The CAD-Based Mapping Approach

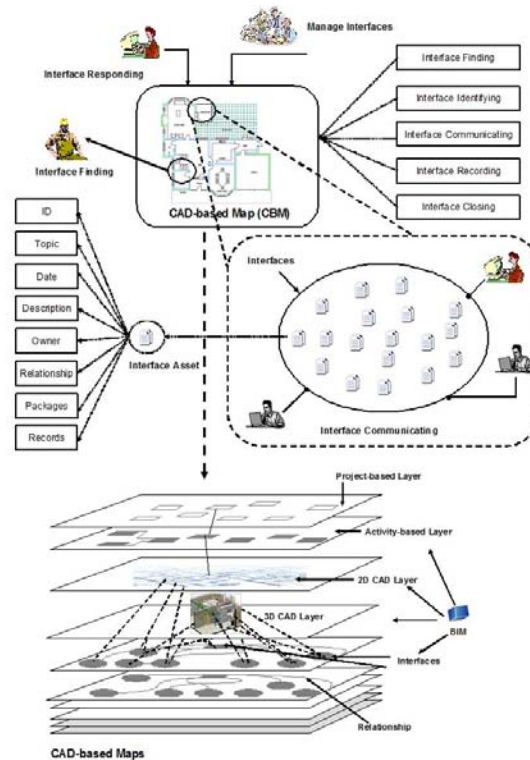
The proposed CAD-based Mapping (CBM) approach is designed for 3D illustrations that easily link interface events and with project activities. The key purpose of the CBM approach is to simplify and share combined interface information for construction project management. CBM is one of core solutions in the CBIM system. The role of CBM in the CBIM system is to save the

interface information in the 3D environment. The interface information submitted by project participants can be identified, tracked, managed, and solved during construction projects when using the proposed CBM approach. The most recent interface problems and solutions can be acquired from participating engineers, and then shared and saved as CAD-based map units in categories for efficient collection, management and future reference.

The proposed CBM approach is novel and specific to construction IM. The CAD-based Map (CBM) can be defined as a diagrammatic and graphical representation of relationships, linking between interfaces and attributes of a 3D CAD. The CBM approach mainly provide assistance to users for easily obtaining the interfaces. The primary advantages of the CBM technique are as follows: (1) the 3DCBM approach provides simple and clearly represented interfaces in the CBIM system through the BIM approach; (2) the CBM illustrates available interface events for activities in construction projects using 3D illustrations; (3) the CBM can freely extend interface relationships for 2D and 3D graphic representations; and, (4) the CBM helps users identify the most critical interface events and activities relevant to a particular project.

The CBM are designed to be easily integrated with 3D CAD illustrations and construction interfaces and changes. Figure 2 illustrates an

Figure 2. The concept and framework overview of CBM



overview and conceptual framework of a CBM utilized in construction IM. Interfaces generated by activities in previous projects can be collected, managed and applied to future projects. The interfaces acquired from participating engineers can be accessed and saved for efficient collection and management.

CAD-based Maps have multiple levels and are constructed from variables that can be broken down by, decomposing activity units into CBM units, that store the identified interface. The project-based unit is modeled as the first layer in a CBM; the activity-based unit is modeled as the second layer; the third-level layers model the 2D CAD units (2D illustrations); the fourth-level layers model the 3D CAD units (3D illustrations) through BIM; and the lower-level layers model the interface event units (interface illustrations). The CBM structure allows users to access interface information stored in the layers based on attri-

butes and types of interface problems. Interface information stored in the 3D CAD units includes both interface problems and solutions. Interface problems may be interface event topics, interface event descriptions, descriptions of problems faced or interface event attachments (e.g., documents, reports, drawings and photos). Interface solutions can include descriptions of problems faced, explanations of problem solutions, suggested solutions and history of previous solutions. Additionally, a CBM allows users to review available interface event maps for a selected project to enhance IM effectiveness. Interface problems and interface solutions in CAD-based IM are associated with projects, activities, people and organizations. Identifying the relationship between identified interface events and all interface information is essential for managers and engineers when tracking and managing construction project interfaces.

ACBM has components and procedures based

on construction IM. The CBM components and procedures are described as follows. The proposed CBM has nine components. These nine components are as follows: interface event topic; interface event date; interface event description; interface event owner; interface event relationships; interface event responses; interface event ID; interface event packages; and, interface event record. Each CBM component is saved through BIM in 3D CAD units. Information sharing via the web-based platform in this study is achieved by allowing access to the central project database in which the BIM is stored. Information sharing via a central database allows multiple applications to access product data and use database features such as query processing and business object creation. Thus, participants can use different formats and maintain data consistency during the construction phase. Portals, which are unique and sometimes complex tools introduced in the late 1990s, are websites that collect information related to specific topics and provide users with access to related services and information sources. When a portal is utilized, all project-related information in a centralized project database can be obtained via a web interface.

Building Information Modeling

Building Information Modeling is a digital tool that supports continual updating and sharing of project design information (Gould and Joyce, 2008). Originally implemented in Autodesk, BIM is extensively adopted in industry to describe 3D, object-oriented CAD (Eastman *et al.*, 2008). While facilitating integration, interoperability and collaboration, BIM enables users to integrate and reuse building information and domain knowledge throughout the lifecycle of a building. However, BIM in this study facilitates interface management, interface information sharing and exchange for IM during construction. Among its several definitions, a building information model (BIM) refers to a computable representation of

all physical and functional characteristics of a building, as well as related lifecycle information, subsequently forming a repository of information for building owners and operators throughout the lifecycle of a building (Renaud *et al.*, 2008). BIM has three main features. The first feature is it can be stored in databases to facilitate collaboration. The second feature one can manage changes throughout BIM databases such that a change in any part of a database affects all other parts. The third feature the BIM can capture and preserve information for reuse by adding industry-specific applications (Renaud *et al.*, 2008). The National Building Information Model Standard (NBIMS) categorizes BIM based on three axes, i.e. product, collaborative process, and facility (NBIMS, 2007). The product axis is an intelligent digital representation of a building. The collaborative process axis encompasses business drivers, automated process capabilities and open information standards utilized for information sustainability and fidelity. The Facility axis focuses on information exchange, workflows, and procedures to make repeatable verifiable and sustainable information-based environments throughout a building lifecycle (NBIMS, 2007).

There are many previously research publications regard to BIM issues in construction. (1) Khanzode (2008) proposed the challenges the teams addressed and the specific benefits that the team accomplished using virtual design and construction and BIM tools for the MEP coordination process. (2) Vanlande (2008) proposed an extension of the BIM technology to manage information during the entire lifecycle of an AEC project. (3) Goedert (2008) extended BIM technology into the construction process and to create a single repository of facility data for the owner. (4) Succar (2008) explored publicly available international guidelines and introduced the BIM framework, a research and delivery foundation for industry stakeholders. (5) Kaner (2008) illustrated how BIM can help managers of structural engineering firms to avoid some of the pitfalls

of replacing 2D CAD practices. (6) Tse (2005) presented the primary barriers and recommends for the use and application of BIM technology in construction industries.

The application of BIM exists in the design and construction phase in Taiwan. Notably, project participants can utilize BIM during the construction phase to access project updates and rapidly update digital records of tasks completed during construction. BIM includes components, details, quantities, and interfaces to data. Additionally, a general contractor and subcontractors can easily access current conditions for interfaces and changes via BIM owing to its ability to store all change and interface information in the construction phase. Moreover, BIM can also be viewed as an attitude that facilitates the sharing of electronic information for interfaces and changes among all project participants. Furthermore, in addition to storing original, actual, and modified interface information, BIM encourages all project participants to assess the latest information from their own organizational perspective.

Development of the CBIM System

In this study, the BIM is interpreted as an information model in the CBIM system. The primary purpose of this study is to extend BIM into the construction phase and to create a single repository of interface data for the general contractor and subcontractors. The objective of the study is to use BIMs to capture and store interface information including interface events description, people, interface records, and interface report in the CBIM system.

The developed CBIM system runs on Microsoft Windows 2003 software with an Internet Information Server (IIS) as the web server. The CBIM system is developed using Java Server Pages (JSPs), which are easily incorporated with HTML and JavaScript technologies. The program code is developed using C language and AutoCAD

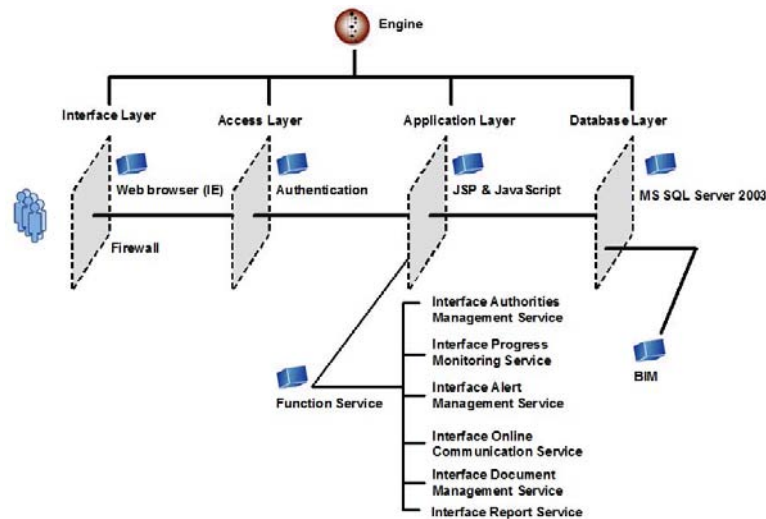
Visual Basic Application (VBA), which are integrated to CBIM system. The entire construction CAD files are developed using AutoCAD Revit Software. All the necessary information in BIMs can be exported to an ODBC database. The CBIM system server supports four distinct layers i.e., the interface, access, application and database. Each layer has its own functions (see Fig. 3). The interface layer defines administrative and end-user interfaces. Administrators control and manage information via, the web browser or a separate server interface. The access layer ensures system security by restricting access via firewall services and system administrative functions. The application layer defines various applications for acquiring and managing information. These applications offer indexing, interface mapping, full-text searching, collaborative work and RSS functions. The database layer consists of a primary Microsoft SQL Server 2003 database. The web and database servers are on different computers. Firewall and virus protection software can be used to protect the system database from attacks and intrusions. The CBIM system allows project category searches, keyword searches and activity category searches. One significant feature of the proposed CBIM system is that it allows individual engineers or all engineers in an enterprise to request assistance in interface/change sharing and exchange by submitting a request through the BIMs. Users can select the 3D CAD unit from the CBIM to request assistance or send an interface problem directly to the CBIM system to request further interface-related confirmation or contact.

The following section demonstrates the implementation modules of the proposed CBIM system.

Interface Authorities Management Module

The interface management module is an access control mechanism which prevents unauthorized

Figure 3. The concept and framework overview of CNIM system



users from entering and/or retrieving sensitive interface information. The CBIM system requires that all relevant project teams register. To register, users must provide a unique User ID and password for authentication purposes. As the interface information or reports required by different project participants vary, general contractors are allotted different access rights and authorities.

Interface Progress Monitoring Module

This progress monitoring module enables project participants to track interface events. Additionally, project participants can share information regarding the current progress or status of selected interface events. The progress monitoring module has an easy access option allowing participants to trace and record all information related to interface events through the BIM. Additionally, project participants can share the latest interface information and trace all historical records of interface problems and solutions.

Interface Alert Management Module

This module helps general contractors, subcontractors and suppliers observe the impact of the most recent interface information through the BIM. Importantly, the dates related to notification of interface information are recorded systematically; thus, project participants can easily determine who is responsible for specific interface events. Furthermore, this module provides convenient access and a push-based function to help engineers respond to certain situations before interface events are tracked and before others respond.

Interface Online Communication Module

This communication management module is an interface event-based communication platform similar to instant messaging or email which enables online “threaded” communications. Members associated with specific interfaces can post questions, responses and comments, thereby generating a permanent record of discussions regarding specific issues. For sensitive topics, the discussion can be restricted by using a secure password.

Interface Document Management Module

The document management module enables users to directly download electronic documents via the CBIM system. This module has a “search” function for easy search and retrieval of information. Most uploaded files are automatically converted to PDF files by the CBIM system. This process allows participants to manage, track and organize these files from a central location. This feature also allows participants to determine when and by whom the files have been accessed, downloaded, edited or uploaded.

Interface Report Module

Users can easily access the interface report module to identify their needs and analyze interface information according to their requirements through the BIM. All interface results can be presented in the CBIM system or extracted using commercially available software (e.g, Microsoft Excel). Authorized records are maintained by contractors, subcontractors and suppliers and can be extracted, summarized and reported.

The proposed CBIM system was utilized by an 8-month Taiwanese construction building project to verify the efficacy of the proposed methodology and demonstrate the effectiveness of sharing interfaces during the construction phase. All engineers were encouraged to collaborate and communicate interfaces via the CBIM system. The case involves a contractor with 15 years of experience in construction building projects in Taiwan. Furthermore, the general contractor want to take full advantage of interface management to avoid rework, time wasting, and financial exposure in the project. Therefore, the contractor has encouraged all participants to use the CBIM system and apply interface management to effectively manage interfaces.

The CBIM system was then applied in a Taiwan construction project to verify the efficacy of the

proposed methodology and to demonstrate the effectiveness of interface management during construction. The case study was a construction project with approximately 1769 scheduled activities. Moreover, all engineers were encouraged to track and handle the interfaces via the CBIM system. One significant function of BIM is to support collaboration and communication regarding construction interfaces in the case study. During the construction phase, project participants can trace and manage interfaces, changes, and conflicts. All project participants fully utilized BIMs for interface management. The general contractor applies BIM to manage installation of components, elevation of components, and finishes. The mechanical electrical and plumbing (MEP) engineers utilized BIM (i.e. digital) models when working on building heating, cooling, and plumbing subprojects. The subcontractors utilized BIMs to manage subprojects. The general contractor also utilized BIM to plan work in phases and identify construction sequences. Using BIM accelerates quantity takeoff for building work and cost estimating during the construction phase. All subcontractors and those fabricating structural steel can use BIMs to fabricate building components.

During field trials, the verification test assessed whether the CBIM system performed the specified system analysis and design tasks. The validation test selected case participants to use the system, who then provided feedback via a questionnaire. The CBIM system was installed on the main server operated by a general contractor during field trials. The fifteen respondents included two project managers, four senior engineers, three mid-level engineers and six junior engineers; the respondents had 5, 20, 10 and 1 years of experience, respectively. After observing a demonstration of the CBIM system, the respondents were asked to evaluate the system via the questionnaire. A field test was performed over an 8-month period. The total number of interface events in the system was seventy-three with 169 interface event packages after complet-

Table 2. BIM usage evaluation result

The application of BIM	Mean Score
Applicable to Construction Industry	4.4
Applicable to Construction Phase	4.2
Improve Coordination	4.3
Enhance Interference Check	4.6
Reduce Rework Problems	4.6
Enhance Time Saving	4.6
Improve Construction Plans and Sequences	4.7
Enhance Interface Tracking Progress	4.3

Note: the mean score is calculated from respondent's feedback on fivescale questionnaire: 1 (Strongly Disagree), 2, 3, 4, and 5 (Strongly Agree)

ing the project. The interface events included 81 connection interfaces, 52 schedule interfaces and 36 organizational interfaces.

Questionnaires were distributed to assess system functions and user satisfaction with system capabilities. System users were asked to grade system conditions, system function and system

capability on a five-point Likert scale from 1 for "not useful" to 5 for "very useful.". Table 2 shows the performance evaluation for the application of BIM in construction. Table 3 presents the detailed results of the performance evaluation and the general contractor satisfaction survey conducted during field trials.

Table 3. System evaluation result

The functionality of System	Mean Score
Ease of interfaces sharing	4.5
Reliability	4.4
Applicable to Construction Industry	4.8
The use of system	Mean Score
Ease of Use	4.6
User Interface	4.5
Over Information Sufficiency	4.6
Over System Usefulness	4.3
Over Dynamic Respond	4.2
The Capability of system	Mean Score
Reduce Unnecessary Costs	4.1
Reduce Happening Mistake Percentage	4.3
Ease of finding Interface Information	4.7
Improve Communication Problems	4.4
Enhance Interface Controlling	4.5
Enhance Interface Tracking Progress	4.2
Improve Interface Sharing Problems	4.7

Note: the mean score is calculated from respondents' feedback on fivescale questionnaire: 1(strongly Disagree), 2, 3, 4 and 5 (Strongly Agree)

The CBIM system provides solutions to interface-related problems, and supports all interfaces and changes during the construction phase. The CBIM system assists engineers in communicating interface and event information during a project. The primary advantages of the CBIM system, based on questionnaire results, are as follows. (1) The CBIM system enables project managers to trace and manage interface information and events during the construction phase (89% agreed). (2) The CBIM system enables participants to collaborate and communicate interfaces and changes through a CBM (88% agreed). (3) The CBIM system enables participants to find the identified interfaces and changes to solve in advanced (91% agreed).

Questionnaire results indicate that the primary advantages of the CBM in the system are as follows: (1) The CBM provides clear 3D representations, thus identifying interface information and events relevant to tasks and projects (93% agreed); (2) The CBM clearly identifies available interface information and events when requested for a current project (86% agreed); and (3) Users can trace interface information and events easily and effectively (92% agreed).

The application of BIM based on questionnaire results has the following advantages: (1) the BIM generates accurate and consistent 2D drawings with interface reports, thus identifying interface information and events relevant to tasks and projects (90% agreed); (2) the BIM easily provides automatic corrections and notices when interfaces and changes are made to a current project (81% agreed); and (3) the BIM integrates with interface and change management easily and effectively (87% agreed).

The following recommendations are based on received feedback. (1) Policy and strategy must be considered to encourage use of BIM because effective use requires that changes be made to almost every aspect of a firm's business. (2) Further effort is required to update interface information related to various interface events in a project. (3)

Senior engineers and experts require substantial time and assistance to edit interface information. (4) Most senior engineers cannot edit their interface information without assistance in typing. (5) Initial case study results should be used to educate potential users about the adoption of BIM software, and additional staff training is needed.

4 FUTURE TRENDS

BIM applications continuously evolve owing to its increasingly apparent technological benefits and increasingly stringent market demands with respect to productivity, costs, and time for the construction lifecycle. In sum, BIM has pioneered to provide the collaborative environment in the construction management. Restated, while encompassing geometry, related information, construction quantities and details, BIM represents a novel approach for collaborating with project participants by adopting a model based on reliable related information to facilitate efficient decision, speed construction operation and improve performance. While aspiring to streamline the efficiency of construction projects, BIM enhances the operation process in terms of project team communication and integration. The application of BIM has the potential to significantly provide detailed data and information to access for project participants involved in the any phase of construction project lifecycle.

5 CONCLUSION

This study presents a novel CBIM system for all project participants as an interface-sharing platform. The CBIM system illustrates interface events, problem descriptions and solutions thought the CBM in 3D representations. BIM is a highly promising means of enhancing interface management during the construction phase of a project. Collecting interface events and problems

stored using BIM concept and models in construction projects allows managers and participants to trace and manage the most recent interfaces and changes to current information. The BIM approach generates accurate and consistent 2D drawings with interface reports, thus identifying interface information and events relevant to tasks and projects. Additionally, BIM provides automatic corrections and notices when interfaces and changes are available. The content of BIM in the system includes specific problem solutions, and supports all interfaced events and experience from projects. Although effort is required to update interface events for various problems and solutions, the proposed CBIM system benefits IM by (1) providing an effective and efficient platform to assist IM tasks in a 3D CAD environment, (2) all graphical views, design documents and schedules automatically reflect this change when a change is made to the building model, and (3) facilitating implementation of a web-based interface management system for construction projects.

Notably, BIM integrates 2D and 3D objects comprising a building design by incorporating external factors, e.g., interface events, interface descriptions, and interface conditions, into a virtual construction database that functions as the sole integrated source for all construction project-related information. This information is compiled in an integrated database, which subsequently contributes to all construction project-related interface data and information. Effectively utilizing web technologies and BIM during project construction phase allows project members to identify, monitor, coordinate and access interface events for future A/E/C projects. Case study results demonstrate that the effectiveness of a CBIM-like system for IM by incorporating BIM and web technologies in the construction phase.

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KEY TERMS AND DEFINITIONS

Building Information Modeling (BIM): Building Information Modeling facilitates the

integration, interoperation and collaborative activities in A/E/C.

Interface Management: Interface management attempts to systematically control all communications that facilitate a process operation.

Change Management: Change management addresses how changes within a system or project are managed and controlled manner based on a pre-defined strategy with acceptable modifications.

Web-Based Information Management: A web-based information management coordinates information via a web browser over the Internet or a company intranet. Software applications coded in a browser-supported language, e.g., HTML, JavaScript, and Java, and dependent on a web browser to execute related applications are also involved.

Really Simple Syndication (RSS): RSS easily distributes headlines and updated information to a large number of computer users through software programs that organize promulgated information for easy reading.

Cad-Base Mapping: Cad-base mapping schematically and graphically represents relationships between interfaces and attributes of 2D and 3D CAD presentation.

CAD-Based Interface Management: CAD-based interface management focuses on CAD-applications in construction projects for management purposes in interfaces.

Chapter 8

A Comparative Analysis of 2D Computer–Aided Estimating (CAE) and BIM Estimating Procedures

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ABSTRACT

Most estimators are trained with, and are used to, manual and Computer-Aided Design and Drafting (CADD) two dimensional (2D) drawings. The spatio-temporal limitations of these designs complicate information management, estimators' judgments, speed and accuracy. In addition, conventional estimating practices also need to cater to the nuances of diverse standard methods of measurements (SMM) and unstable market conditions. Building Information Modeling (BIM) promises major improvements that overcome the limitations of conventional 2D methods in both design and construction processes. It provides platforms for value integration, robust information sources, simultaneous access to design database, automated quantification, project visualization and simulation, among others capabilities. These capabilities facilitate accuracy, objective risk assessment, comprehensive information management and early integration of cost management principles during design. Arguably, the uptake of Information Technology (IT) in construction is increasing and this discipline-specific study on BIM highlights its considerable potential for improving professional service delivery. Consequently, the integration of BIM and process driven Computer-Aided Estimating (CAE) tools and applications provide robust opportunities for process improvement in Architectural, Engineering, Construction and Facilities Management (AECFM) industries. As part of a research initiative, this chapter reviews the impacts of BIM on cost

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estimating procedures. In a bid to develop a conceptual framework for underpinning BIM-propelled changes in estimating practice, CAE applications are categorized and compared. Moreover, some features for producing automated quantities from BIMs are compared with provisions of SMM used by estimators. The research concludes with recommendations about the capacity of BIM to revolutionize construction procurement and systems.

1 INTRODUCTION

Variability in the quality and accuracy of construction estimates present distinct challenges in the construction industry. This is also true for cash flow management. Professional opinions about estimating and cash flow management are often characterized by uncertainties, errors, conflicts of interest, omissions and other inadequacies (Tse, et al. 2005). Evidence abounds in literature regarding the impact of these problems on the image of construction project performance (Kometa, et al. 1995; Egan 1998 ; Hansen and Vanegas 2003; Kashiwagi and Richards 2004 ; Ankrah and Proverbs 2005). Issues like construction contract fraud, cost overrun and professional inadequacies have recently been prime concerns of governments and media discourse (Priemus 2004). This has resulted in various actions. For example, to alleviate the impacts of such challenges on national and territorial economies, the Honk Kong Housing Authority (HKHA) (2000) and Egan (1998) have suggested that it is necessary to develop realistic frameworks to restore public confidence in the industry. This is necessary if construction is to maintain its pride of place as a 21st Century procurement system driven by digital technology innovations.

Overcoming the effects of inefficient construction estimating procedures is an Achilles heel of the industry. This is because conventional design systems are mostly driven by geometric data only (Penttilä, et al. 2008). Chains of evidence from industry reports on the geometric limitations of manual and 2D CAD conventions indicate that these tools are vulnerable to omissions, conflicts, uncertainties, information dissipation and frus-

tration of work relationships (Bertelson 2003; Davison 2003; Gorse and Emmitt 2004 ; Acharya, et al. 2006; Abd El-Razek, et al. 2007). Olatunji and Sher (2009a) have related the impacts of these limitations to the sufficiency of constructed facilities in terms of their buildability, constructability, sustainability, energy sufficiency and other indices of project feasibility. Other reports have also argued that the processes and procedures of designing, estimating, planning and controlling projects could be jeopardized because of conflict between drivers of value and methods of expressing design information in conventional manual and 2D CAD systems (Gould 1998 ; Poon 2003; Kashiwagi and Richards 2004 ; Gruneberg and Hughes 2006).

Consequently, the industry is in dire need of systemic improvements which render stakeholders more accountable for their actions and inactions. Interestingly, from an estimating perspective, the industry is familiar with manual and computer-aided estimating (CAE) procedures, to which a new dimension is being added - that of Building Information Modeling (BIM). Whilst some reports argue that estimators are subjected to some tedious energy-sapping procedures that compel them to spend more time on manual estimating than on CAE methods, the accuracy of estimates generated using manual processes leaves more to be desired (Sher 1996; Endut, et al. 2005). Although, Ogunlana (cited in Lowe 1998) argues that the reliability of estimators' judgments is more likely to improve as the quality and quantity of their experience improves, emerging indications show that the industry may no longer be at the mercy of human manual limitations. Rather than

exacerbating systemic problems (which may be influenced by estimating errors, omissions, subjective judgments and listlessness) there are lessons the industry can learn from other industries which have been radically revolutionized by the adoption of digital technology.

To generate effective estimates, estimators need to calculate proposed quantities of work and project appropriate and accurate costs whilst avoiding trade-offs between risk and value for money. Both variables (i.e. quantity calculation and cost projections) have differing potential to consume time and affect the value of estimators' professional service delivery. However, whilst factors of costing remain stochastic, largely due to uncontrollable market forces, estimators could save time in their calculations of quantities and spend more time on indexing volatile extrinsic variables of costs. To achieve this, Information Technology, (IT) must be adopted and applied effectively. Although IT applications are not new to estimating practice, there is limited empirical evidence justifying the extensive trade-offs between gains from efficiencies of computer-aided estimating and limitations of manual estimating procedures. Williams (2008) and Souza (2008) also reported that the industry has not witnessed major improvements in the accuracy of cost estimating tools and the procedures being used for facilitating value for money.

Some attempts have been made to reduce systemic inaccuracies and inconsistencies in cost estimating processes through the application of information technology. Akintoye and Fitzgerald (2000) observed that the proliferation of estimating software could be misleading and may aggravate the problem. Regrettably, there are gaps between developers' claims about the efficiencies of their estimating applications and their actual capacities in use. Moreover, there are few comparative analyses of existing CAE applications in relation to the fairly radical improvements in design technology and the frameworks for appraising existing estimating practice. Citing Morrison and Seven

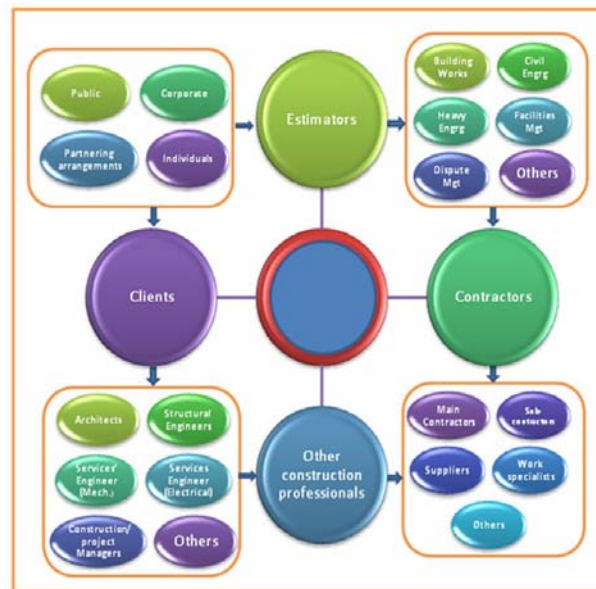
and Ogunlana, Lowe (1998) argues that improvements in implementing systems that predict the costs of construction projects are achievable by focusing on sharing innovative values from other sectors (especially manufacturing); a challenge that the construction industry has grappled with for decades. Therefore, it is expedient to consider the capacities of CAE tools and techniques in improving traditional construction estimating procedures.

As improvements over manual and 2D CAD design systems that are limited to geometric data only, Building Information Modeling (BIM) promises; robust and integrated information, automated quantity take-off, project visualization, less fragmentation of team activities through interoperability, value sharing, integration, networking, effective communication and robust information databases of design components (Langdon 2002; Young et al. 2007; Dean and McClendon, 2007; Gu, et al. 2008). Consequently, there is considerable evidence supporting the rapid adoption of BIM and digital estimating as these approaches promise to positively impact on the future of the construction industry. BIM and digital estimating are not simply effective construction tools; they provide a systemic catalyst for improving major aspects of decision-making, design, estimating, planning and control. The purpose of this study is to review manual and conventional CAE procedures in relation to BIM capabilities. Its objectives are as follows:

1. To compare frameworks for cost estimating using selected two-dimensional (2D) CAE tools with BIM-based estimating procedures, and;
2. To suggest alternative BIM estimating approaches which facilitate compliance with Standard Methods of Measurement (SMM).

This study has four main sub-sections. The first sub-section presents the background to estimating

Figure 1. Typical grounds for defining estimating practice (Olatunji, 2009)



practice and procedures, while the second reviews different approaches and roles of estimating in construction processes. The third sub-section focuses on computer-aided estimating; whilst the last reviews the gap between BIMs, formats and conventional standard requirements on estimating variables.

2 BACKGROUND TO ESTIMATING PRACTICE AND PROCEDURES

Effective processes and procedures of project economics are imperative for the successful planning, construction and lifecycle of any construction project (Grissom 2005). Variables of project economics include cost estimating, planning, control and management of estimating variables. Others include analyses and management of estimated value and facilitation of frameworks for harmonious relationships. Due to the multifaceted approaches in which construction complexities are defined, estimating may mean slightly different things to different people. In some cases,

estimating may be viewed in relation to stakeholders' interests, the professional obligations of estimators, or the methods and fields where it is applied. Figure 1 shows some typical perspectives of estimating practice.

Whilst some estimators' opinions of estimating practices may be slightly different from those of other professionals in the industry (Davis and Baccarini 2004), the opinions of clients may only be limited to the nature of the assignments and the types of projects that estimators are involved in. It may therefore be difficult to generate a perfectly over-arching definition of estimating to satisfy all interests (Micro-Estimating-Systems 2000). Paradoxically, there are informal claims that there is more to the roles of estimators than the industry is aware of; hence conflicting opinions are possible (Nkado 2000; Ogunsemi, et al. 2008).

In a broad sense, estimating involves systematic professional judgments regarding the accurate measurement of quantities of work whilst taking into account associated cost implications. The procedure includes tactical evaluations of inherent risks in ways that show they are comprehensively

considered, quantified and analyzed without ambiguity. This may involve striking a balance between tangible and intangible variables of project costs. The Association for the Advancement of Cost Estimating (AACE, 2003) further defines construction cost estimating procedures as the comprehensive consideration of the stochastic and deterministic variables of a proposed project in a standardized manner. This includes the evaluation of risk (indirect) and direct costs involved in the procurement and application of materials, labour, management and professional services, and the cost of finance and other factors deemed necessary in a project.

Referring to Flanagan and Norman Abdou, et al. (2004) argue that the reliability of construction cost estimates is more susceptible to the amount of external risk involved in construction than to the level of sophistication of tools or techniques used. Poon (2005) also opined that the systemic uniqueness of construction products and allied product development processes could showcase construction as far more risky than other industries. Consequently, estimating efficiency could be dependent on the magnitude of construction risks and uncertainties. Moreover, apart from inconsistencies in the methods and frameworks for generating estimates, the quality and quantity of estimators' experiences are also likely to impact on the accuracy of estimates. Arguably, the quality of information provided in project documents and designs, and the quality of interaction between the project team are also important factors that could affect the quality of construction estimates.

CAD and BIM applications are two successive techniques that are being deployed to redress inadequacies in manual drafting and design methods. However, while CAD drafting applications are limited to two dimensional or three dimensional drawings which are based on geometric-data only, BIM combines both geometric and non-graphic information on design components. Although BIM provides other capabilities, it has certain features that relate to cost estimating. Such at-

tributes include; the automated measurement of quantities contained in BIMs, simultaneous access to design databases, improved frameworks for communication between project teams, project visualization and simulation (Acharya, et al. 2006; Lee, et al. 2006; Dean and McClendon 2007; Gu, et al. 2008).

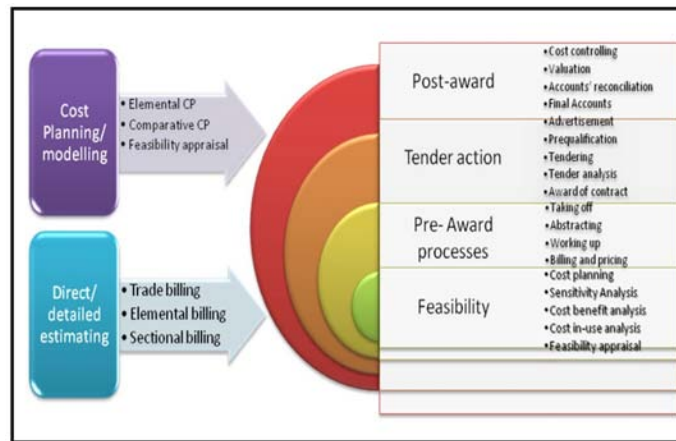
This study aims to explore the relationship between BIM and estimating through its capabilities, such as improved access to project information, improved communication between project team and automated measurement of cost-impacting variables in project models. It is therefore imperative that different construction estimating approaches and roles are reviewed.

3 APPROACHES AND ROLES OF ESTIMATING IN CONSTRUCTION PROCESSES

Accountability is an essential component for any type of construction activity (Hatush and Skitmore 1998). Most clients require comprehensive information on the different economic variables of their proposed project. This is not limited to cost, time, quantity, quality or value estimates. Rather it could extend to being an integral part of the definitive frameworks used to predict the overall feasibility of projects. This may also involve the objective assessment of risks involved in project development and how sensitive project milestones and goals could be rendered less vulnerable. Therefore, depending on the complexity of estimating products desired by clients, the general objectives of estimates include; to extol 'value for money', accountability, equal opportunity, transparency, probity, openness and balance in procurement businesses. Figure 2 provides an illustration of the possible indices of estimating procedures.

On the other hand, to remain in business, contractors and other secondary stakeholders require effective estimating techniques to improve their competitiveness, maximize profits, control costs,

Figure 2. An illustration on possible indices of estimating procedures (adapted from Olatunji 2009)



sustain project management capabilities and simplify project feasibility (Serpell 2005). Attempts have been made to define other roles of estimating. These arguments underpin the implications of several misconceptions about how estimating relates to some of the challenges of the industry (Akintoye and Fitzgerald 2000; Odeyinka, et al. 2008). The roles of estimating in construction include the capacity to facilitate the best price for a project with fairness and respect for the interests of all the parties involved. Arguably, achieving this is very difficult.

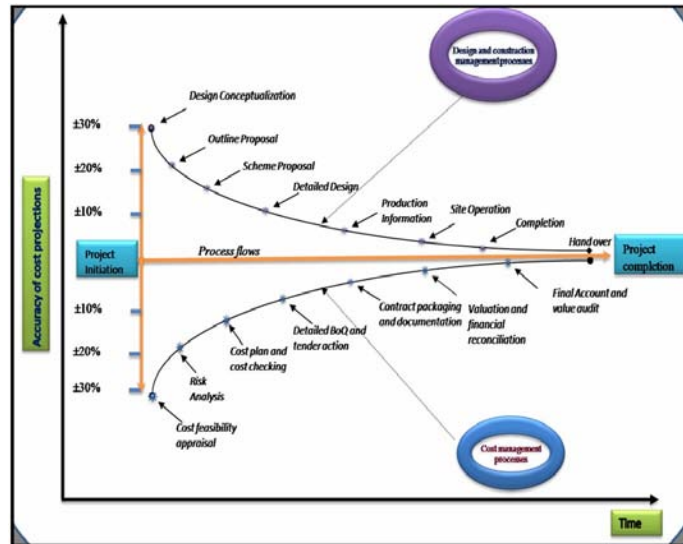
(Gray 1996) has argued that competition has not been the best tool to generate value and fairness for all the parties involved in a project because it is vulnerable to abuse, especially when it is mainly cost-led. Other authors (Lowe 1998 ; Bresnen and Marshall 2000; Abdou et al. 2004; Kashiwagi and Richards 2004 ; Wong et al. 2004) have argued that innovative and integrated design and procurement systems would facilitate openness and trust, protect the ethos of competition, ensure value for money and transparency, and that accountability is not misplaced.

The nature and quality of available information on project components may affect the reliability of cost projections. Estimating approaches range from using approximate quantities to generate

approximate estimates to using more comprehensive project information to generate detailed cost information. The process of generating approximate estimates follows relative modelling procedures whereby cost models are applied to generate conceptual estimates. They are often used when detailed project information is not available. The concept is based on information generated through an analysis of historical data collected from similar projects executed in similar circumstances. This approach is always limited to providing an overview of approximate estimates or cost plans, which can be used to guide design teams within a reasonable range of cost values or limits.

The strength of this technique lies in its flexibility to be tested and refined on an iterative basis. It therefore allows alternative construction techniques to be considered so that work is contained within budgetary limits. Also, it enables designers to design within cost limits and at the same time limit costs to project constraints. The degree of reliability of this method could be about 30 percent more or less in reference to initial projected cost (Cheong 1991; Odusami and Onukwube 2008). This depends on the complexities of the project in question, its location, time, as well as the tools and methods used to develop cost models. Moreover,

Figure 3. Process flows in design, construction and cost management in construction (adapted from Cheong, 1991)



it is often difficult to predict the exact amount of money required to accomplish a given task, using firm cost estimate due to the high degree of variability in market indices and design components. Figure 3 shows the various stages of cost estimation in a typical construction process.

Some reports on the UK construction industry suggest that project economics in construction are largely ineffective (Banwell 1964; Latham 1994; Egan 1998). This could be attributed to weak cost projection frameworks which reflect the unstable and high costs of construction as well as the costs of adversarial complexities in construction interests. Whilst, Gray (1996) queries the fundamental capacities of estimators to significantly reduce the cost of construction, Endut et al, (2005) and Acharya, et al. (2006) have argued that variability in construction costs is largely caused by design inefficiencies and inadequacies in teamwork. Such challenges include; poor integration frameworks, lack of collaboration, ineffective communication, design omissions, design conflicts, poor specifications and negligence or inexperience within the project team.

Construction clients' opinions are the ultimate in construction processes (Egan 1998). However, Kometa, et al. (1995) has argued that it is better to involve construction clients in the construction process than to shift all the risks and responsibilities to consultants, contractors and end-users. Hansen and Vanegas (2003) observe that clients' capacities and keenness to adopt auto-briefing could have a major impact on simplifying project requirements and would sustain an appropriate framework for digital estimating and future technological innovation in the industry. The following section discusses the trends and current capacities of computer-aided estimating systems and their impact on the cost performance of construction projects.

4 COMPUTER-AIDED ESTIMATING (CAE)

The limitations of manual estimating practices are evident in the quality of results they generate. Arguably, the effects of some of these limitations

on cost performance could be very damaging to client interests (Poon 2003). It is therefore necessary that estimators use better tools and techniques to provide time-savings and enhance the accuracy of judgments taken during the estimating processes. However, RiverGuide (2006) argued that artificial intelligence in estimating is an alternative that may not mean an absolute solution to estimating woes.

Although there are many CAE applications in the industry with different capabilities, it is still impossible to generate comprehensive construction estimates automatically without manual input and circumstantial errors (Akintoye and Fitzgerald 2000). Thus, rather than trusting automated results, estimators are likely to be more confident in using their manual techniques and skills. They may also double-check automated estimates to avoid possible complications arising from automated techniques as a result of garbage-in garbage-out syndrome. Consequently, a combination of manual effort and computer use is common in estimating practice.

The goals of the adoption of digital technology and automated measurement in estimating are relative to the desire for improvement in speed, accuracy, interoperability and objectivity in estimating processes. This further enhances the comprehensive capture of all estimating variables without omissions, conflicts and inefficiencies in project documentation (Sher 1996). This is the ultimate inevitable desire of construction clients regarding estimating and construction contract packaging – that project procurement and management processes epitomize comprehensive cost information management systems (Ogunsemi et al. 2008).

Estimators are always under pressure to produce error-free and near-perfect cost information within a limited time during the earlier stages of construction (Akintoye and Fitzgerald 2000). Sommerville and Craig (2003) observed that Electronic Data Management Systems (EDMS) provided an alternative to overcome the limitations

of paper-based information management systems. However, for a long time, clients' have preferred paper-based contract management systems over electronic alternatives in traditional procurement practice (Kashiwagi and Richards 2004; Wong, et al. 2004).

Clients' capabilities and opinions on IT use are different. Whilst some see it as the best way to go in modern times, others may be reluctant as a result of personal limiting factors. Moreover, in certain circumstances, clients might sometimes be vulnerable to choices that do not support the use of Electronic Drafting, Design and Documentation (EDDD). However, notwithstanding the disincentives and inherent challenges from clients, estimators use information technology tools as a major factor to secure market competitiveness and improve professional service delivery. Popular uses of IT include; calculating, automating, analyzing, manipulating and reporting on basic variables of project designs to enrich project information databases. Oyediran and Odusami (2005) and Ugwu and Kumaraswamy (2007) report that the use of IT for estimating both reduces errors and entrenches systemic cost benefits in the long run.

Other challenges faced by estimators, especially contractors' estimators, include time and systemic limitations. They always have insufficient time to confirm and analyze the measured quantities from the Bill of Quantities (BoQs) before taking final decisions on project planning, specific methods and techniques for project execution, and the appropriate cost implications for their commitment on any projects. Moreover, construction data could be multivariate and complex. Hence, a considerable level of IT sophistication is required by contractors to effectively process data regarding cost management on different parts of projects; many of these data usually extend beyond intrinsic the functions of estimators. Quick access to information databases and compatibility of data sources and formats are imperative to the quality of information relied upon for decision making. Therefore, EDMS does not only enhance the tech-

nical and management capabilities of contracting firms, they improve communications and save costs (Sommerville and Craig 2003).

Over time, IT use for estimating has not remained static. However, it is relative to changes in design technologies. Langdon (2002) reported that the use of CADD could be traced to 1930s – before the advent of the computer revolution. However, the adoption and use of digital data in construction, especially for estimating processes, was not very popular in the industry until 1980s and 1990s (Sher 1996; RiverGuide 2006). Initially, estimators grapple with the constraints of capturing or calculating quantities and costs from different sources, forms and formats. These data when captured are used for project planning and cost management.

For business reasons, contractors always have causes to challenge the accuracy, appropriateness and comprehensiveness of client-estimators' judgments. This is because certain estimating procedures may protect the client at the detriment of contractors. For instance, project elements are measured 'net', while site situations imply that they are applied 'gross'. Such elements include; site preparation, woodworks, roof-works, pipe-works and other work items where substantial amount of resources could go into concealed works, such as lapping, off-cuts and wastes. Omissions and these nuances in measurement techniques may trigger confrontation regarding variations and other forms of claims.

To avoid doubts, contractors may confirm and adapt or extract computed quantities from tender document in hardcopies into regulated formats for analytical purposes, comprehensive documentation and project planning. Until recently, the use of Optical Character Recognition (OCR) technology, document imaging and digitization techniques are the most common options. (Sher 1996) illustrates the 'pros and cons' of these systems. Arguably, some of the unique problems of these technologies are yet unresolved. The costs of software, hardware and personnel to drive them are not

likely to suggest significant economic benefits for contractors, compared to the cost benefits of other emerging technologies and the interests of clients, which could be cost-led rather than being value-led.

The adoption computer-aided estimating (CAE) has witnessed marked radical changes recently. Compared to some decades ago, the cost of computers has reduced and the frameworks for using CADD have improved and increased significantly. This has improved opportunities for learning and skill development on IT applications in different spheres of construction. Innovation and value integration within construction project teams have also improved. Before the proliferation of CAE applications in the last century, Spreadsheets (such as *Lotus 1-2-3*, *Apple-Macintosh*, *VectorTM*, *Microsoft Excel* and other related application) are prominently used for estimating. Although Sean (2008) argues that other applications can perform more advanced functions, Microsoft Excel remains the most popular CAE tool in the industry. Apart from its integrated capabilities with other office, desktop and other dedicated applications, many estimators use Excel because of its unique power of *functions*. It is easy to use, highly flexible and has more enduring value than other software applications. Thus, it has been an important baseline in the development of contemporary CAE applications.

Aside from the basic attributes of computing and merits over other applications, Excel has some limitations. Data must be inputted before basic calculations are automated. Following the *garbage-in garbage-out rule*, the accuracy of an estimate largely depends on the appropriateness of command and accuracy of inputted data. Arguably, the data inputting processes are not free from errors - there could be typographical errors, omissions, application errors, such as *circular redundancy* and such like. Except for cases where databases are linked, there could be many complications when basic variables, such as the calculation of *Quantities* and *Rates*, are not automated. This is

because separate bases are needed for processes, such as *taking-off*, *abstracting* and *working-up*, before standardized data on quantities can be fed into spreadsheets. These processes are vulnerable to errors as much as they are manually driven.

This constraint is a major contrast to what is obtainable in some dedicated CAE systems. Among other capabilities, these applications allow cost and resource data to be primed into production data. Evidently, specific capabilities vary according to types and groups of estimating applications – this will be expatiated later in this chapter. Whilst some are limited to a massive input of data (e.g. BuildSoft, WinQS, MS Excel), others such as CostX, Timberline, MasterBill, Carlson and QSCAD) can capture quantity data directly from drawings. Some applications (e.g. Sychro and Primavera 6) can also extrapolate into other functions beyond cost estimating. Therefore, estimators might no longer be justified by their confidence in manual skills and may use the limitations of some applications as reasons for not adopting the more sophisticated IT tools. As digital information processes are becoming more popular, software developers have continued to develop custom-made software applications that address the expectations of estimators, such as mobile technology, improved speed, accuracy, flexibility, integration and automation, among others.

The limitations of the *Standard Methods of Measurement* (SMM) are part of estimating challenges. Estimates are usually based on rules and standard phraseologies are prescribed in SMMs to provide clear and comprehensive descriptions of work items. Although, SMM is expected to provide common ground for documentation in estimating, nuances arising from its use are enormous. While countries still use SMM 1 without minding its limitations, the UK construction industry is currently using SMM 7 published since 1998 by the Royal Institution of Chartered Surveyors (RICS). Furthermore, SMM 8 is underway. Australia is still using SMM 5 (AIQS 1990). Although there

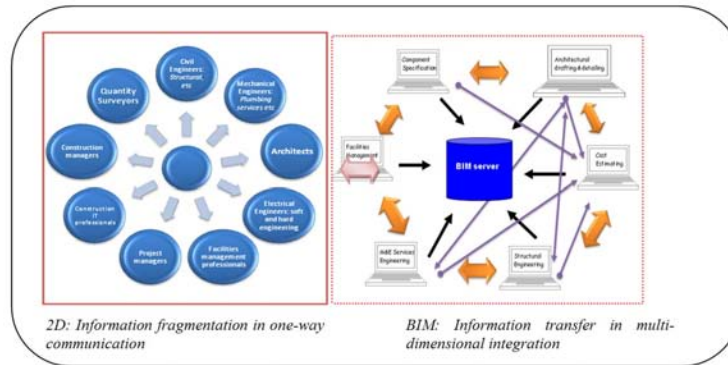
are separate models for building, civil engineering (e.g. CESMM 1 – 6) (ICE 1991) and heavy engineering projects (e.g. HESMM 1), there are other models that integrate both building and engineering standards (e.g. BESMM 1- 3) (Davison 2003). Therefore, while different countries implement separate models of SMMs, all with different high-points and weaknesses, there is the need to define and adopt strategies for harmonization and universal use.

Until the recent adoption of 3D technology, estimating procedures for construction works were largely based on 2-Dimensional (2D) drawings. This format conceptualizes design as a tool for generating construction products based on basic geometric data. However, 2D drawings are limited to providing rigid features like lines, arches and symbols. Evidence from industry reports shows that geometric data drawings do not interfere with the fragmentation processes of conventional design systems (Maher 2008; Gu, et al. 2008). They also lack adequate capacity for the integration of values and robust information into design model databases (Tse, et al. 2005; Häkkinen, et al. 2007). A new technology – Building Information Modeling (BIM) - promises major improvements on the limitations of 2D. The following section reviews the influence of BIM on computer-aided estimating

5 THE IMPACTS OF BUILDING INFORMATION MODELING (BIM) ON ESTIMATING

Several authors have defined BIM (Tse, et al. 2005; Aranda, et al. 2008; Aranda, et al. 2008). These authors argued that BIM means different things to different people. However on a generic level, BIM could be defined as an integrated repository for digital information on tangible project components. Rather than rendering designs in 2D or 3D with lines, arcs, splines and other rigid “unintelligent” features, virtual objects could be used.

Figure 4. Transition of information flow from fragmentation in 2D to BIM's integrated system



Object-oriented designs enhance productivity and creativity in design processes through simultaneous creation, access, management, storage, use, update and sequencing of both geometric and non-geometric data to simplify project life-cycle information management.

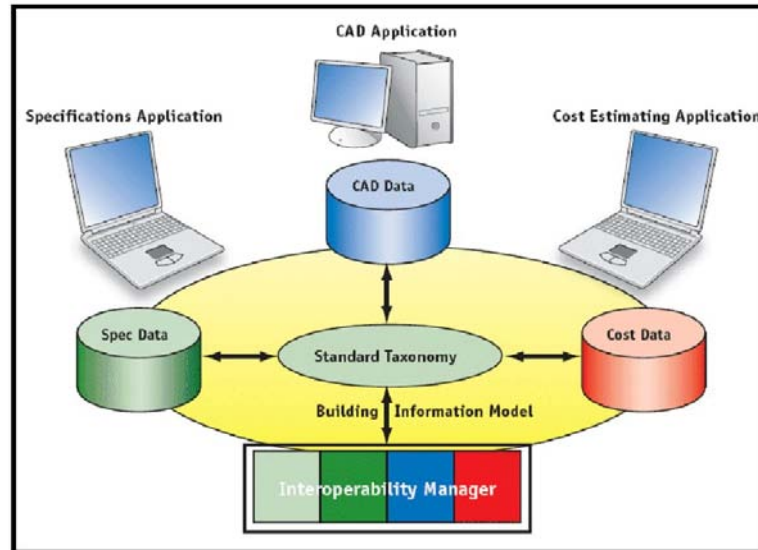
BIM also allows project teams to share data using different applications. In this way, conflicts and insufficient information can be minimized in design processes. While 2D CAD does not interfere with conventional fragmentation in the construction process, BIM facilitates thorough integration through collaboration, digital communication, robust information and value sharing. Evidence from previous reports indicates that these capabilities are significant incentives for effective estimating processes (Tse, et al. 2005; Acharya, et al. 2006). Figure 4 illustrates changes in information flow from conventional 2D to integrated information flow in BIM. reviewed the benefits of BIM adoption in the construction industry, as the industry is transiting from 2D, and its limitations, to BIM

Considering BIM capabilities, many researchers and industry practitioners are currently focusing on its prospects across different construction disciplines. Some of the areas that are receiving attention include how to improve the slow pace of BIM adoption, and inter and intra-discipline

understanding and interpretations of BIM impacts. Gu, et al. (2008) suggested that sustaining these attempts underpins and reinforces BIM's capacity to revolutionize construction procurement. However, BIM is yet to achieve sufficient frameworks for managing fully integrated digital information across disciplines. Figure 5 illustrates the partially integrated relationship between CAD, specification and estimating

Dean and McClendon (2007) concluded that some of the goals of deploying BIM are still vulnerable to certain complications arising from ambitious integration and contrast between model information and existing standards. For instance, (www.digitalalchemypro.com) claims that BIM generates automated quantity take-offs, cost estimates and project scheduling. However, there is no evidence indicating that the automated quantification and cost estimating facilities in BIM-model formats follow prescribed standards in SMM. While this limitation might have major psychological implications on some estimators, conflicts between automated information in models and existing estimating standards could damage the bottom line – responsibility, accuracy and harmony between stakeholders in the construction processes. Appendix 1 shows typical BIM-models of building components, automated quantity measurement format and conventional

Figure 5. Taxonomy of CAD, specification and estimating applications (adapted from, Dean and McClendon, 2007)



estimating variables. To avoid this, estimators need to sort-out what they need from information databases.

BIM envelops the technologies used to manage repositories of digital information. These technologies are targeted at improving design, engineering, estimating, construction planning and co-ordination, and facilities management. BIM promises major impacts on estimating practice in some tangible ways. However, estimating practice and procedures still struggles under the limitations of 2D design conventions as a result of the intra-discipline constraints and challenges that are associated with the slow adoption of BIM. Whilst estimating practice and procedures are increasingly being pressured by errors, inaccuracies, omissions and ethical flaws, there are indications that BIM could overwhelm these challenges in several ways. Some of the capabilities estimators would find very helpful include automated quantification, robust information that underlie models, project visualization, object model spatiality, photo-real presentation and communication between project teams.

Although there are positive indications that suggest BIM adoption would improve, some of those capabilities BIM promises are not yet realistic in estimating. To overcome this challenge, model development should underpin, rather than complicate, existing standards. Firstly, BIMs could be developed according to estimating processes based on activity-based procedures rather than being limited to the product information that object models usually contain. Moreover, estimators are used to sorting cost sensitive information according to trades, elements or building stages. This could be time-consuming, complicated and tedious in BIM. When such information is compiled, it could contract provisions made in meta-data models and this may further affect the purposes BIM is set to achieve.

Some of the problems of existing method-based estimating procedures are associated with the regulatory, circulation and cultural challenges of institutions to explore or maintain constant possibilities of improvements in the system. However, BIM transcends these limitations and could provide a medium to alleviate some of the

Table 1. Categories of estimating tools and applications

Category	Tools and applications	Capabilities
Manual process	Paper-sheets: Dimension sheets, billing sheets etc Scales, Digitizers, OCR etc	Support keenness Catalyzes experience
Partly automated application	Spreadsheets-based: MS-Excel etc Digitizers, OCR, Vector, Apple Macintosh, Buildsoft, WinQS, Synchro etc	Flexible Easier May relate with common applications
Geometric data Auto-capture applications	MasterBill, QSCAD Timberline etc	Fast Auto-captures geometric data from designs Fully integrated with billing Auto-report
Integrated applications	Primavera, Construction Computer Software (CSS), MS Project etc	Combines estimating with planning Auto-generates Illustrate graphical analysis
Project specific	Carlson (CVE) etc	Dedicated applications for specific project Could take-off and bill complete Fully integrated with designs/GIS graphics
Pro-BIM applications	CostX, Inovayya, Tocoman, CRC estimator, Winest etc	Auto-captures geometric data from designs Can relate with BIM Integrated with design Flexible

concerns about existing methods. As much as near-perfect relationship exists between the design and estimating team, the underlying information on models could contain less conflicting data such that could be adopted as unifying prescription for setting design data in the industry. Moreover, as BIM adoption improves, there is likely to be steady growth in construction technology, while the systemic complexities of BIM continue to be simplified in the process.

The relevance of BIM in the future of the construction industry is an issue that concerns all construction professionals. It will provide avenues for training on current roles of information technology, teamwork, innovation, value-sharing, creativity and improved service delivery. This is necessary to spur the spontaneous, simultaneous and effective change promised by BIM and most importantly, to bridge the gap between concerns, generations and cultures. However, if this need is not properly taken care of, there could be far reaching effects on the industry - as stakeholders are liable to delineate the construction market

across the technological divide. In other words, while those who believe in their manual skills and regulated conventions feel convenient not adopting major changes due to systemic disincentives to training and development, others working mainly with geometric-data based CAE could maintain their status quo while the industry is yet to adopt a rapidly emerging new discipline in BIM estimating and management. The bottom line however is that, arguments about improvement in service delivery could remain issues of professional interest rather than addressing clients' desired interest in meeting project goals. To initiate procedure for implementing BIM estimating, it is necessary to compare the framework of existing CAE applications with BIM properties. Table 1 compares the categories of estimating tools and applications currently in use in the industry.

Some estimators are reluctant to adopt CAE applications – hence they are addicted to the use of manual tools like dimension and billing papers and scales. Many reasons could be responsible for this, which could include training background

and confidence in manual skills. Some are also discouraged by complications that may arise from incorrect results triggered by faulty commands and defaults. Also, accidental loss of data and insufficient incentive from clients may discourage some estimators.

From Table 1, Category 1 of estimating applications includes applications that estimators extensively input data from drawings to generate measured quantities. Such applications include WinQS, BuildSoft and MS-Excel. These applications are flexible, simple to use and could relate with other desktop applications. Category 2 includes applications those that automate measured quantities from 2D CAD. Applications in this category include MasterBill and QSCAD. They are fairly sophisticated and fully integrated. They are also very flexible and can generate comprehensive reports at minimal efforts.

Category 3 includes estimating applications with integrated capabilities that extended to project planning, cashflow analysis and project monitoring. Primavera and Construction Computer Software (CCS) are in this category. Category 4 is for project specific applications. Carlson is an example of this. It is used for automated Civil Engineering measurement. It integrates all estimating procedures and can work with both CAD and Geographic Positioning System (GPS) graphics. Category 5 applications are being used to estimate BIMs. Such include CostX, Inovaya, Tocoman, Australia's Construction Research Centre (CRC) Estimator. Further information on all these applications can be retrieved from their respective vendors and developers.

Applications in Categories 1 and 3 cannot auto-extract quantity data and model information from drawings. Notwithstanding, they improve estimators' productivity as their manual efforts are mostly put to use to extract and manipulate data from drawings. This could be extended to prepare BoQs and the necessary data for project planning. On the other hand, the consequences of data miscomputation when handling complex

projects could be very severe. There is no facility to alert estimators about mistakes, errors and miscomputations. However, these systems are very flexible and easy to manipulate.

Category 2 estimating applications can automate quantity calculations based on geometric data extracted from CAD drawings. These data integrate automated libraries to standardize descriptions without ambiguities and misconceptions. Generic assumptions may be made in situations where such data are not available in drawings. Because of the formatted templates, omissions are possible in certain circumstances, while the assumptions applied may sometimes imply inaccuracies.

Categories 4 and 5 can automate quantity take-off and align measurements to prescribed SMM provisions. However, estimators do need to sort the information provided on BIMs, many of which may not conform to these standards. This is because modelers only prepare model information based on graphic views and manufacturers' details. Estimators require that information on models are made more flexible to reflect estimating variables.

6 CONCLUSION

The success of construction processes largely depend on the accuracy of estimates. Unfortunately, the limitations in estimating procedures are linked with the quality of information prescribed by the design team and quality of tools used for measurement and evaluation. While estimators' skills are not limited to quantity measurement, their manual skills largely depend on the level of experience and their academic and professional qualifications. While computer-aided estimating is gradually becoming more popular, there is still a gap between the capabilities available in computer-aided estimating and computer-aided design and drafting application software. However, as the future of design technology continues to favour

the systematic adoption of BIM, construction education and innovation should be focused on training and resource development such that future generations of universal benchmarks are set accordingly. Whilst several computer-aided estimating applications generate information from libraries and auto-generated quantities, others combine manual skills with automated capabilities. However, some of the significant limitations of existing estimating applications include the inability of the applications to auto-alert estimators of errors, omissions and conflicts. Although, developers' estimating applications are making progress, it has also become necessary for BIM modelers to embed design models with adequate information to assist estimators. Most automated quantities are likely to contradict traditional estimating practices. BIM databases can also help reduce some of the limitations of SMMs. It is therefore necessary for BIM modelers to provide frameworks for model data which recognize estimating variables. In addition, the involvement of estimators in taking decisions through virtual enterprises and interoperability is likely to become increasingly important. It is therefore recommended that further studies be conducted to establish the relationship between the quality of estimating and the nature of information provided on BIMs.

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KEY TERMS AND DEFINITIONS

Bill of Quantities (BoQ): Construction bidding or costing document that contains an itemized list of required works, tasks, materials, parts, elements, labor (with their costs), terms and conditions under which a contract is to be left to construct, maintain, or repair a specific structure.

Building Information Modelling (BIM): Building information modelling (BIM) encompasses integrative concepts being used in digital information repository systems to simultaneously create, store, share, simulate, engineer and visualize whole life information in building models.

Estimating Practice: Estimating practice encompasses standardized processes and procedures that are involved in the evaluation, determination or calculation of the cost of a proposed construction project.

Interoperability: *Interoperability* is the ability of different information technology systems and software applications to communicate, to exchange data accurately, effectively, and consistently, and to use the information that has been exchanged.

Metadata: Metadata provides information about, or documentation of, other data managed within BIM application or environment. It commonly defines structures or schemas for graphic and non graphic attributes of BIMs.

Specification: Specification is the précis documentation of standardized technical expectations which allow streamlined and consistent communication between project teams and stakeholders.

Standard Methods of Measurements (SMM): Standard Method of Measurement (SMM) is the documentation of rules and provisions that could be applied in the measurement of works for all major tasks, trades, sections and elements of construction projects.

APPENDIX 1

Table 2. Typical BIMs of building components, automated quantity measurement format and conventional estimating

S/N	Main BIMs	BIM auto-measured Quantity format	Conventional estimating variables
01	Substructure - Ground floor slab - Foundation bases and forms; all attached to wall and building frame - Sub-base components are identifiable	Measured in relation to gross floor area - Measured in m ³ or m ² with thickness details - Measured as part of frame or similar component to which the sub-structural component is attached. - Measured in m ³ or m ² with thickness details	Many items other than auto-measured items on the model are usually considered e.g. excavations, treatment and supports to surfaces, working-up levels and filling, maneuvering works on sub-base, all trade/section components and allied treatment are measured separately including lapping into superstructures and protection
02	Frames - concrete frames - steel/portal frames - timber frames - composite	Measured net - Measured in m ³ with factored reinforcement - Measured in tonne as whole items - Measured in length, giving other details - Measured in length, other details inclusive	All items in this section are measured directly gross and grouped according to volume, length, weight, depth/height and type of frame members, types and nominal sizes of reinforcement (including lapping), types and orientation of formworks, treatment to surfaces with reference to application standards. Ancillary works not shown in the models are also considered.
03	Walls and partitions - all types	Measured gross; at times with lintels, arcs and other features inclusive	Items here are measured net in relation to height, thickness of wall and other features like arcs and lintels measured separately, without considering location as many models would do.
04	Roof - roof covering and ancillaries - roof carcasses	Items are measured net without considering lapping in covering and other ancillaries like ridge, barge boards, eave angle and so like.	All components are measured gross with allowances for lapping; while all other visible elements are accounted for separately.
05	Finishes, painting and decorating - Ceiling, floor and wall	All items are measured superficially gross, considering treatments to thin edges, reveals and arriss as part of the area	Items are measured net and separated accordingly; stating width and nature of treatment
06	Doors and windows - proprietary and common units	Items are measured net without considering comprehensive description of units and other related ancillaries like hinges, lockset, barrel bolts etc	All components are measured separately with adequate information on application details, models codes, including special treatments
07	Services - electrical - plumbing/mechanical	Items are measured net without considering related ancillaries like loops, in-line fittings (threads and related treatments), in-line equipments (bends, taps, reducers, gums, etc)	All Items are measured with adequate consideration of all related ancillaries stated and grouped in types and sizes

Chapter 9

Automated Building Process Monitoring

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ABSTRACT

Monitoring of building process activities is the basis for effective control and management of a building project. In its traditional way it is, however, time consuming, inaccurate and expensive. To improve the monitoring process researchers are investigating methods to automate monitoring and support project managers with accurate and timely information about activity progress. The chapter describes some of these methods and then concentrates on a solution, which takes into account all three aspects of project management: coordination, control and communication. Activity progress is monitored directly by using a combination of data collection methods, which are based on the building information model (BIM), especially on the 4D model of the building. The resulting system is described, evaluated and discussed.

1 INTRODUCTION

Building projects are exposed to many unforeseen events and site conditions, which are causing changes in planned activities. If activity changes are not adequately monitored, the project will much likely run out of schedule and budget. Research in the area of IT-supported automated monitoring methods has intensified in the last few years and brought some interesting results.

The main goal of this chapter is to present, i) the problem and possible solutions, ii) the current research in this area and iii) one of the current systems that authors are developing and testing.

Management Information Systems (Shahid and Froese 1998, Li et al. 2006) and new approaches, such as dynamic planning and control (Lee 2006), help to improve project control, but any chosen system or methodology depends on reliable and relevant information. In practice, data assembling and activity-progress monitoring is still mainly based on traditional methods, which are slow, inac-

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curate and expensive (Davidson and Skibniewski 1995, Chang and Chen 2002). If on-site activities progress according to plan, the time-interval between, an on-site event and the moment data is fed to a control system is irrelevant. However, if a critical-path activity is being delayed, the whole activity plan has to be promptly rescheduled in order to minimize the negative impacts to the project. According to experience, activity monitoring is efficient if it is performed on the daily level (Navon and Sacks 2007).

Construction companies are gradually recognizing the problem of timely information and are putting lots of efforts into capturing and analysing activity data (McCullough 1997). Regrettably, in real situations too many construction projects sooner or later erode the benefits of carefully-prepared activity plans and degenerate into improvisation. The only solution for ensuring a consistent flow of relevant information seems to be the automation of data collection (Kiziltas, 2008). Many attempts have already been made using various approaches in order to control construction project performance. They have been based on indirect indicators such as labour productivity (Stauffer and Grimson 2000, Navon and Goldschmidt 2002), use of equipment (Sacks et al. 2002), material's flow (Cheng and Chen 2002, Ergen et al. 2007) or directly-measured activity progress, and some recent methods are based on site image recognition which will be detailed in the following sections.

2 AUTOMATED MONITORING SYSTEMS

Most of the present research in automated monitoring of construction project activities is based on direct identification of already built construction elements. In this section some of the current research projects and results will be presented in a more detail. Additionally, research based on indirect approach of tracking material resources is

considered due to global trends in RFID development and application.

Automated Object Identification Based on Site Images

The technological advancements in digital imaging, the widespread popularity of digital cameras, and the increasing demand by owners and contractors for detailed and complete site photograph logs have triggered an ever-increasing growth of construction image data collections, with thousands of images being stored for each project. However, the sheer volume of images and the difficulties in accurately and manually indexing them, have generated a strong need for methods that can index and retrieve images with minimal or no user intervention. The development and research efforts in indexing and retrieval of construction site images have reached a level where automated site-image recognition is becoming feasible.

Material-based construction site image retrieval (CBIR) method (Brilakis et al. 2005) is based on image retrieval techniques, which matches known material samples with material clusters within the image content. The evaluation has shown that this method can successfully suit material-based image queries by pre-identifying the materials in each image and comparing material signatures instead of image signatures. This method enables the engineer to retrieve images in real time according to more efficient higher-level, domain-specific concepts such as materials instead of the lower-level concepts of colour, texture and structure. Moreover, the proposed method addresses all of the issues and limitations of other methodologies. It takes advantage of the domain-specific characteristics of construction and is overcoming the problem-specific deficiencies of the image retrieval methods for generic content based construction site.

The large amount of pictures collected daily at construction sites and the time needed manually classify them motivated the researchers to inves-

tigate methods for content recognition of pictorial data in search for patterns that are significant from a construction manager's perspective. The main objective was to develop novel criteria for classification and retrieval of construction site images. Specifically, the goal of the classification step was to devise methods for the meaningful and automated indexing of pictorial data, while the goal for the retrieval step was to find images based on criteria the user is familiar with. Both of these goals were accomplished with the development of the material cluster recognition approach. The proposed method is based on CBIR method and presents a novel material related image retrieval method that enables recognition of material clusters on each image (by automated shape and object identification). With this method the pixels of each image are grouped into meaningful clusters and subsequently matched with a variety of pre-classified material samples. So the existence of construction materials on each image is detected and used later for image retrieval. The method allows engineers to search for construction images according to content in a meaningful manner. The evaluation of the results (Brilakis et al. 2006) has shown that the materials identification method for the retrieval of construction site images can successfully extract material information from each image and allow comparison of material signatures instead of image signatures.

Brilakis (2008) presents a complementary technique, which automatically identifies construction objects within the image content and uses the information to enhance the performance previously described construction site image retrieval approach. The findings of his work are also the first step in recognizing objects from construction site images. Aside from construction site image retrieval, construction objects recognition can potentially assist a large number of construction inspection and management applications such as productivity and progress monitoring, automated as-built/as-designed checks for deviation detection

and others. These shape recognition aspects are the next target authors research.

Kim and Kano (2008) suggested a determination method for the 3-dimensional viewpoint and the direction vector of a construction photograph to perform comparison of the construction photograph and the corresponding VR image of a 3D CAD model. The method was tested on a construction site for visual assessment of construction progress. Furthermore, to improve comparison accuracy of VR images and construction photographs, correction of the camera deviation angle in horizontal plane and the 3-dimensional viewpoint of a construction, photograph has been presented in details.

Usually, determining the flat surface's dimensions in buildings under construction, such as window cavities and façade coating materials, are done by direct measurement methods i.e., using tapes and plummets. Sometimes these methods are a slow and highly risky work for operators. The substitution to these procedures was proposed by Ordóñez et al. (2008) by indirect methods based on close range photogrammetry and laser distance measurement. Such a system is composed of a digital camera and a laser meter mounted on a support with multiple turning positions. In the experiment two different façade element measuring methodologies were used. The method was based on taking a single photograph and measuring the distance to the object. Additionally, the basic method was updated to deal with multiple photographs and distances measured for particular calibrated positions.

Methods Based on Laser Scanning

A scanner can digitalize 3D information of a real world object such as building, tree and terrain detailed to millimetre. A series external and internal scans can produce an accurate 3D model. Arayici (2007) proposed to slice a model through different planes to produce accurate 2D plans and

elevations. This novel technology improves the efficiency and quality of construction projects such as maintenance of buildings or group of buildings that are going to be renovated for new services. In addition, the laser scanner technology can be used in integration with differential GPS for terrain modelling to accurately analyse and inspect terrain structure. The generated digital model can be compared with a physical model of the same object. This will be useful for the communication between the stakeholders in the refurbishment process in particular clients and architects and for the publicity of the real object or building under refurbishment.

Automated and robust retrieval of 3D CAD objects from laser scanned data would have many potentially valuable applications in construction engineering and management. The cost of 3D range scanning is rapidly declining due to recent developments and use of 3D images is accordingly increasing. A new approach for automatically retrieving 3D CAD objects in 3D range point clouds was also presented recently (Bosche and Haas, 2008). This approach takes advantage of 3D/4D CAD models and referencing technologies. Experimental results demonstrate that this completely automated approach is quite robust, including in case of occlusions due to other CAD elements. Another experiment also illustrates these strengths and demonstrates how it could robustly support applications such as automated construction progress tracking. Future work will focus on confirming these results with full-scale structures. The impact of uncertainties in referencing values and in point measurement values will be further investigated. Also methods for automating the estimation of the required threshold parameters will be further tested. Finally, the authors would like to re-emphasize the fact that this new approach has applications not only in automated construction work progress tracking, but also in construction quality control, in 3D image database information retrieval and very likely in many other areas.

Gong and Caldas (2008) proposed another laser based method and a test bed to investigate different approaches to post-process high frequency laser scans for real-time applications. Experiments conducted indicated that the proper combination of data filtering and transformation techniques, such as wavelet transform, morphology filter, median filter and low intensity filter, could greatly facilitate the data clustering process. The proposed method DBSCAN is a density clustering method. It is particularly useful to accurately find clusters of any shape, but requires exact parameters, which are hard to determine. With occupancy grid it requires no human intervention and yields fast accurate results at the cost of losing certain object details, thus it is suitable for real-time applications. Clustering algorithm K-means on non-grid fitted data provides fast accurate results with each minute detail, but human input is required to specify the number of clusters. Future research comprises quantifying the detail loss from the filtering process for later compensation, supporting direct or unorganized 3D point cloud segmentation, incorporating other performance metrics and including edge information from intensity images into current post-processing approaches.

Hybrid Methods Based on Laser Scanning and Photogrammetry

3D scanning is an automated method used for modelling 3D images from point cloud scanned images. For 3D modelling purposes many scans are required from different positions and with reasonable accuracy to get enough information pertinent to the scanned object geometry. A new method for automated site data acquisition (El-Omari and Moselhi 2008) jointly utilizes 3D laser scanning and photogrammetry to support progress reporting and documentation of as-built information. The developed method circumvents limitations associated with the separate use of laser scanning and

digital photo imaging. Working with the LADAR equipment only for estimating quantities of work performed require scanning the construction site from different sides, which is proven to be time consuming and in some cases may not be feasible. The proposed method saved, e.g. around 75% of the time required to scan the construction site, by integrating the scanning and photo imaging technologies. Time was saved by scanning one side of the building only and by increasing the resolution angle. The proposed method enables cost effective and timely extraction of valuable information regarding quantities of work performed at the end of each working day. These quantities are then used to estimate completion percent and to report the progress made on site.

Recent advances in computer tools have improved the ability to store, navigate and display large and complex 3D models. This is a step forward in architectural and urban planning. Generation of photo-realistic models is a time-consuming task that requires significant human input, despite the current developments in photogrammetry and 3D scanning technology. Though computer vision techniques operate automatically, they do not produce useful models due to occlusions and changes in illumination. To solve these limitations Alves and Bartolo (2006) used a new biologically based system called BioCAD, which mimics the human vision process. This novel system is specifically designed for the rapid and accurate generation of 3D computer models from existing large objects (like buildings) allowing a direct link to rapid prototyping systems. This system is based on procedures of both photogrammetry and computer vision combined with biologically based algorithms, and successfully applied on the rapid generation of 3D computer models from existing buildings. 3D and 2D models or STL models are then produced to be subsequently materialized into physical prototypes through rapid prototyping systems. BioCAD allows the integration with rapid prototyping systems and other computer-assisted technologies. It is a key advantage regarding other

reverse design technologies, facilitating the digital reconstruction and physical representation of objects. In future the BioCAD optimization will be directed towards development of more intelligent BioCAD system with three novel routines. The first one is a straightforward step as it will allow establishing a direct link between the points cloud from BioCAD to rapid prototyping systems. The second routine is intended to generate smaller and better STL meshes for simulation purposes based on controlled points cloud and thus eliminating redundant information. The last routine will enable in a computer model to allocate particular regions corresponding with different materials through a proper mathematical algorithm that recognizes the way incident light is reflected by the object. This algorithm will enable us getting more realistic digital representation of the scanned object.

Material Resource Tracking

Visibility and tracking of material resources in construction projects plays an important role in the total project success (Navon and Sacks 2007, Vrijhoef and Koskela 2000, Ala-Risku and Kärkkäinen 2006). This is especially valid in highly customized construction environments where buildings are erected from components designed specifically for the project (engineered-to-order) (Ergen et al. 2007). For this reason, construction industry adopted the supply chain management (SCM) methods used by manufacturing industries to assure better control and thus better flow of materials.

Another important trend to improve productivity and quality of construction products is industrialization, started in construction sector several years ago (Koskela 1992). Reports and case studies from different parts of the world have shown that prefabrication and on-site assembly are becoming common practice (Johnsson 2007, Tam 2007). Industrialization is trying to address the problems of low profit margins in comparison to other industries and shortage of skilled work-

ers (Paevere and MacKenzie 2006, McGuinness and Doyle 2005). Prefabrication of building components at a remote facility saves space for material storage on site, assures better quality control of part production, reduces waste and enables reengineered and more efficient supply chain management.

Current practice shows that construction supply chains and activities on construction sites are stepping behind well recognized and automated approaches in material management and control that are common in other industries (Navon and Sacks 2007, Vrijhoef and Koskela 2000). Manual data collection at construction site is not an approach, which could satisfy today's projects information requirements (Ala-Risku and Kärkkäinen 2006, Ergen et al. 2007). Data quality is low and manual collection requires too much time and effort. It results in infrequent and incomplete project control and uninformed decision making. From the perspective of existing IT solutions, the construction industry also faces many practical problems, especially as far as information handling, data integration and information systems are concerned. As pointed out by Johnsson (2007), construction task related ICT tools do not support automated manufacturing, and tools developed for the manufacturing industry lack support for structural design and detailing. In this regard the CAD and ERP systems come from two different, in ICT terms, unconnected worlds.

On the other hand, IT supported supply chain management implementations already exist at construction sites and represent important information source that can be used by project management decision makers. Following principles of industrialized construction, building process can be observed as a two stage procedure. The first part is undertaken in mostly organized environment of pre-cast production facility. It is characterized by the use of highly developed information management systems like enterprise resource planning systems (ERP) that support automated manufacturing. So the users can get high qual-

ity information at the time when it is crucial for decision making. The second part takes place at construction site in highly flexible environment usually characterized by harsh conditions. Here it is normally difficult to cope with traditional information technology designed for office and manufacturing. The lack of appropriate project monitoring solutions leads to inaccuracies and untimely information, which can affect construction project. In this regard our past research shows some promising results in combined use of mobile computing, computer vision techniques and tracking of material components through supply chain. As described by Rebolj (Rebolj et al. 2008), the combination should reduce the need for complex solutions of each particular technology and increase performance and reliability of complete system.

When observing material tracking in detail, we can notice that prefabrication and construction processes run in parallel and why close coordination between these two groups of activities is needed. If the manufacturing plant does not provide enough building elements on time costly delays can occur at the construction site. On the other hand too early production of building elements, when they are not needed increases the storage cost. That makes on site material manipulation more complex and this might highly affect other projects supplied from the same facility in a multi-project environment. Therefore an integration of on-site activities and industrialized parts production should be achieved.

From the project perspective, construction components are shifted through manufacturing that can be spanned among several stakeholders and finally they converge at single location of construction site. It is usually difficult to keep the level of control over the components in time with manufacturing environment. Manual process is time consuming and often dangerous for involved personnel. Material tracking is therefore usually reduced to the point where only one status (if any) of material is known. We usually know

if the elements actually either arrived on site or not. Use of such broad information about building components is not sufficient for the project monitoring and management purposes. Hence we want to increase the level of granularity of material tracking on site. We should be aware of specific construction site characteristics that prevent us of using well established solutions used in mass production. Two important issues can be identified in this regard: component types and location.

Component types: Building components with the same material and geometrical characteristics are commonly interchangeable. We refer to these components as components of the same type. It is not practical to track such components as different until they are used in building activities at construction site. Therefore the status of components of the same type is tracked on a level of manipulation unit that can contain several elements. However, when these components are mounted, it is necessary to link each component to its exact location in the building and hence bring the status of the component to the level of particular item.

Location: Location tracking in well organized production line or warehouse is quite straightforward. Process phases are defined and space use is planned for a long time. Construction site storage yards and temporary layoffs are much more flexible and established for one project or only a short part of the project. Material is often moved around or put aside for just a very short period of time on some location. Therefore it is impractical and often expensive to establish several “portal” based storages around construction sites. Therefore pure “portal” paradigm for on-site tracking of material flows is not a feasible solution. This is recognized also by other authors (Song et al. 2007). To track components on site, proximity based methods using “movable portals” can be an interesting solution where the portal is represented by material handling equipment or tools that identify the material in close distance.

Since material tracking became popular topic in construction, many initiatives have appeared

who try to automate the process. Supply chain management techniques play important role in material tracking in construction projects. So it does not surprise that like in other industries radio frequency identification (RFID) technology also paved its way as one of the main streams in a search for automated SCM solution in construction. RFID promises more accurate and timely material management data collection. General description of RFID and its potentials in construction can be found elsewhere (Wood and Alvarez 2005, EraBuild 2006). These studies clearly point out that planning logistics, supply chain management and inventory tracking should stay on researchers’ agendas. Here we want to point out some current research topics.

A set of studies exists related to capabilities and technical characteristics of RFID. In construction industry the research started with comprehensive work at Fiotech (Wood and Alvarez 2005, Song et al 2006). The researchers explored potentials of RFID technologies in the critical task of documenting the delivery and receipt of uniquely tagged construction materials – prefabricated pipes – and equipment. RFID is used in this project in combination with metal and it is very important, that the results show RFID can be successfully used in such environments. Most of the potential benefits will be realized when the use of RFID technology is extended over shipping, receiving, inventory and scheduling to construction and other stages of the project life cycle. This suggests new applications should be developed to leverage portal and/or hand-held systems in other project stages. Based on described results a new approach that combines advanced sensing devices and localization mechanisms was developed. The appropriate combination of global positioning system and radio-frequency identification (RFID) facilitates an infrastructure-free data collection process, capable of detecting a large number of RFID-tagged components in short period of time. Based on the collected data the localization mechanisms precisely estimate the coordinates of the tagged

components and hence improve identification and localization of construction components on large industrial projects.

Another project recognizes that RFID benefits construction engineering and management by improving efficiency and control (Tzeng and Chiang 2008) and therefore the team is searching for appropriate technical solutions. This study focuses on technological issues and describes the behaviour of RFID built into interior decorating materials. Tag space layouts, technical limitations and optimal performance strategies are described. Influence of material on RFID, tag reading distances and antenna configuration were the main research questions.

Studies also explore technical issues when using RFID with concrete (i.e. Wang 2008). This study proposes Radio Frequency Identification (RFID)-based quality management system, which functions as a platform for gathering, filtering, managing, monitoring and sharing quality data. The integration of promising information technologies such as RFID technology, mobile devices (PDAs) and web portals can help enhance the effectiveness and flexibility of information flow in material test management. With regard to material tracking it is important that the results show usage of RFID is not influencing concrete characteristics. However, the researchers claim that difficulties exist on the tags positioning in the concrete to achieve sufficient reading quality.

In another study, RFID and 4D CAD models are combined in an information system to manage the logistics and progress control of structural steel works (Chin et al. 2008). The study is based on practical aspects of manufacturing and erection process in high-rise building construction. Technology application strategy takes into account three aspects: technological availability, domain applicability and information management strategy. Findings show that such systems can positively influence time and cost aspects of the construction project. However, training on the use of RFID, proper utilization of collected in-

formation and technological maturity of involved project partners are among the most critical factors of success. Similar findings are reported also by Rebolj (Rebolj et al. 2008) and will be illustrated later in detail.

Song (Song et al. 2007) reports on novel methods of RFID use on construction site for the tracking of the tagged materials' precise location on construction site. The authors proposed the combination of low cost RFID tags and GPS equipped readers to form the backbone of a construction materials' tracking system, which exploits limited range of reader antennas and information on the tags proximity. The system tracks material on site and lays down yards without relying on a fixed communication network. It uses modified existing hardware instead of GPS technology to lower the costs. There is more RFID related work accomplished on leveraging proximity based systems. An example of proximity based system explored by Čuš Babič (Čuš Babič and Rebolj 2008) is demonstrated in the following section.

At present, reported research results on automated identification of material flows still lack coverage of crucial dimension of SCM, which is interoperability across the supply chain stakeholders. The problem is known and clearly pointed out by many research groups, however the lack of appropriate standards and huge diversity of application areas hinder the process of inter-enterprise automation. Interesting initiative has been reported by Ergen (Ergen et al. 2007) which targets management of engineered-to-order (ETO) components. Information flows, content and structure are observed from the perspective of whole building life-cycle and among many organizations. Proposed idea provides a vision of intelligent components, which know their identities location and history, and communicate this information to their environments. RFID technology is proposed for streamlining the information flow through supply chains. They demonstrate technical feasibility concept of RFID base intelligent components in construction supply chains,

Figure 1. Construction activity information loop



where component status can be automatically collected and information can be transmitted into maintenance phase.

3 THE INTEGRATED 4D BASED ACTIVITY AND RESOURCE TRACKING SYSTEM

The goal of an automated monitoring system is to acquire data, convert it to information and deliver information on-time for better project performance. In our approach we have focused on activities as the main entities in the construction information loop of a building life-cycle, which includes activity plans (schedule plan, 3D model), on-site activity progress and activity reports (Fig. 1).

The automated data collection methods of our system are based on the Building Information Model (BIM). Due to the important role of activities in the monitoring process these have to be defined consistently in a way that there is a clear

relation between activities and elements of the 3D model, which is a known process of forming a 4D model (e.g. McKinney and Fischer 1998, Chau et al. 2004). The same 4D model is then used for two independent tracking subsystems.

The first automated method is based on site images of the building, which are then compared to the 4D graphic representation of the building within the same time-frame. The main task of this subsystem is to discover differences between, the planned and built elements of the building, and thus between planned and executed activities.

The second data collection method is based on automated material tracking. It can be used as a stand-alone system, but when in combination with the first one, it has an additional function of improving reliability of activity data. Data from both subsystems are cross-checked regarding consistency using the activity plan.

The concept of our automated monitoring system has been first published by Podbreznik and Rebolj (2005). In the first prototype we have also intended a third component, the Dynamic Commu-

nication Environment (DyCE), which adds expert information to each activity being performed on-site. This information is delivered by the on-site staff, by using mobile computers to communicate project-related information (Rebolj et al. 2008). The DyCE environment is not an integrative part of the automated monitoring system.

Automated Construction Activity Tracking System (4D-ACT)

Information technologies enable combining different types of information into a consistent structure called 4D model. The 4D model contains the product and the process model and thus integrates information about geometry and building activities. For the effective detection of differences between as-planned and as-built situation we proposed a solution and developed a 4D model based Automated Construction Activity Tracking System (4D-ACT). It uses logical, temporal and spatial information from a 4D model and images of the construction site. The system is

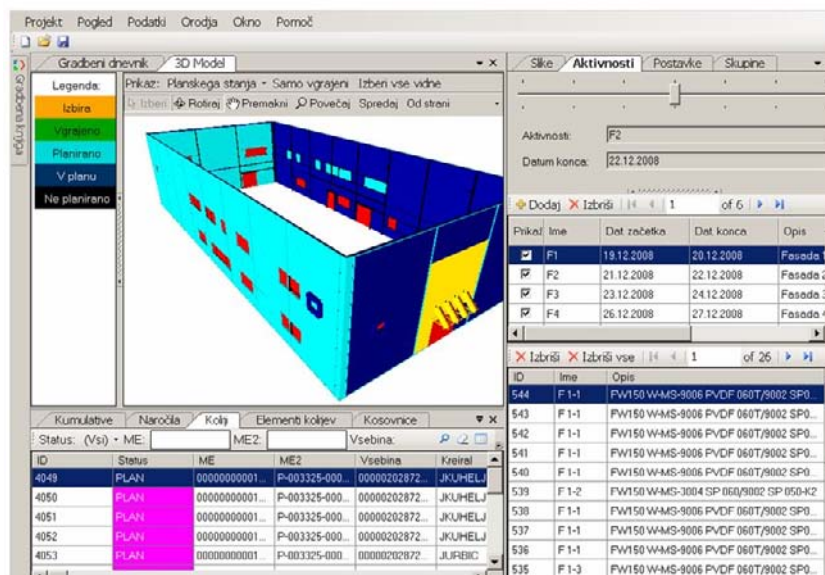
performing a real-time comparison between site images and images extracted from the 4D model. 4D-ACT contains application modules (4D tool, segmentation, camera calibration, recognition, etc.), which have been separately tested on different real cases. The integrated system has been tested in experimental environment as well as in site case study.

4D Tool

To construct 4D model, the 4D tool is using two inputs: the IFC product model and the schedule plan in MS Project format. Connections between building elements of the geometry model and activities are performed by manually selecting element or group of elements and corresponding activities (Fig. 2). The main motivation to develop our own 4D tool was to get full control over the data structure in the 4D model.

The most important 4D tool feature is the 3D reference model, which is presenting the 3D model at a defined time point in the build-

Figure 2. 4D tool enables 4D model construction using product model and process model. Only façade panels were made visible for easier element selecting.



ing process. A model view image of the 3D geometry (total or partial) is generated from the 3D reference model based on parameters of a virtual camera. The virtual camera has same parameters (position, orientation and viewing direction) as the camera on the building site, but it is observing a virtual building – the 3D reference model (Fig. 3).

Image Segmentation

Images contain a lot of information. To establish the recognition process of building elements it is necessary to extract the various levels of information (colours, gradient, textures etc.) and the segmentation is the most common way. The region growing (Potočník and Zazula 2002) was chosen as the most suitable method for segmentation of noisy building site images. Segmentation process is based on finding areas of pixels with similar predefined features.

Before starting segmentation process the algorithm establishes criteria from a learning set. The user marks small pieces of image, which are members of the area that the user wants to segment. These pieces are defining the learning set. The result of segmentation is an extracted image area, which has a certain level of similarity regarding the learning set. In this way parts of image, which do not belong to the building (for

example temporary equipment) are filtered out. The segmentation module has been tested using images of an experimental wooden model and images from a real building site.

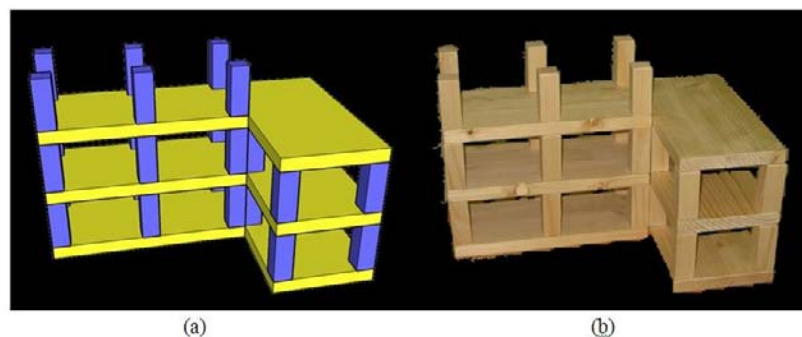
Building Elements Recognition using a Single Camera

The segmented site image and the model view image are both showing the same elements in the same perspective, considering that parameters of the virtual camera and the building site camera are same. Comparison between the segmented site image and the model view image is done by automated recognition algorithm, which is based on minimum differences between element features from both images. If the difference is under a predefined threshold, the element from the segmented image has the highest probability to be identified as an element from the model view image.

Different scenarios can be expected during recognition process. Successful matching of all elements from the segmented image is the best scenario and means:

- the learning set has been marked optimally,
- images from the building site were successfully segmented

Figure 3. Virtual camera view generated from 3D reference model (a) and segmented experimental site image – a wooden model (b).



- on-site activities match with planned activities.

In case of unsuccessful matching 4D-ACT identifies and lists unmatched elements as either missing elements or unknown elements (intruders).

Various reliability levels of building elements recognition can be reached depending on building complexity, camera system, building site or building process technology. Segmented area on the site image (Fig. 3b) has been compared with elements on the view image. For a particular element to be recognized, it has to be visible on both images. 4D-ACT has successfully recognized all visible building elements from the site image of experimental model using a single camera. For these particular building elements, differences between as-planned and as-built can be confirmed.

4D-ACT Accuracy

Accuracy of the 4D-ACT system depends on different parameters. One of them is the number of interconnections between building elements and activities in the 4D model, which defines the level of detail. Since the recognition process is based on comparison between elements on the view image generated from the 3D reference model and segmented elements from the site images, the activity tracking accuracy basically depends on the 4D model detail level.

Another accuracy aspect of the proposed system is based on the pictorial material, which depicts the observed objects. This accuracy can be defined using following equations:

$$N_x = d \frac{f_\alpha}{r} \text{ and } N_y = d \frac{f_\beta}{r}, \quad (1)$$

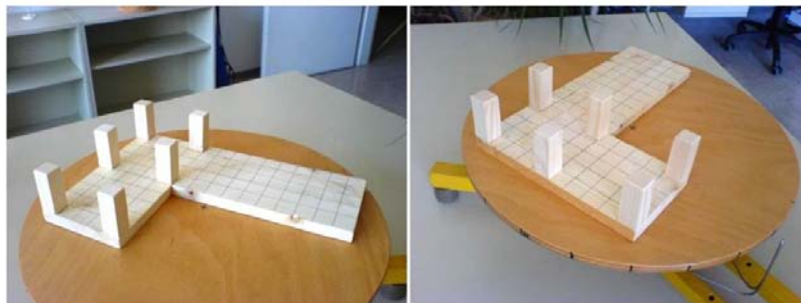
N_x and N_y are numbers of pixels on image in x and y directions, r is distance and d is length of observed object. Parameters f_α and f_β are defined as focus length in x and y direction expressed in pixel, and are calculated as:

$$f_\alpha = kf \text{ and } f_\beta = lf, \quad (2)$$

k and l are spatial resolutions in x and y directions (unit pixel/m) and f is the focus length. Equations (1) and (2) determine number of pixels required to represent observed object with length d on distance r unit from camera.

Camera vision field and observed building elements overlapping degrade the system accuracy. In the 4D-ACT system we solved this problem by using multiple cameras. Such system requires establishing relations between different camera parameters. Building elements recognition and comparison of recognized elements with the 3D model is still in experimental phase.

Figure 4. Two different views of the same object in world coordinate system



Fundamental Matrix Estimation

When a segmented shape extracted from a site image matches with a shape of the 3D reference model image, the building element is easier to be recognized. But usually parts of building objects are covered by temporary equipment and thus, information collected on the observed objects are not applicable. For this reason the images are being captured from multiple cameras with different positions and orientations. Merging data from multiple cameras is possible after they are related. Fundamental matrix can be estimated by various methods (Zhang 1998, Forsyth and Ponce 2002, Hartley and Zisserman 2004) like: eight-point algorithm, LMedS, RANSAC, M-estimator, etc. The M-estimator calibration method was chosen to be used in 4D-ACT.

3D Reconstruction and Recognition using two Views

3D reconstruction is the process that transforms corresponding points or feature from different views of the same object into world coordinate system and is conducted by the following sequence of tasks:

- image feature detection (corners, edges),
- feature matching between image different views,

- calculation of camera projection matrices,
- 3D point determination in world coordinate from image points and
- 3D model transformation from projection via affine to Euclidean space.

Particular tasks of the process is based on mathematical background and each task is described in details (Forsyth and Ponce 2002, Hartley and Zisserman 2004).

The last research period was focused on 3D reconstruction from two views (see Fig. 4) and the topology for reconstructed 3D points was searched.

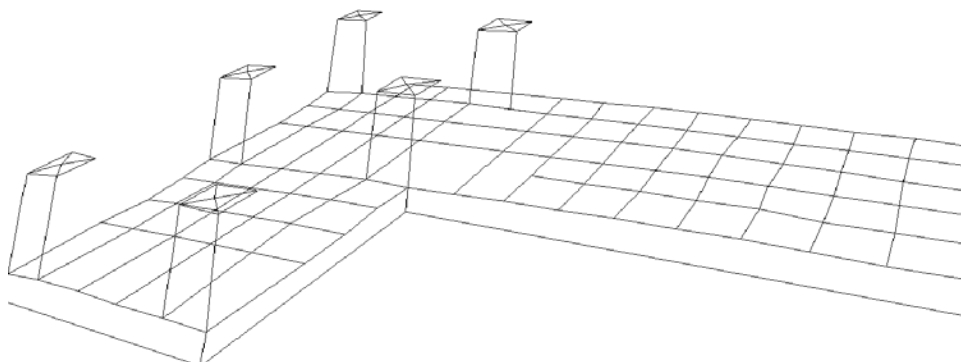
After all previously mentioned tasks 3D reconstruction has been done and reconstructed 3D point linked into wired 3D model, which is depicted in Fig. 5.

Future work will be focused on multiple view 3D reconstruction to improve system accuracy. The most critical tasks are correspondence estimation between features of images and topology construction from corresponded feature.

Material Resource Tracking (4D-ART)

To illustrate how information about material resources spending can effectively serve as an indirect project progress measure, let us observe a solution where building information model (BIM) is used as the basis for integration of off-site and

Figure 5. Snapshot of 3D model reconstructed from two images



on-site information systems and applications. Existing data gathered through supply chain management activities (when properly integrated into project information system based on BIM) can be further used to derive information on project progress.

In described case, implementation of BIM is realized in a 4D model form and the product geometry is enriched with project schedules. On top of the BIM some kind of supply chain management method should be implemented. In general, implementation can follow different SCM approaches. The minimum prerequisite for integration is a link between material resources and BIM elements. The material status has to be propagated in both directions between BIM and SCM system. One appropriate solution would certainly be implementation of “Materials management and control model” defined by Navon (Navon and Sacks 2007). It would satisfy these criteria via its input unit and tracking unit.

Figure 6 shows how supply chain management is mapped to the main contractor information system in order to achieve additional benefits for the project monitoring purpose. Building information is available in the 4D model, where building elements are linked to the project plan activities. For, every point in time (during the project), material quantities and material scheduling requirements can be derived for prefabrication processes and material procurement. These requirements are more or less detailed depending on applied planning methods, like for example incremental planning, and on progress of the project. On the other hand material flow is registered on construction site. Basically, the information later describes which material is delivered to the site and when material is spent in building activities. Information handling at construction site is related to the building itself and is managed via 4D model. Information is transmitted from construction site back to the information system of the main contractor.

Site manager performs detailed activity planning based on the existing 4D model. The plan de-

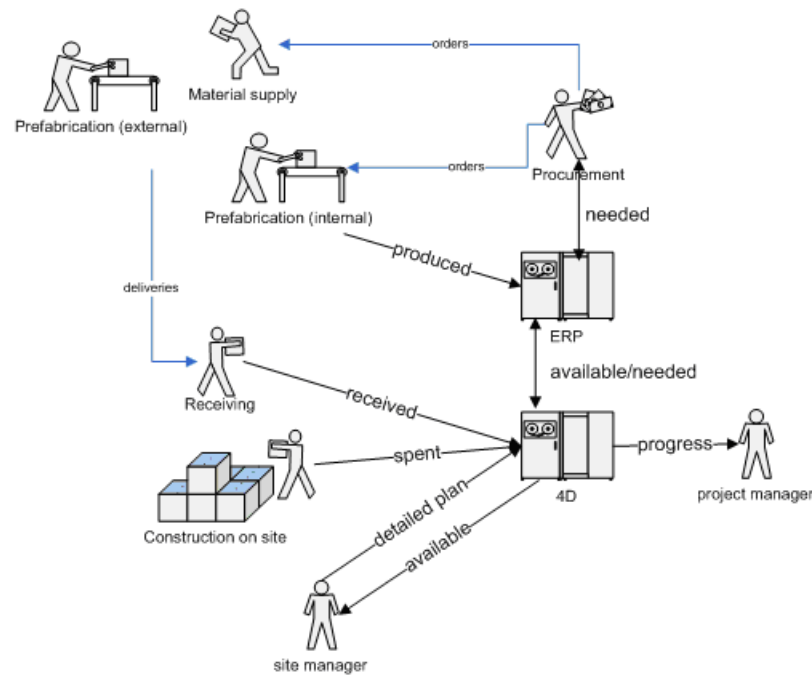
fines successive activities based on the 3D model, which displays current state of the construction site. The model shows accomplished work and available material. Site manager has immediate information of possible material lacks and can act on time. Activity plan is then used as an input for procurement and prefabrication requirements.

In addition to the process described above, project tracking continues with activities of direct progress monitoring like on-site inspection by a site manager or for example by capturing images of construction site and using image recognition systems. These activities confirm or reject validity of assumed progress indicators.

For the automatic collection of material flow information, we have also completed experiments about the RFID technology use. Previously described concepts and ideas were tested on a pilot implementation of a system, in a company with industrialized construction process. The company produces steel construction, roof and façade elements. In addition, the same company erects buildings from manufactured elements by its own construction groups. Our work has been focused on construction site processes. Since almost all construction components are made from metal and to avoid problems (EraBuild 2006, Chin et al. 2008) with traditional RFID systems used in merchant supply chains, we have used Visible Assets' RuBee IEEE 1902.1 tags (RuBee 2008), which can be tuned for use with metal objects. This technology implements long wavelength (131 kHz) protocol utilizing magnetic waves instead of radio waves used by traditional systems.

From the business and mass production point of view, it is important to know what type of material or building element is produced and in which quantity. In mass production, identification of particular element is usually not so important since elements are interchangeable. From the design and construction perspective, it is important to know the position of a particular element in the building. We face a problem of different levels of granularity when we try to link a mass

Figure 6. 4D based supply chain management & coordination



production system with an on-site information system. To achieve required level of identification and component status granulation, we have placed tag reading antennas at several points on construction site. First of all, we have identified incoming material flow, at construction site entry gates. At this point, the system recognizes building components at the level of manipulation units. This is the same granulation level that is used also at manufacturing plant where completeness of building components and their availability is tracked in groups, suitable for transportation.

Preferably, at construction site the material is temporarily stored near the mounting location. When the components are unloaded from the delivery vehicle, manipulation units are registered again by antenna mounted on handling tools. Location of the manipulation unit on the site is defined by location of the handling tool and is stored in the database. If components are moved at some later time, the location information is accordingly updated. In the described scenario,

it is normally not possible to move manipulation units without material handling tools due to their heavy weight. Therefore most of relocations are properly registered.

When components are unpacked and should be mounted, they are registered again by the lifting engine. Until this point all the elements of the same type are distinguished only by their status in the process, defined by the status of the whole manipulation unit. For example, it is possible to get information on, how many components are in production, on stock or delivered to the site. Via the location of the mounting equipment, like lift engine position and elevation, building components are paired with the Building Information Model elements. From this point in time the granularity level changes. However this change is taking place only in virtual space – in the BIM. This switch is very important from project progress monitoring perspective, because all consecutive project documents and reports require exact position of the component. When a component is built in

its status is changed accordingly and then used for generating project documentation, like work reports, invoices, etc. At the same time the system user can get information about manipulation units, their status in supply chain and the properties of component types. The information is later crucial for detailed planning, project monitoring and the supply chain management.

When all the elements from the particular manipulation unit are mounted, identification tag is removed from the unit and tag recycling process starts. Removed tag triggers the assignment of “assumed to be mounted” status to all building components from this manipulation unit. This information notifies responsible project managers such as site manager and project manager about the corresponding activity progress.

This last step closes the loop and brings information about project progress to project management level faster than existing progress reporting. Our experience shows that site managers on small to medium sized projects are responsible for several construction sites and are not able to monitor every site on a daily basis. The control period can extend to a week or even more. Automated collection of project progress information is therefore valuable. Despite the fact that activity status like “supposed to be finished”, which is automatically generated when material is spent, is just an assumption of real activity progress, our pilot project showed that timely information excludes problems triggered by false alarms. This approach reduces latency between occurrence of some event and acknowledgement of the same event at project management level. We can conclude that transfer of principles like supply chain management and data collection automation from one environment – like manufacturing – to another – like construction site – is possible, however the concepts should be adjusted to specific needs and limitations of the target environment. In our case, crucial requirement was the level of granularity of progress tracking and transfer of traditional portal based identification to proximity based identification model, and it is more suitable at construction

site, also in scenarios when tag reading is not primarily based on hand-held devices.

System Integration

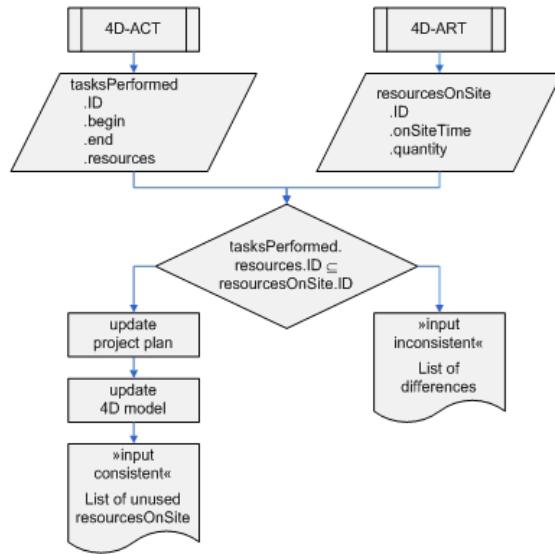
Both tracking systems described in the previous sections can produce false results, caused by numerous reasons, like basic component failures, uncontrolled change of camera position, unexpected visible obstacles or extremely bad weather conditions, corrupted RFID tags, malfunctioning RFID readers, software bugs, etc. For this reason the output control is needed, especially if the site and project managers should rely on the proposed rescheduled activity plan. Human control is always necessary, but reliability can be much improved if independent systems can be cross-verified, thus forming an automated control loop (Fig. 7).

The tracking information control loop is a program with the following input, which is constantly being updated:

1. performed tasks submitted by the image recognition based tracking system (4D-ACT)
2. resource on-site from the resource tracking system (4D-ART)

By a simple input data cross-check the control program provides the output as confirmation or negation of input data consistency. If the input is consistent then the project schedule and the 4D model are updated and the changes are sent to the responsible manager. If the input is inconsistent then the differences between planned and tracked information is shown and the site manager is asked for manual checking. In this case there is a need for an adequate time window, because there is always a time gap between the moment when the resource tracking system detects a certain resource at the building area gate and the time when the corresponding activity is detected by the activity tracking system. The time gap is set according to the building technology for each type of activity.

Figure 7. Information consistency cross-checking



The system has been tested as a case study in a company with industrialized construction process. The company is medium-sized and primarily produces storage house buildings, industrial halls and large store buildings. The buildings mainly consist of load-bearing steel or concrete structure, a metal roof and façade elements. A single camera has been used to test the automated image based activity tracking system. Figure 8 shows an example of difference recognition between as-planned and as-built situations. A site image (Fig. 8a) has been successfully segmented by the segmentation module, whereby the vehicle has been filtered out as it has not been recognized as a member of the learning set (Fig. 8b). The building elements recognition module compared the segmented image and the adequate image extracted from the 3D reference model (Fig. 8c) and identified the roof element (Fig. 8d) as the difference between both images, thus the difference between the existing and planned situation.

The automated resource tracking system was constantly updating a list of all resources delivered to the site. In the test case some resources

were tracked manually and some automatically, because we only could use a limited number of tags. On Figure 9 we can see the actual on-site situation and the 4D model showing information confirmed by the consistency checking module. Building elements, which have been detected by both tracking systems, are shown in black and those elements detected by resource tracking system only are in red (horizontal elements between first and second column on the left). These unused elements can actually be seen lying on the ground on the bottom left side of Fig. 9.

In case of a clear link between material resources needed for an activity and a specific material ID in the material flow (for example unique prefabricated elements), the 4D-ACT results can be checked with high precision. But even when material resources are not unique for a single activity (for example concrete), its consumption can be checked against the resources needed to perform an activity, which has been detected by the 4D-ACT subsystem. In each case the system reliability as a whole has been improved.

4 DISCUSSION

Our experience shows that site managers on small to medium sized projects are responsible for several construction sites and are not able to monitor every site on a daily basis. The control period can extend to a week or even more. Automated collection of project progress information is therefore valuable. Despite the fact that supposed-to-be-finished status is just an assumption of real activity progress, our case study showed that timely information outperforms problems introduced by false alarms. Our approach reduces the latency between occurrence of an event and acknowledgement of the same event at project management level. Less supposed-to-be-finished status indicates potential problem at construction site faster than traditional progress tracking. Described approach brings more control to the project

Figure 8. a) Site image, b) Segmented site image, c) Image of the 3D reference model, d) Difference between b and c.

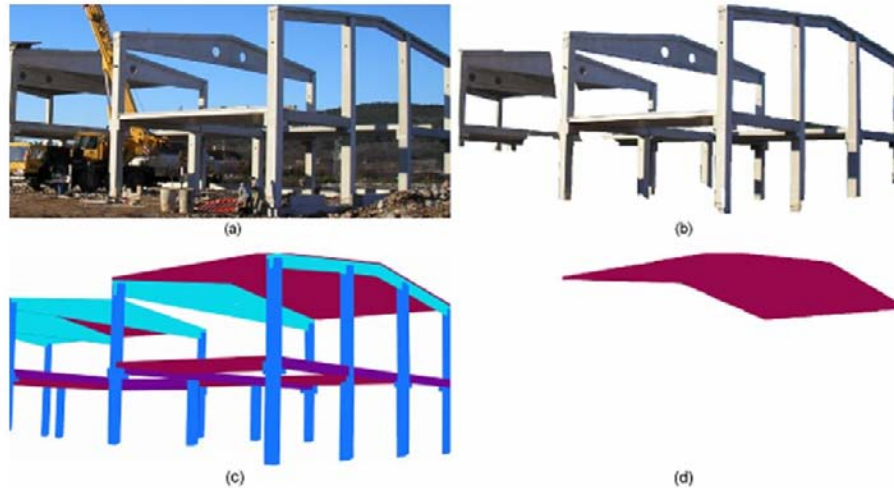
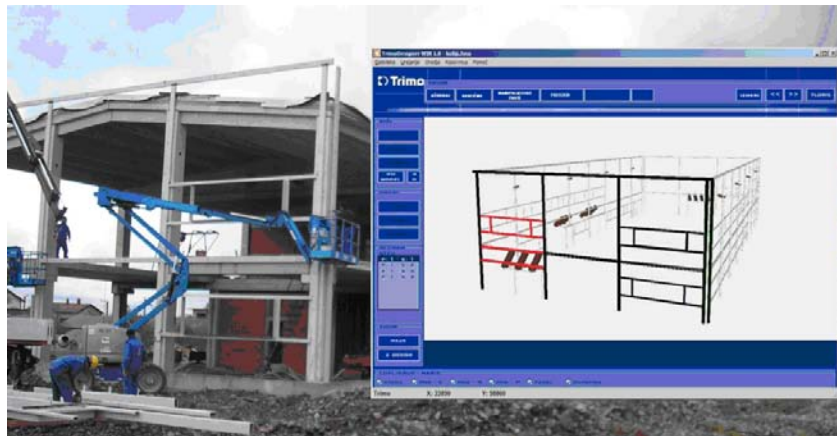


Figure 9. Reporting of work progress on a 4D model.



and reduces possibility of heavy consequences on project schedule and budget. The proposed 4D activity and resource tracking system in its current state of development is only appropriate for very limited types of buildings, where building elements are visible using fixed cameras standing outside the building (e.g. skeleton constructions). In the future we plan to use multiple moving cameras inside the building as well. By mounting the cameras onto workers helmets it will become possible to capture every detail of the building, where activities are

being performed. The recognition process itself will, however, remain the same.

5 CONCLUSION

This chapter is dedicated to the information bottlenecks problem in the information-loop during the construction phase of a building. The problem of gathering data on-time to support those decisions which are necessary for better project performance

has been recognized by many authors. Many systems are in a phase of a prototype or even tested on real projects, but so far no system for automated construction monitoring is yet in everyday use.

In our research we have recognized the following on-going problems:

1. Image based activity recognition is not yet fully developed and has to reach a higher level of reliability; the use of multiple camera should solve the problems of obscured elements.
2. BIM technology has to be used to its full extent, but it has not been fully accepted by the industry yet.
3. Activities definitions in practice are inadequately related to BIM elements; a method of consistent activity definition has to be developed.
4. Material resources are not always adequately related to activities - one of the reasons being -not clearly defined and identifiable material units.
5. Use of any automated construction monitoring system requires a good understanding of its concepts and components by all participants, thus additional training is necessary.

Although no system has yet been fully implemented and applied, the published results, as well as our own experiences show that automated construction monitoring systems will become an important tool for ensuring on-time information for adequately timed reactions to unexpected events on-site and thus better project performance.

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KEY TERMS AND DEFINITIONS

Automated Monitoring: Monitoring of activity parameters by automatically generate and process input data (like digital images).

Image Recognition: The process of automatically recognize objects on an image.

Image Segmentation: Extracting various levels of information (colours, gradient, textures etc) from an image.

Laser Scanning: The process of shining a structured laser line over the surface of an object in order to collect 3-dimensional data.

Material Resource Tracking: Following the path of raw material or prefabricated elements used as resources in building activities, from origin to destination

RFID: Radio-Frequency Identification is a technology that incorporates the use of electromagnetic or electrostatic coupling in the radio frequency (RF) portion of the electromagnetic spectrum to uniquely identify an object.

4D CAD: A CAD system that allows to interlink 3D elements of a building with the corresponding activity in the schedule plan, which gives each element the 4th dimension for the duration of the building process.

Chapter 10

Extracting Fire Engineering Simulation Data from the IFC Building Information Model

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ABSTRACT

Fire engineering is a distinctive discipline within the construction industry that has its own language, design goals and analytical approaches. The use of sophisticated and computationally intensive numerical fire simulation tools is becoming more prevalent and the ability to share building-related data is getting serious consideration within the discipline. This chapter examines what fire engineers would like to achieve and how building information modelling (BIM) fits in with those goals. It discusses the types of fire simulation models that fire engineers use and gives a brief description of two particular fire growth models which use different means to represent a fire scenario. The chapter then considers how the IFC building product model can be used to transfer building geometry and property data to fire simulation models. Two commercial BIM tools have been used to create some simple test case buildings to illustrate the transfer process and highlight some of the problems encountered. Finally, the chapter describes some of the challenges involved in sharing building data with fire simulation models and provides recommendations for further work.

1 INTRODUCTION

Fire engineering is a relatively young and specialised discipline within the construction industry. The protection of people, property and the environment from the effects of fire means that fire engineers are involved in the design of everything

from super high-rise towers, large capacity sports stadia, industrial and petro-chemical facilities to major road and rail tunnel projects. The chapter describes current developments in use of BIM for fire engineering design particularly where computer simulation models are used. The chapter provides a brief background to the needs and challenges of fire engineering simulation modelling and how BIM might be integrated into this design aspect.

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Simple case study buildings are described in the chapter to illustrate some of these developments through the use of STEP files conforming to IFC Building Product Model (simply referred to here as the 'IFC Model') which have been generated by commercially available BIM applications. The contents of this chapter are predominantly based on recent work carried out by the author and co-workers which has been published in various places (Spearpoint, 2003a; Spearpoint, 2003b; Spearpoint, 2006; Spearpoint, 2007; Spearpoint and Dimyadi, 2007; Dimyadi et al., 2007; Dimyadi et al., 2009).

Fire Engineering Design

Fire engineers are involved in many aspects of a building's construction, fit-out and renovation with the objectives of providing means of escape to occupants, reducing the loss of property, preventing the spread of fire to neighbouring structures, providing protection to fire service personnel during fire and rescue operations and limiting the effects of fire on the environment. These objectives are met through the consideration of issues such as exit route design, fire and smoke spread mechanisms and structural stability. There are essentially two broad approaches to fire engineering design. The first is a prescriptive or 'deemed-to-satisfy' approach in which the design needs to follow a set of predefined rules that achieve regulatory compliance. The second approach is where specific engineering design is carried out to match a set of performance metrics that form the regulatory system.

There are many aspects of a building that are common to the fire engineering, architecture, structural engineering and building services domains. Fire engineers need to have the basic geometry and topology of a building which includes information on the size and shape of rooms, openings and hidden voids, the exits from a space and where those exits lead. In addition, fire engineers need to determine the fires that could likely

occur through an assessment of the fuels in the building. This analysis requires the fire properties of lining materials, the contents of the spaces in terms of total fuel load, the arrangement of fuel packages and the relative flammability of those packages. Fuel packages might include furniture and fittings plus wall, floor and ceiling coverings and the fuel load is the total calorific value of the fuel packages per square metre of floor area. The severity of the fire can be assessed by the rates of energy release from fuel packages, the peak rate of energy release and the products generated by fire such as toxic gases and smoke volumes. The specification and design of fire safety systems such as alarm, suppression and smoke management systems requires details of system components plus electrical wiring layouts, plumbing and pipe work, ducting networks etc. Information regarding the site of the building may also be necessary. Weather may be a factor and temperatures, wind velocities, humidity may all be required in order to specify the performance of the fire safety systems. Finally, fire engineers need to obtain details of the occupancy characteristics of the building. This may include information such as the primary use of the spaces, numbers of people, times when the building will be occupied and by whom, the physical and mental state of the occupants.

In order to carry out designs, fire engineers are likely to conduct computer simulations particularly where the building is complex and prescriptive regulations are not appropriate. The availability and accessibility of faster computer processors with larger memory capacity makes it practical for fire engineers to use sophisticated and computationally intensive numerical simulation tools to solve fire engineering problems. There are a large number of software tools available to the fire engineer that can be used to carry out distinctly different tasks (Olenick and Carpenter, 2003). However, the current fire modelling practice often uses a paper-based approach to gather basic building geometry information which contributes to high overhead costs in preparation

for fire simulations. It is not unusual for the fire modelling process to start with the manual gathering of building geometry and other building information from either printed plans or electronic CAD drawing files. The information is then transcribed either manually or electronically and used to construct a set of data and instructions in the format recognised by fire simulation models. Each fire model may require different types of information and have different requirements on how to represent the building geometry which adds to the complexity. The conventional paper-based approach of transferring building information from printed drawings to computer software applications for engineering analyses has been shown to be inefficient and error prone.

BIM for Fire Engineering Applications

BIM offers an alternative to the current paper-based or CAD transfer methods used by fire engineers wishing to carry out fire simulations. There are a number of scenarios in which BIM could be used in fire engineering design:

- A building model could be imported into a BIM authoring/editing tool in which the building can be studied in detail in preparation for a preliminary assessment from a fire engineering perspective.
- Using the modelling or editing tools in the BIM tool, the fire engineer may be able to make simplifications to the building or add certain elements and properties to the building model in order to create a fire scenario to be analysed.
- The revised building model could be used to generate the input data required by one or more fire simulation models using interfaces developed specifically for this purpose.
- The generated input data for the fire simulation models can further be edited if

required using any dedicated software interfaces developed specifically for a particular fire simulation model.

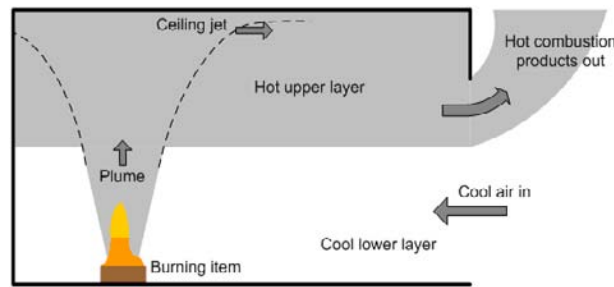
- Any recommended modifications or additions to the building as the result of the fire engineering assessment may be highlighted or incorporated into the building model using a BIM tool. For example, the fire rating of a door may be changed in the building model, or new fire engineering properties may be added to the building model as appropriate. The result may be communicated to the principal designer through the building model from which the revised elements or new properties could be extracted and incorporated into the master BIM.

The above scenarios assume that software tools have adopted a common BIM standard and have implemented standardised data interoperability methods to guarantee the integrity of the information exchanged. Recent studies have shown that there are still issues associated with two-way sharing of building model information. The main issues relate to the level of compliance to the data interoperability standards being adopted by various software implementations and the inherent complexity of the current IFC Model (Amor, 2007).

2 FIRE SIMULATION SOFTWARE

There are a large number of computer software tools for a wide range of fire engineering applications including egress design, sprinkler system specification, smoke management and structural performance. Fire models can be divided into two broad categories; probabilistic and deterministic. Probabilistic models set input values using probability distributions resulting in statistical output predictions. Some models of this type do not make direct use of the physical and chemical principles involved in fires, but make statistical

Figure 1. Zone model representation of room fire development



predictions about the transition from one stage of fire development to another. Deterministic models take a given set of input values which lead to a determined set of outputs. For example, deterministic fire growth models use the physics and chemistry associated with the fire environment to make predictions about fire development and can be further classified into two main sub-groups; field models and zone models which are discussed in further detail below.

As already noted previously, much of the initial simulation effort is spent obtaining and transferring the basic building description into the specific fire/egress simulation model. Very few of the currently available commercial fire simulation models can import building information in an electronic form and even those that do are limited by the information available such as provided in a DXF file. Examples of fire engineering software using this DXF data exchange include Simulex (Thompson and Marchant, 1995) for egress simulations and SMARTFIRE (Frost, 2001) for fire growth simulations. The use of DXF often requires that the source data extracted from the building model contains certain compatible types of elements and are constructed in a specific manner to be interpreted correctly. For example, Simulex would not interpret walls correctly if they are exchanged as polylines rather than as separate line elements. There have also been other third-party software utilities, add-ons and plug-ins available to allow CAD data to be accessed and exchanged by external applications. The data exchange process generally involves retrieving

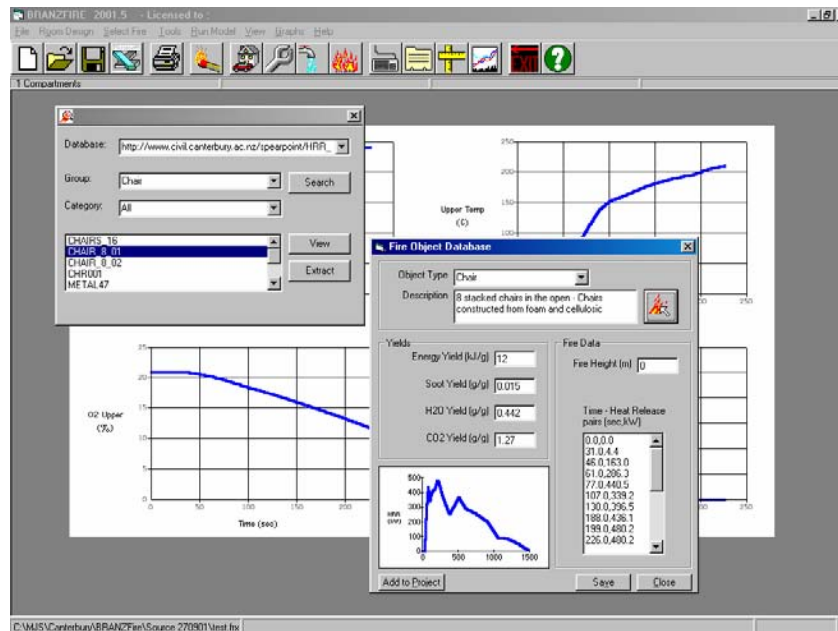
predefined attribute values of elements and exporting them to a database table or a spreadsheet or direct linking them with the external applications. For example, this method of data sharing has been used in some HVAC and fire sprinkler design packages.

Zone Models

Zone models are a common category of fire simulation model available to the fire engineer. The atmosphere within a room is normally split into two vertically and horizontally uniform zones; the hot upper gas layer due to the fire and the cool layer below (Fig. 1). Interaction between the two zones takes place through the fire plume above the burning object. The fire plume rises through buoyancy to the room's ceiling, entraining cool air as it rises. The combustion products and entrained air then is assumed to spread across the ceiling as a jet. Once the jet reaches the walls the hot layer deepens until the depth is controlled by the ventilation through any openings. The fire then stabilises its burning rate to match the available air supply. If there are no large openings, the hot layer will descend to the level of the fire and burning will reduce as the fire is starved of oxygen.

Although zone fire models all follow the same basic philosophy regarding the way in which the fire environment is represented, individual software tools may have facilities that are not present in others. BRANZFIRE (Wade, 2003) is a widely available multi-compartment zone model which can simulate the movement of smoke between

Figure 2. The BRANZFIRE zone fire model graphical interface



up to ten spaces inter-connected by openings. Fires are specified by the modeller or by using a built-in fire spread model in the case of room linings. The model also has the ability to incorporate sprinkler and smoke detector activation, the breaking of window glass and the effects of mechanical fans.

BRANZFIRE comes with a graphical interface that allows the user to input the room and fire specifications (Fig. 2). However this input process has to be carried out manually through the use of dialogue boxes as there is no automatic data exchange process in the commercial release of the software. Although data exchange from the IFC Model to the BRANZFIRE fire simulation model is specifically explored in this chapter, the issues are representative of those faced integrating many of the available zone fire model family.

Computational Fluid Dynamics Models

In Computational Fluid Dynamic (CFD) models, a space is divided into many thousands or millions

of computational cells throughout the enclosure. CFD models solve the conservation mass momentum, energy and species in each cell, thus giving a 3-dimensional field of the dependent variables including temperature, velocity, gas concentration, etc. CFD codes for general fluid and heat transfer problems are available as well as codes that have been specifically developed or modified for fire engineering applications. CFD models are significantly more computationally intensive compared to zone models and simulations can take many hours or days to complete.

Fire Dynamics Simulator (FDS) developed by McGrattan (2007) and co-workers is one of the most well-known CFD codes used by fire engineers. It uses the Large-Eddy Simulation (LES) numerical technique to solve large-scale hydrodynamic turbulence, a condition that typically occurs in fires. FDS also employs sub-models to deal with specific fire related phenomena such as heat transfer, detector activation and sprinkler sprays. The FDS input file specifies the building geometry, material types, computational scope, grid resolution, boundary conditions, fire source

parameters, fire safety and mechanical systems specifications, as well as specification on the types of outputs. The computational domain is user defined and made up of one or more rectangular meshes, each with its own three-dimensional rectilinear grid. Building enclosure elements and solid objects are specified as a series of rectangular blocks representing flow obstructions, whereas doors and windows are viewed as voids allowing fluid and particles to flow through. All solid obstructions and voids are forced to conform to the numerical grids and an inclined or diagonal wall or roof must be modelled in a stair-stepping manner conforming to the grid cells.

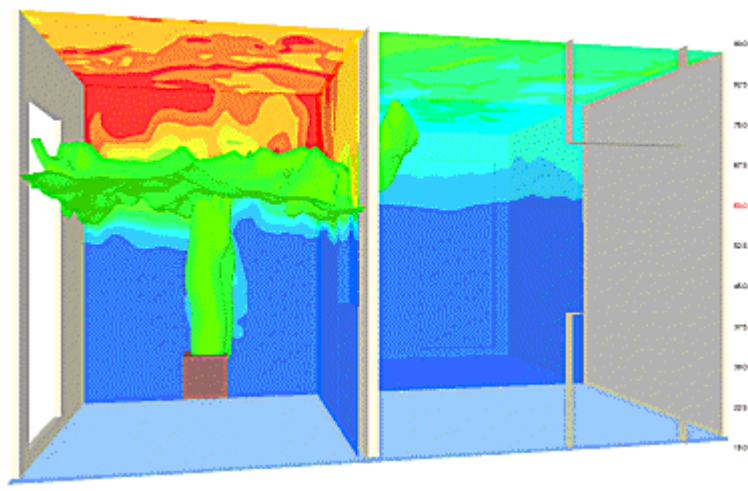
FDS is a command-line software application written in Fortran 90 without a graphical user interface and requires an input file in a simple text format. Generally, the most time consuming part of the input data creation is the transfer of building geometry information from paper or CAD drawings to the format required by FDS. At the most laborious level, all the coordinates for the obstruction blocks representing the building geometry are manually determined by measurements and calculations from printed drawings.

There are software tools currently available to assist with the creation of the FDS input data, particularly with respect to the transfer of the building geometry and topology information. However these tools require the reconstruction of the building in one form or another, using information derived from printed plans or CAD files. The software tools available are either only compatible with specific CAD output data formats, or they require manual data entry of the building geometry and topology from scratch in a proprietary format. DXF2FDS (Sheppard, 2006) reads a DXF output created by a CAD tool and generates the FDS equivalent obstruction blocks representing the building geometry. It can also incorporate a set of pre-defined FDS input parameters such as the computational domain and grid sizes, selected surface materials, prescribed

fire source, etc. DXF2FDS has a limitation in that it only reads 3DFACE flat surface elements and ignores all others from the DXF source file. A model constructed using other surface or solid modelling techniques often cannot easily be converted directly into 3DFACE entities. Therefore, a tedious conversion process is often required or, alternatively, the model needs to be reconstructed using 3DFACE elements exclusively. PyroSim (Thunderhead Engineering Consultants, 2006) has been developed to construct, read and edit FDS input files. To assist with the construction of the 3D building model similar to the obstruction blocks in FDS, a 2D image of the building plan can be overlaid on the graphics editor screen to allow three-dimensional wall elements to be manually positioned by tracing over the lines. Stair-stepping is automatically applied to diagonal or curve walls to conform to the numerical grid system.

The simulation outputs from FDS can be visualised graphically in an interactive 3D environment using a companion application called SmokeView (Forney, 2007). FDS can produce graphical output files containing the 3D model geometry, animated quantities per unit time as well as static pictures of the flow field in Plot3D format which can be accessed and visualised using SmokeView. Figure 3 shows a SmokeView snapshot of a space temperature profile (indicated by a colour spectrum) at a particular time in the FDS simulation of a test case building model. At the start of each FDS simulation, a SmokeView output file is first created containing the building geometry visualisation data. The duration of the simulation can be set to zero initially which prevents any computations from taking place except for the generation of the building geometry data. This enables the building model specified in the input file to be previewed and verified before any intensive and time-consuming computations take place.

Figure 3. SmokeView output of an FDS model output (Dimyadi et al., 2007)



3 INTEGRATION OF IFC BIM AND FIRE SIMULATION SOFTWARE

This chapter will not go into detail about the IFC building product model other than to relate it to fire engineering. The IFC Model (IAI Tech International, 2009) is highly complex containing over 650 entities and over 300 supplementary data types to represent building storeys, spaces, walls, slabs, doors, windows and openings etc. Since the IFC Model is a general product model rather than being domain specific (Ito, 1995) it is not intended to define properties for every building element that may exist or contain entities that may be required by a specialist domain such as fire engineering. Mapping a general product model to a highly domain specific application can present limitations as demonstrated by Karola et al. (2002). A 'property set definition' mechanism overcomes some of the limitations by allowing extensions to be made outside of the main IFC Model specification. As the IFC Model matures it is expected that new entities and property sets will be added as well as refining those that already exist. IFC files are primarily exchanged using the STEP encoding specifications given in ISO 10303: Part 21 (ISO, 2002) although an XML

version of the IFC Model has also been made available (Liebich, 2001). The STEP encoding is an electronic data interchange standard which has the aim of completely representing a product over its whole lifetime in a neutral format. The representation includes geometric data and non-geometric data such as properties and costs (King and Norman, 1992). A physical STEP file uses only ASCII characters and is a human readable format although software tools are often used to parse a file.

Early versions of the IFC Model only had a limited set of specifically fire engineering related properties but since the IFC 2x Edition 2 release there is a considerable amount of material that is useful to fire engineers who are looking to exchange data with fire simulation models and a review of fire engineering specific properties in the IFC Model and their compatibility with BRAN-ZFIRE is given elsewhere (Spearpoint, 2006). It would seem that the IFC Model is ideally suited to meet the requirements set out by Mowrer and Williamson (1988) for room fire modelling. The object-oriented structure of the IFC Model and the ability to associate properties to objects were two of the key points identified by these researchers. The IFC Model can be used to begin to achieve

interoperability between electronic building descriptions created in commercially available BIM tools and fire simulation models.

Fire growth, egress and structural fire simulation models have quite different underlying philosophies regarding the way in which they represent fire scenarios and therefore also have distinct differences in the way in which the geometrical and property information is specified. These differences pose a number of challenges when exchanging data with the IFC Model. The translation of geometrical and topological building information requires the identification of spaces, boundaries (walls and slabs) and openings (windows and doors) and their relationship to one another. Properties are also of interest to fire simulation tools and might be thermo-physical if simulations are to consider heat transfer, mechanical performance and/or surface fire spread. Properties may also be relevant to the human activities in a building or may relate to regulatory requirements. These differences are illustrated by describing how various building elements and properties can be extracted from the IFC Model and mapped to fire simulation software with the focus here on fire growth models as this is where most developments have been taking place recently.

Properties

In general, a subset of common material properties that are likely to be relevant to fire simulations is available in the IFC Model. The IFC Model also contains a number of properties that are specifically targeted towards fire engineering design however their mapping to fire simulation models is not necessarily direct. The IFC Model does not control the semantics used for naming materials and there needs to be a specific mapping created where a fire simulation model includes a database of materials with its own naming conventions as is the case with BRANZFIRE and some releases of FDS. Within the context of fire safety, the

properties of building elements can be thought of as belonging to three general categories.

- **Category 1:** The fundamental thermo-physical properties of a building element. These properties might include the thermal conductivity, specific heat capacity and so on.
- **Category 2:** Fire specific properties that may have been obtained by measurement or some other means. This might include such things as the heat release rate (i.e. the energy release over time) and the properties of the smoke generated by a burning item.
- **Category 3:** Properties that have been obtained for regulatory or standardisation purposes. These might include the fire rating of a system such as a fire door or wall or the flame spread index of a lining material. These properties are generally obtained from some form of standard test method and are derived properties that have a specific regulatory meaning.

This classification is particularly relevant to the practice of fire engineering within the building regulatory environment. At the deemed-to-satisfy level of regulatory compliance, only Category 3 properties would likely be needed to be evaluated. For performance-based design involving fire simulations, Category 1 and/or Category 2 properties are likely to be needed as well as a possibility that Category 3 properties would also be of use.

Many of the Category 1 fundamental properties that are useful for fire engineers are already available in IFC Model. There is scope to extend these fundamental properties to include additional ones that would be useful for fire engineers such as heat of combustion, apparent ignition temperature and many others. However many of these might be better seen as Category 2 properties as they might not be considered fundamental properties that have a wider application outside of fire engi-

neering. The majority of fire engineering specific properties that already exist in the IFC Model are essentially Category 3 regulatory properties and examples are given in Table 1.

For a fire engineer wishing to conduct simulations with the use of one or more software tools then the provision of Category 1 and/or Category 2 properties would allow the transfer of those properties to the simulation software. This would require that such properties are available in the product model in a form appropriate to fire engineering and that values for these properties were available and present in a specific instance of the product model. Providing such properties would make the task of conducting simulations more efficient and would therefore meet the one of the major objectives of the BIM approach. Category 3 properties are suited to tools in which a building is assessed against deemed-to-satisfy requirements. Regulatory assessment tools could automatically determine whether a particular design meets the requirements by matching Category 3 properties against the prescriptive rules.

Ideally all three Category levels should be included in the product model. Some property data would need to be provided by a human at some stage of the project, some data might be available from external databases, whilst other properties might be determined automatically by a software tool, using the properties already specified. For example, a property such as the SFI (spread of flame index) as required in the New Zealand deemed-to-satisfy document (Department of Building and Housing, 2006) might be determined through a simulation analysis of the fundamental flame spread properties of an item already included in the project. The SFI would then be appended to the project and another software tool might be used to evaluate regulatory compliance.

It is difficult to give a comprehensive list of every property required by fire engineers in each of the three categories without knowing what analysis a fire engineer wishes to conduct, what

software tools they have available and what regulatory environment they are working in. Property requirements associated with specific building elements in relation to the BRANZFIRE and FDS fire growth models are discussed below.

Spaces

Zone fire models such as BRANZFIRE represent buildings as a collection of rooms with specified length, width and height dimensions. The representation does not require the exact position of the room or the openings relative to their parent walls. It is also typical (but not necessarily always the case) to assume that spaces have a rectangular footprint and that ceilings are smooth and horizontal and most zone fire models have a limited number of allowable spaces and/or a limited number of connections between spaces.

In FDS, boundaries are positioned using their exact placement to create computational enclosures and openings are placed with boundaries relative to their parent wall. FDS is a lot more flexible with regard to the shape of floor footprints, number of openings and the orientation of space boundaries. Thus exact positions of space boundary elements are not required for BRANZFIRE but must be determined for FDS.

Fire growth models do not generally require specific properties associated with spaces however this may not be the case if the fire simulation model was concerned with people movement. Specific properties that provide details of the number and type of occupants and the activities that normally occur in the space would be desirable.

Walls

Walls form the primary vertical space boundaries in a building. The IFC Model has two wall entity types: a simplified 'standard' type and a more complex generic type, and three methods of solid model representation described below:

Extracting Fire Engineering Simulation Data

Table 1. IFC Model fire-related properties

Property set definition and associated IFC class	Fire specific property name	Data type	Definition
<i>Pset_DoorCommon</i> (<i>IfcDoor</i>)	<i>FireRating</i>	<i>IfcString</i>	Fire rating of complete door assembly. Given according to the national fire safety classification.
<i>Pset_Insulation</i> (<i>IfcDiscreteElement</i>)	<i>FlamabilityRating</i>	<i>IfcString</i>	Insulation flammability rating.
<i>Pset_CoveringCommon</i> (<i>IfcCovering</i>)	<i>FireRating</i>	<i>IfcString</i>	Rating indicating the time duration before fire would penetrate this ceiling
<i>Pset_RoofCommon</i> (<i>IfcRoof</i>)	<i>FireRating</i>	<i>IfcString</i>	Time duration for fire resistance the roof assembly is rated.
<i>Pset_SlabCommon</i> (<i>IfcSlab</i>)	<i>FireRating</i>	<i>IfcString</i>	Fire rating of slab.
<i>Pset_SpaceCommon</i> (<i>IfcSpace</i>)	<i>MainFireUse</i>	<i>IfcString</i>	Main fire use for the space which is assigned from the Fire Use Classification.
	<i>AncillaryFireUse</i>	<i>IfcString</i>	Ancillary fire use for the space which is assigned from the Fire Use Classification.
	<i>FireRiskFactor</i>	<i>IfcInteger</i>	Fire Risk factor assigned to the space
	<i>SprinklerProtection</i>	<i>IfcBoolean</i>	Indication whether the space is sprinkler protected (true) or not (false).
<i>Pset_StairCommon</i> (<i>IfcStair</i>)	<i>FireRating</i>	<i>IfcString</i>	Fire survival rating = length of time the stair enclosure/ assembly will survive in case of fire
	<i>ExitStair</i>	<i>IfcBoolean</i>	Is this stair counted as an exit stair in case of fire?
<i>Pset_WallCommon</i> (<i>IfcWall</i>)	<i>FireRating</i>	<i>IfcString</i>	Fire rating of wall assembly.
<i>Pset_WindowCommon</i> (<i>IfcWindow</i>)	<i>FireRating</i>	<i>IfcString</i>	Fire rating of complete window assembly. Given according to the national fire safety classification.
<i>Pset_FireDamper, Pset_FireSmoke-Damper</i> (<i>IfcDamper</i>)	<i>FireResistance-Rating</i>	<i>IfcReal</i>	Measure of the fire resistance rating in hours (e.g., 1.5 hours, 2 hours, etc.).
	<i>FusibleLink-Temperature</i>	<i>IfcThermo-dynamic-Temperature-Measure</i>	The temperature that the fusible link melts.
	<i>ControlType</i>	<i>IfcString</i>	The type of control used to operate the damper (e.g., Open/Closed Indicator, Resettable Temperature Sensor, Temperature Override, etc.)
	Plus other associated properties...		
<i>Pset_SmokeDamper</i> (<i>IfcDamper</i>)	<i>ControlType</i>	<i>IfcString</i>	The type of control used to operate the damper.
	Plus other associated properties...		

Note: not all damper properties shown.

- A clipping representation is the geometric representation as the result of Boolean operations such as union, subtract, and intersect, etc. on Constructive Solid Geometry (CSG) solid objects. CSG is the extrusion of a rectangular surface object or region in the X, Y or Z axes.
- Swept Solid representation is the geometric representation of solid models created with profile sweeping using either linear extrusion or revolution techniques.
- Boundary Representation (BREP) represents a solid by a series of connected boundary surface elements, which are defined by vertexes, edges and loops rather than by profiles and extrusions. BREP is the fallback position in the IFC Model for any geometry that cannot reasonably be represented using parametric solids.

The combination of the two wall entities and three representations adds to the complexity of the exchange of walls from the IFC Model to fire simulation models.

Since zone models such as BRANZFIRE do not explicitly require the position or size of wall elements there is little geometrical conversion required. For an FDS obstruction group of input data, the parameters required is the sextuplet of coordinates defining the lower and upper bound of the cuboids. A void in an obstruction block is specified with similar parameters to the obstruction group. Any solid grid cells within the volume specified by the void sextuplet are removed and the obstructions intersecting the volume need to be broken up into smaller blocks (Figure 4).

A space generally has more than one bounding wall and these are not necessarily defined as having similar construction. BRANZFIRE assumes that a room has a single type of wall enclosing it and this can lead to inconsistencies when mapping from the IFC Model. Where a set of walls bounding a space have a mix of properties, the

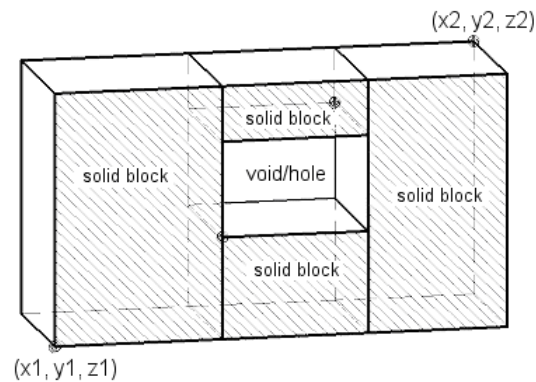
BRANZFIRE wall materials will need to be appropriately selected. In contrast FDS can have different surface types and material definitions for each wall. Walls may also be constructed of one or more layers, each of different materials and thicknesses, and these properties may be required where the thermal and/or mechanical performance of a wall is needed. Both BRANZFIRE and FDS can include heat transfer through walls (and other boundary elements). Furthermore, where multiple layer walls include air gaps it is possible that one of the BRANZFIRE wall lining properties (generally the substrate) will be designated as air rather than as a solid material. Again FDS is more flexible with regard to materials layers. The user needs to be aware of these issues and check the scenario setup before continuing with any simulations.

Floors and Ceilings

Floors and ceilings form the primary horizontal spacing closing elements. In a multi-storey building it is possible that a single building element may represent both the ceiling and the floor of several spaces and this needs to be considered when interpreting a building model. BRANZFIRE generally requires that rooms be given a floor and ceiling material type and thickness similar to walls. Similarly FDS can use obstruction groups to create obstruction blocks to form floors and ceilings.

The IFC Model does not explicitly contain ceiling or floor entities and one simple approach is to represent the construction of floors and ceilings using slab entities. The IFC Model does define a roof entity which is an assembly that groups together related entities that make up the roof such as slabs, rafters and purlins or other included roofs, such as dormers. Properties of floors and ceilings can be allocated using property sets included in the IFC Model which are associated with a covering entity. The complexity of identifying walls and

Figure 4. A void in an FDS solid obstruction block (Dimyadi et al., 2007)



ceilings and the use of slabs to represent these building elements in BRANZFIRE and FDS is discussed later.

Whether a slab forms a floor or ceiling is relevant, for example, where a fire engineer wants to assess the properties of a slab exposed to a fire in which the slab is a composite of different material layers. Whether a slab forms the floor or the ceiling of a compartment is not immediately apparent in the IFC Model. It may be possible to identify whether a slab forms the upper or lower boundary elements of a space from the vertical position relative to the space or the walls. The user of a BIM tool may be able to specify the relationship of a slab to a space or define a property that specifies the use of the slab.

Openings

Door and window openings are exchanged in the IFC Model as opening element entities. Filling elements such as a door or a window are described by voiding or filling entities respectively. The local placement of door and window openings is exchanged as the horizontal and vertical offset distances from the placement origin of the wall. This can be obtained from the IFC Model, where the horizontal offset distance is found from the placement origin of the wall to either the near or

far edge of the opening depending on the facing of the opening (Figure 5).

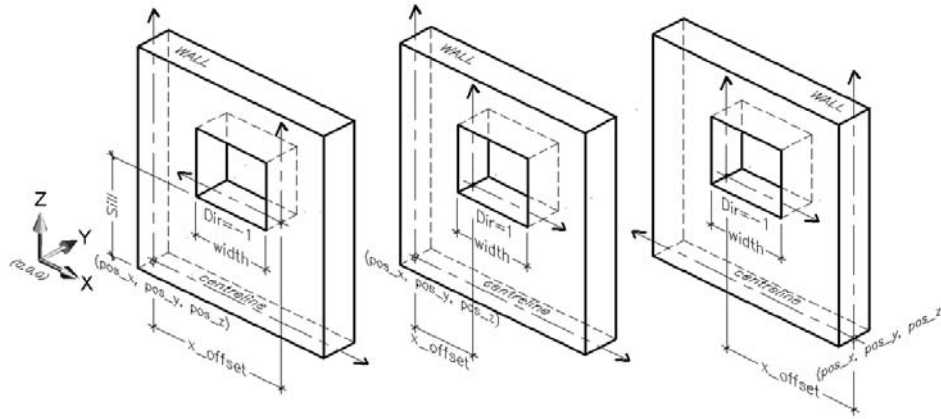
FDS voids can be determined from the opening placement while BRANZFIRE only requires opening dimensions and so might be assumed to be in the centre of the parent wall rather than at their actual location. The connection of neighbouring spaces by an opening is simply determined in FDS by the void in a solid boundary. A more complex approach is needed for BRANZFIRE in which the relationship between an opening, its parent wall and the spaces that the wall bounds need to be determined. The IFC Model encodes these relationships although it is not a trivial task to extract and interpret these relationships.

Similar to walls and slabs, the properties of entities that fill an opening may be of interest to fire simulation software and these properties may include window glass or door materials. Furthermore the state of the opening (i.e. whether it is open or closed) might be important where the flow of hot combustion products to neighbouring spaces is going to be analysed.

Topology

The topological relationships between openings and associated spaces are expressed in the IFC Model. Where this topology needs to be explicitly

Figure 5. Placement of door and window openings (a) wall in positive direction and opening in negative direction; (b) wall and opening both in positive direction; (c) wall in negative direction and opening in positive direction (adapted from, Dimyadi et al., 2007).



defined, a map which identifies the connecting openings between rooms is required. Building topology in BRANZFIRE is expressed by identifying pairs of rooms that are connected by a specified opening and the dimensions of that opening. Connections with only one associated space are assumed to connect with the 'outside' which is the case for most windows and for doors located on external walls. If only a portion of a larger building is selected the connections to spaces in the unselected portion will be treated as outside connections. Conversely FDS does not use the concept of rooms per se but simply uses solid boundaries to enclose computational volumes. The result of these differences means that specifically identified spaces and their relationship to openings are essential for BRANZFIRE but are not necessary for FDS.

Contents

In many fire safety problems it is the contents and interior surface linings of a building which form the major hazard to life and property rather than the building structure itself. The IFC Model includes the ability to describe contents and the BIM tools include libraries of furniture and fixtures.

The most important information that is needed from the building model with regard to contents are the fuel burning properties. In particular the heat release rate is seen to be the critical property needed for fire growth modelling (Babrauskas and Peacock, 1992). Since the IFC Model is a general product model it does not contain the highly specific fire engineering domain properties needed to characterise the burning of the contents in a building. However this limitation can be addressed through the use of the property set definition capabilities of the IFC Model and this is illustrated later in this chapter.

The size and location of a fuel package is also of relevance to a fire growth model. The fire plume from fuel package that is close to walls will entrain air differently to those remote from walls. The development of the ceiling jet and its interaction with any fire safety systems will also be affected by fuel package size and location. BRANZFIRE does not need to know the exact location of a fuel package but only needs to know if it is close to or remote from walls. FDS is able to position fuel packages in their exact location and as a minimum it would be useful to be able to place a box in the middle of a room to represent a piece of furniture or a group of fuel packages. This can

be achieved by incorporating a piece of furniture item in the source building model, which would be exchanged as a furnishing element.

4 DATA EXCHANGE PROCESS

The complex relationship between the IFC Model and the range of fire simulation models means that a complete data exchange procedure cannot be simply laid out in advance but needs to be developed and tested through an iterative process. The use of a series of trial buildings that are created in a commercially available BIM tools, exported as STEP files and then processed as input files for one or more fire models is a suitable approach to this process. These trial buildings test the ability to correctly interpret the building geometry (i.e. wall and opening dimensions and positions), the building topology (i.e. the connections between spaces and to the outside) and the extraction of material property data from the IFC Model and determine where difficulties occur. This chapter describes how such a development process has been undertaken to investigate the transfer of building model data to BRANZFIRE and FDS. The specific needs of these fire simulation models means that a program has been developed to parse the IFC Model from the STEP physical file format to generate the fire model input files.

BIM Tools

Early work investigating the sharing of electronic building information with fire simulation models (Spearpoint, 2003) used Microsoft Visio Professional 2002 and a tool developed as part of the BLIS projects (BLIS, 2004) to create building descriptions and export them as IFC files using the XML encoding specification. However, it appears that no further development has taken place on MS Visio to keep up with new releases of the IFC Model and so IFC conforming STEP

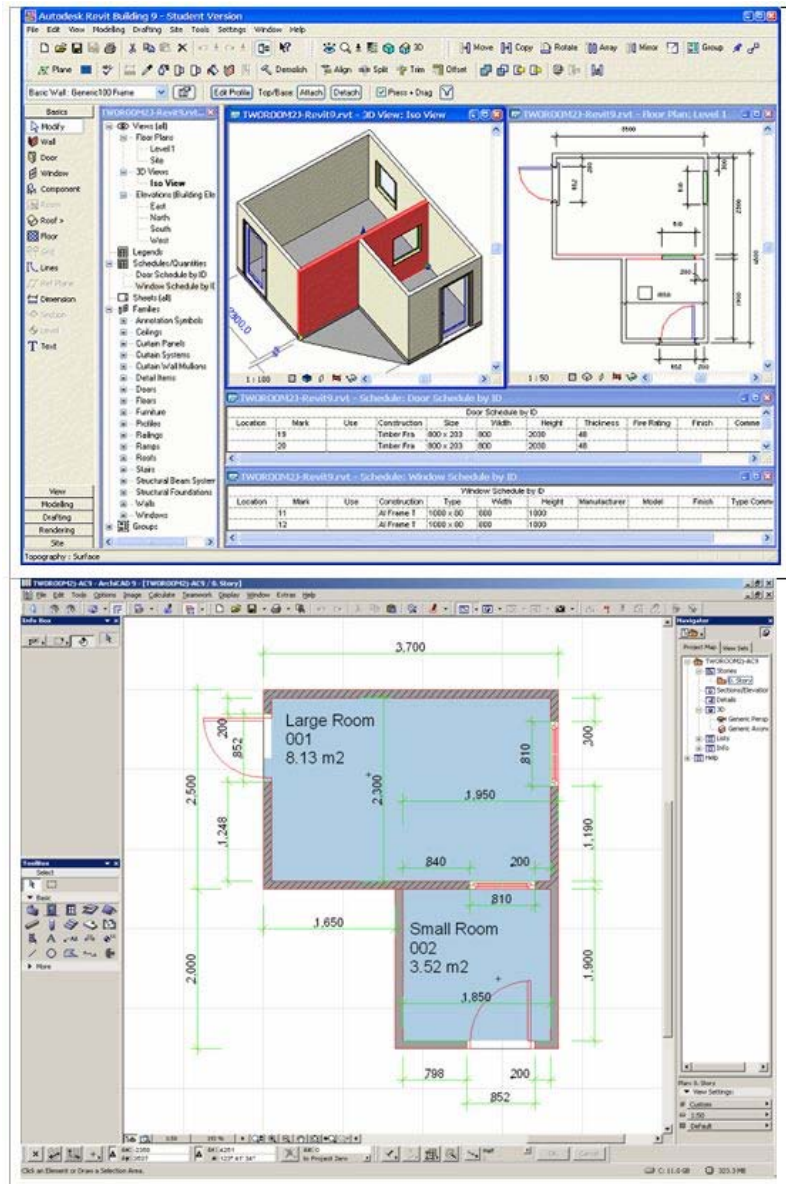
files have been generated using two commercially available BIM tools: ArchiCAD from Graphisoft and Revit Building from Autodesk (Figure 6). Both of these tools are integrated architectural design tools that represent buildings using a 'virtual building' model stored in a central database. Building elements such as slabs, walls, doors etc are used to construct a 3-dimensional model of a building. Building elements are intelligent objects that have their own associated properties and behaviour. The object-oriented approach means that the building model is more than the 2-dimensional line representation of a building that is common with traditional CAD systems. The tools can be used to view a building model not only as plans, elevations and sections but also can generate perspective and virtual reality presentations of the building.

Due to variations in modelling and IFC export implementations adopted by these two different BIM tools it has been found that the same nominal building model may be exchanged slightly differently in the STEP files and this is discussed in more detail later. Any exchange process must be able to cope with these variations and interpret the model correctly as intended.

Parser

Direct exchange between IFC Model conforming STEP files and fire simulation models is not currently possible so a parser is required. The purpose of the parser is to translate IFC Model files exported from the BIM tools into input files for either BRANZFIRE or FDS (and other fire models in the future) through an intermediate data structure (Figure 7). The current version of the parser software was built on earlier work in which the previous Release 2 of the IFC Model was accessed through its XML encoding. The reading of STEP files is accomplished by incorporating the IFC SECOM Server (SECOM, 2006) into the parser. The IFC SECOM Server tool includes

Figure 6. The Revit and ArchiCAD BIM design environments

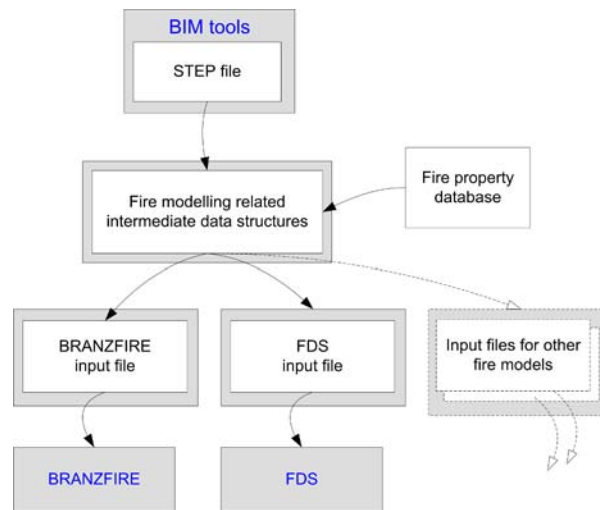


routines to interrogate and extract elements from a specified STEP file and it can be interfaced to Visual Basic or C++ source code.

The version of the parser is a stand-alone in-house program written in C++. It runs through a command line and does not include any form of graphical interface. The complex nature of the IFC Model means that it has been impractical to completely develop the parser software to process

every available entity in the IFC Model. Instead the initial software implementation has focussed on the interpretation of the geometry of spaces, connections between spaces and the basic material properties of geometrical elements such as walls and doors. The parser is also currently limited to interpreting CSG and Swept Solid wall representations that must be orthogonal to one another. The processing of simple buildings such as though

Figure 7. Fire modelling data exchange process



describing this chapter only takes a few seconds at most on a dual-core Pentium PC.

Test Case Building Models

In order to examine the mapping implementation from IFC Model to fire simulation models through the parser tool, a set of test case building models have been created. These test cases are used to verify the exchange of wall geometry as well as opening sizes and their positions from the original building models. The IFC Model compliant STEP (Part 21) files for each of the test cases were obtained by exporting directly from the BIM tools. The test case models were all constructed with the following common parameters and constraints:

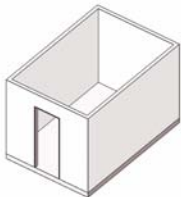
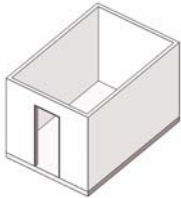
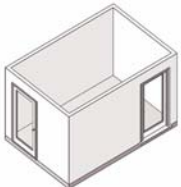
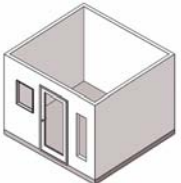
1. A topographical surface entity was specifically created where necessary and included for exchange as a site entity as this is required by the parser at the top level of the IFC Model data structure.
2. Due to the current limitations of the parser, all walls were constructed upright, equal height and orthogonal with respect to each other.

3. Space entities were not specifically created or included in the building models for the translation to FDS.
4. Door and window components included in the BIM tools were used. Wall openings in Revit were created using the wall cut-out modelling tool.
5. All building models consisted of only a single storey.

The test case building models were created with increasing levels of complexity and variations to specific details as noted in Table 2. Building representations consisted of simple rooms, pairs of rooms and finally complex multi-room models with external doors, a series of internal doors and a series of windows on external walls to create realistic modelling geometries that might be encountered in fire engineering practice. In general these buildings were not created for architectural considerations but were sufficient to test the capabilities of the parser.

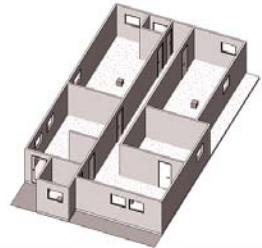
One of the simple trial buildings (Two-Room J) is discussed here in more detail to illustrate process of transferring the geometrical data. The building consisted of two different size rooms, the larger having approximately twice the floor

Table 2. Example test case building models

Name	Description	3D view
Single Room ISO9705 A	Single room 3.6 m x 2.4 m and 2.4 m high used in ISO 9705 fire test (ISO, 1993) with a single 0.8 m by 2.0 m door. Walls are all attached to the floor slab. Used to verify the exchange of basic wall geometry.	
Single Room ISO9705 B	Same as ISO9705 A, except that the door has been replaced with a wall opening of the same size. Walls are all attached to the floor slab.	
Single Room 2	Single room 3.5 m x 2.3 m and 2.4 m high. Two doors with different swing directions on the external walls used to verify the exchange of doors with different 'placement directions'.	
Single Room 3	Single room building with different types of opening, i.e. a window, a door and a plain opening, on an external wall. Used to observe how different types of opening are exchanged.	
Single Room 5A	Single room building with a window and a plain opening on one wall, a door and a window on another wall.	
Single Room 5B	Similar to Single Room 5A, except that walls are attached to the floor to investigate the effect of setting bottom constraints and the generation of a BREP profile for the wall.	
Two-Room D	Two-Room building with two external doors and one internal door, different swing directions.	

continued on the following page

Table 2. continued

Two-Room E	Two-Room with a plain opening on an external wall, a door on an external wall, a window on an external wall, and a window on an internal wall.	
Two-Room J	Two-Room with two external doors, one external window and one internal window.	
Multi-room	Complex multi-room building. Walls had no top or bottom constraints and a box object was also placed in the centre of each room representing a piece of furniture or a group of furniture items that might be the source of a fire.	
Cardington house	Ground floor of a residential house based on the geometry of a two-storey building which has been used for various fire engineering-related studies.	

area of the smaller (Figure 8). Two doorways to the outside were placed, one opening outward from the larger room and the other inward into the smaller room. Two windows were also placed, one to the outside from the larger room and another internally between the two rooms. The walls were all 2.4 m tall and 100 mm thick single layer of ‘common brick’. Flat 150 mm thick slab entities were placed at floor and ceiling level.

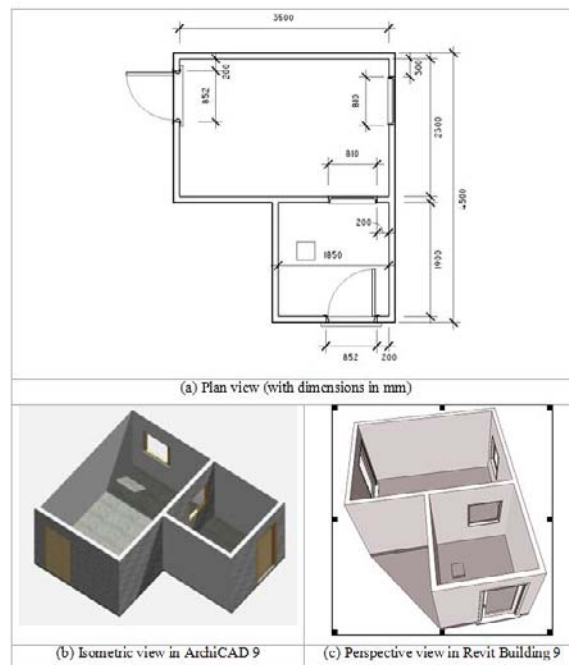
Figure 9 shows a successful conversion of the ArchiCAD generated STEP file as a SmokeView visualisation from FDS and as the dialogue boxes used by BRANZFIRE to define building geometry. The SmokeView visualisation is shown with the simulation duration set to zero seconds so that no

fire has been modelled. The dimensions of the room and internal window have been correctly identified and the room connection through the internal window defined appropriately. The wall thickness and material defined in the BIM have also been extracted. Similar results were obtained for the corresponding Revit generated STEP files, however the exchange of the test case building models raised a number of detailed issues that are discussed below.

Walls and Slabs

During the exchange process it was noted that the definition of a wall placement differ in the

Figure 8. Demonstration two-room building (adapted from, Spearpoint and Dimyadi, 2007)



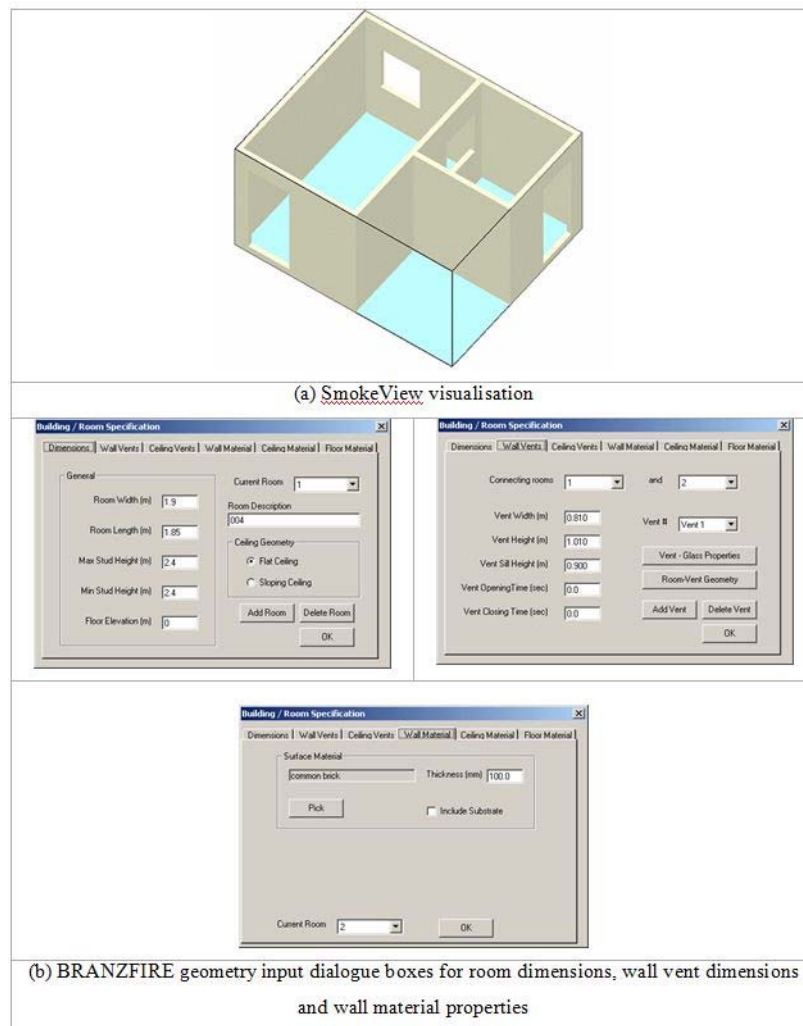
STEP files generated by ArchiCAD and Revit in that the facing of a wall from ArchiCAD is used to define its position by default whereas it is not in Revit. The placement origin or the positional coordinates of the wall exchanged in the STEP file is assumed to be on the wall centreline. This assumption may not always be true, as certain BIM tools may have the default placement origin set on the outer or inner face of the wall rather than the centreline. The parser needs to be able to detect if the placement origin deviates from the centreline of the wall by identifying this property in the STEP file. In the case where they are not on the centreline, the correct length of the wall and the placement coordinates can be determined accordingly. This is particularly applicable when the walls have mitred joints in which case the length obtained from the STEP file could either be that of the outer or inner face.

In Revit and ArchiCAD, floor and roof flat slabs can be used interchangeably and slabs are treated in a similar way as walls in terms of the parser. The parser needs to determine what a slab

represents in an IFC file so that it can correctly construct the fire model input file. The parser uses the position of the slab compared with the dimensions of an associated space entity. Slabs located at the highest vertical dimension of a space are assumed to be a roof slab and slabs located at the lowest vertical dimension of a space are assumed to be a floor slab. However this method will not be able to identify elements such as suspended ceilings that may be contained within a space or where spaces have not been explicitly defined.

One approach is for the user to define slabs on particular drawing layers and currently the parser will interrogate the ArchiCAD draughting property set associated with a slab entity and assume that slabs on a layer containing the word 'Ceiling' is a ceiling and slabs on a layer containing the word 'Floor' is a floor. Thus the user needs to ensure that specific drawing layers exist in their BIM environment and that slabs are placed on those specific layers. Although this approach is somewhat more flexible than the previous method it contravenes an overall philosophy of providing

Figure 9. Conversion of trial building into FDS and BRANZFIRE.



building representations in a form that does not require any user-specific configurations.

The current work only considers single storey buildings and for the FDS exchange the lower and upper boundaries of the computational domain are conveniently specified as being inert surfaces, eliminating the need to map floor and ceiling slab entities. In order to be able to map slab entities, the parser needs to be able to process BREP solid representations as all slabs are exchanged as these from Revit.

Doors, Windows and Openings

It was found that the representation of openings in ArchiCAD and Revit differed in that the reference point for the entity was not defined in the same manner. The Revit STEP file defines the x-coordinate local placement as the edge of the opening element entity whereas ArchiCAD uses the centre of the opening element entity. Similarly, the sill of a window-type opening differed in that Revit uses the local placement of the opening element entity whereas ArchiCAD places the sill

with respect to the parent wall z-coordinate placement. The parser has to be able to deal with these differences which could change with different releases of these and other BIM tools.

A wall opening is a void or hole through the wall without an associated door or a window entity. Wall opening objects must be treated differently as they differ in details to doors and windows openings and are exchanged differently in the Revit Building STEP file. When a wall opening is on a wall that is attached to the floor (i.e. with base constraints), the wall is exchanged with a BREP representation. In this case, the opening would be part of the BREP profile of the wall geometry and would not be exchanged as opening element entity. Due to the current limitations of the parser, in order for the wall opening to be correctly exchanged as an opening element, the base constraints of the wall must be removed in the source Revit building model.

Topology

Spaces and their associated connecting entities are processed by the parser to create a topological map. Internal connecting elements, such as a door between rooms, will appear twice in the map: once as a connection between space A and space B; and then again as a connection between space B and space A. These multiple connection instances are removed from the map before the final connection routes are determined. Currently this map is only required for BRANZFIRE and therefore requires the STEP file to contain appropriate space entities for a successful transfer. Neither ArchiCAD nor Revit automatically determine where a space entity exists within a set of boundaries so it is necessary for the user to insert these elements into the source building model (for example, by using the Zone Tool in ArchiCAD). Omitting the spaces will cause the parser to be unable to create the topological map for BRANZFIRE and also limit the parser's ability to identify floors and ceilings as noted previously.

Contents

Given the current limitations of the parser to resolve BREP geometry, complex shapes such as common furniture items cannot yet be mapped. However, the position coordinates of the furniture item can be exchanged relatively easily. For the purposes of mapping to FDS, this is assumed to be at the centre of the base of a representative furniture item. This assumption may not always be accurate as the position coordinates of the BIM furniture objects may be at different locations. However, for small furniture items located in the centre of the room and not in close proximity to any walls, the slight offset of the position coordinates is considered to be insignificant in terms of fire simulation.

Properties

The category types of property relevant to fire engineering have been described previously. Although some Category 3 properties are given in the IFC Model they are not used by FDS or BRANZFIRE and so are not extracted by the parser. The parser extracts wall and slab material names specified in the BIM and populates the fire simulation model input files with identified materials, but without any mapping to the fire model's internal database. Category 1 thermo-physical properties for walls, slabs and openings are not extracted as the ability to specify them in the commercial BIM software is not generally present.

Category 2 properties are not contained within the IFC Model and so would need to employ the property set definition mechanism. In the case of furniture or similar room contents, a heat release property set definition has been created that contains the information that is necessary to provide heat release rate. Essentially this information is a time-series heat release; however additional information has been included in the property set definition for completeness. The heat release rate can be obtained from basic material properties

for simple fuels such as hydrocarbon liquids but more typically from experiments for fuels found in buildings such as furniture and linings. Databases of experimental heat release rate measurements are available and in particular the XML-based database (Spearpoint, 2001) which is also directly accessible from BRANZFIRE.

5 DATA SHARING CHALLENGES

The exchange of IFC Model STEP files from two commercial BIM tools to two different fire simulation models through a parser highlights a number of major challenges that need to be addressed and these are discussed below.

BIM Implementation of IFC Model

The ability to create IFC Model entities in the BIM tools has potential downstream effects on the availability of those entities and their mapping to fire simulation models. This work has identified that use of the IFC Model and the STEP file output representation implemented by the BIM tools may differ in detail. Variations included whether an entity or property is incorporated by default or is optional, how the IFC Model is used to represent a specific entity (such as with walls) and the dissimilar encoding of entities in an IFC file. These variations required that the parsing software had to have specific algorithms to process IFC files from the two BIM tools.

For the user there is an associated complexity involved with the creation of large buildings in powerful BIM tools where the exchange process is limited by the ability to make use of the sophisticated software. The ability to exchange information is also constrained where a software vendor does not keep up with the most recently released versions of the IFC Model as was the case with MS Visio.

It has been found that the BIM tools do not always implement every facet of the IFC Model

and that few fire engineering specific entities are available even where they are defined in the IFC Model. Thus the mere existence of an entity or property in the IFC Model does not guarantee that a user will be able to easily create it in their chosen BIM tool. In some cases it may be possible to manually add entities or properties in lieu of having an appropriate functionality in a BIM tool through the use of the property set definition mechanism provided in the IFC Model.

Extraction of Elements

With the large number of entities specified in the IFC Model, considerable effort could be required to write the algorithms to extract these entities. The interrogation software may also need to be able to handle IFC files in either the STEP or XML encoding. The availability of software such as the SECOM Server (SECOM, 2006), greatly assists with the interrogation process as it relieves the developer of the need to start from the ground up.

It should be recognised that it is unlikely that every entity present in the IFC Model will be applicable to all domains. The parser described in this chapter for fire simulation models only processes a limited set of the IFC Model sufficient to obtain basic building geometry and properties. Further expansion to handle other entities is desirable but there are many entities in the full IFC Model that have no particular use for fire engineers. However, because of the quite different IFC Model entity properties needed for geometrical specifications, the extraction of entities is not an insignificant task.

Mapping to Fire Simulation Models

The mapping from the IFC Model to fire simulation models is constrained by the representation of the fire scenario as well as the implementation of that representation in a specific program. As already illustrated the zone modelling and CFD

modelling techniques have particular requirements and a specific program may also place further constraints on the ability to map IFC Model entities when compared to another program that uses the same fire modelling technique.

The interpretation of the product model has many challenges. The structure of entities may not be compatible with the requirements of the specific fire simulation model. This can happen where there might be insufficient detail in the product model but also where the requirements of the fire simulation model include simplifications and assumptions about a building that need to be accounted for during the exchange process. For example a space with a complex shaped footprint may have to be represented as an 'equivalent' rectangular room in a zone model. The exchange of material properties between a BIM and a fire simulation model is likely to require a specific mapping for each simulation model or the user will need to make manual changes to the fire model settings before any analysis is performed.

Finally, it is important to recognise that the requirements for a structural fire response analysis model will be quite different to those for a people movement simulation or a fire and smoke spread model and considerable effort is likely to be required to identify appropriate mappings for each type of model.

Efficiency Gains

The objective of using a standardised model of a building to obtain data for simulation software is an increased level of efficiency and whether this can be achieved is a reasonable question. On the positive side this work is showing that it is possible to obtain geometrical and topological data from rooms with a simple shape. However, where rooms are complex in shape or in the properties associated with the building elements, the user still is likely to have to intervene before executing their fire simulations. This raises the issue of whether the effort to create a virtual building

model using a BIM tool is worth it compared to directly setting up scenarios in the target fire simulation model.

Fire simulations conducted by a fire engineer invariably require some form of graphical record of the building being analysed. A virtual building model provides such a graphical representation that can be used to communicate with others in a written or oral report. Furthermore, where the building model has already been created by someone else, such as the architect, it still saves the manual re-entry of basic geometrical information even if some further manipulation is necessary. The benefits of using a common electronic building description become greater when multiple fire simulation models are considered. Changes to the building model are reflected in all subsequent runs of any fire model rather than each change being individually incorporated into each fire simulation program.

6 RECOMMENDATIONS

The work described in this chapter can be used to identify a number of recommendations for improvements to the IFC Model with respect to the needs of fire engineering, the implementation of the Model in BIM tools and the parser software. There is scope to add additional entities and properties that are of direct use to fire engineers as well as making adjustments to the IFC Model to match conventions used by fire engineers, such as discussed by Spearpoint (2006). The implementation of the IFC Model in BIM tools is slightly different in some details both across different tools and different versions of a specific tool. These differences complicate the transfer process so that having a common implementation method would be advantageous.

The complexity and scope of the IFC Model means that there are still considerable enhancements that can be added to the parser. The current version can handle less than ten percent of the entities avail-

able in IFC 2x2 and has not been tested with newer releases of the IFC Model. However it is recognised that there may be many of the IFC entities which will have no direct use in fire simulation software and future changes to the IFC Model are likely to be minimal for the entities of interest. The parser is limited to single storey buildings and the mapping of straight, orthogonal and equal height standard IFC Model wall and opening elements. Complex floor or ceiling geometries will not convert well in the current version of the parser and better algorithms for the identification of floors and ceilings need to be developed. Furniture items are currently exchanged only by their placement origin and no further details are exchanged. The thermo-physical properties of materials and the fire specifications are all user specified. Complex buildings such as multi-storey structures, those with non-rectangular footprints and composite material properties would all challenge the current version of parser and would almost certainly require modifications to the program. There is a need to continue testing the capabilities of the parsing algorithms using additional buildings including blind trials in which the parser representation is compared with that obtained by a fire engineer's interpretation of a building as input to various fire simulation models.

Changes to the parser also could reflect capabilities and enhancements to the available BIM tools in terms of their implementation of the IFC Model. Certain basic IFC Model elements such as a project, site and building storey are prerequisites in the source model although they may not necessarily be created by default in a particular BIM tool. The releases of ArchiCAD and Revit used in this work had limited ability to specify material properties and insert fire safety components into building model. As these BIM tools are developed or alternative BIM tools become available it may be possible to better map material properties and fire safety systems to fire simulation tools.

Both FDS and BRANZFIRE have been updated during the course of the parser development. Some recent work has investigated compatibility with

the current version 5 release of FDS. There are a number of areas where the input requirements for FDS 5 are different to that of the earlier versions particularly regarding the computational mesh definitions and multi-layered material specifications for solid boundaries. Development of the parser needs to correspond to changes in the fire simulation tools. In the longer term it is envisaged that IFC Model exchange with other commonly used fire simulation software will be created such as people movement and structural fire analysis tools. By gaining access to the source code of commonly available fire simulation software tools it might be possible to make the translation of an IFC Model file integral with the fire simulation software rather relying on a separate parser tool. However this may require considerable effort in order to integrate the parsing processes particularly where the original fire simulation source code was written some time ago or not in C++.

Finally, the current focus of the parser development has been to demonstrate the viability of using the IFC Model as an electronic description of buildings. As a result very little effort has been undertaken to develop a user-friendly interface and considerable work is needed to develop one. Some preliminary work on an interface is being undertaken by a third party developer.

7 CONCLUSION

There are benefits using a standardised general building product model such as the IFC Model but these benefits do not come without challenges. The ability to share building information with fire simulation models has the potential to assist fire engineers during the design process. The specification of a building can be quickly and accurately transferred from commercial BIM tools to fire simulation models used by fire engineers. However, the mechanics of transferring the information and the need to interpret that information to match the particular representation of a fire

scenario in a specific fire simulation model are not trivial matters. In terms of the specific parser tool described in this chapter, the current work has a number of limitations. Much more work is required before a tool such as this is available to practising fire engineers in a useful form.

Users and software developers need an appreciation of the limits of the building product model, the capability of specific BIM tools, fire simulation modelling techniques and the extensive range of fire simulation models that is available each of which differs in their specific requirements. Expertise and up-to-date familiarity of all these aspects is not easy to maintain particularly in a specialised domain such as fire engineering.

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KEY TERMS AND DEFINITIONS

Building Element: A physical part of a building such as a wall, floor, door, window, beam, column etc

Building Model: an electronic description of a building (or similar structure) which includes the geometry, topology and the property information related to building spaces and elements

Fire Engineering: The art and science of designing buildings and facilities for life safety and property protection in the event of an unwanted fire.

Fire Rating: The length of time that a building element is able to withstand a standard laboratory fire test.

Room Compartment Space: These are often used interchangeably although ‘compartment’ often has a specific regulatory meaning a space enclosed by building elements that have a specific fire rating.

Rate of Heat Release: The amount of energy released by a burning fuel as a function of time.

Fire Model: A mathematical representation of the processes involved in a fire. The model may include the physical, chemical, mechanical, physiological and physiological elements in which calculations are typically carried out using a computer code

Chapter 11

The Applications of Building Information Modelling in Facilities Management

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ABSTRACT

Effective processes in facilities management are responsive to the quality of information flow across various levels and stages of design, procurement and construction processes. Considerable empirical evidence from industry reports shows how construction and facilities management processes could be jeopardized by some of the limitations of conventional design and procurement processes. To address these limitations, there are promising indications showing that the potential of Building Information Modelling (BIM) will trigger major improvements in both construction and facilities management systems. This study reviews some of the capabilities of BIM which may revolutionize conventional practices in facilities management processes. Specific platforms for this include, integrated analysis and simulation of project variables in virtual environments, effective communication between project stakeholders and project teams and multi-disciplinary collaboration. Others are interoperability, project visualization, value intelligence and other digital facilities management applications. In the study it is argued that BIM capabilities such as project visualization, simulation, auto-alert and value intelligence could stimulate major improvements in facilities management processes. Finally conclusions are drawn on the relationships between BIM and digital facilities management, including suggestions on areas of further studies.

1 INTRODUCTION

Several well-known industry reports define construction as the combinations of inflow and outflow

of multi-disciplinary processes (Koskela 2000), complex systems (Bertelson 2003) and risky, dynamic, uncertain and unique protocols (Flanagan et al. 1987). Despite the limitations that underlie these relative but fragmented fundamentals, construction has continued to be an industry where the mechanics

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of infrastructural needs trigger economic opportunities. Further to this, investment goals in the industry's processes and constructed facilities are stimulated by different kinds of motivations. Ustinovichius et al. (2007) identified some of these investment goals and the nature of risks that are associated with them. Ironically, clients often see beyond or are less concerned about intangible risks. Olatunji and Sher (2009) have suggested that clients always desire absolute feasibility of their investments; and this is done without compromising certain economic goals. Indications from literature (Egan 1998; Latham 1994) suggest that managing project feasibility and clients' economic anticipation has always been an Achilles heel for the industry. Unfortunately, fragmentation of information processes and deficient frameworks that simulate and visualize facilities' life cycle have been the most significant factors that have lead to investment goals in construction not being met.

Recent research (i.e. Atkin and Björk 2008; Liyanage and Egbu 2004) concluded that the goal of facilities management is to, facilitate processes that enable projects to achieve their design intentions, maintain them over a long period of time and service them in flexible ways to widen the economic benefits to clients and end-users (in stable, sustainable and fulfilling project life-cycles). To do this, facilities managers often need information on, design intentions for spaces, equipments and accessories, uses and material limitations, liabilities and business drivers in relation to value enhancements and clients' objectives. Therefore, for constructed facilities to have fulfilling life cycles, project information needs to be systemic, balanced, comprehensive and integrative.

According to Lee et al. (2006), '*guaranteeing how fulfilling facilities will be*' has been a daunting problem that has challenged conventional fragmented processes in manual and CAD design systems. Even in the best scenarios, a wealth of

project documents containing design, construction and procurement specifications need to be transferred to facilities management professionals because these are often isolated from earlier parts of facilities lifecycle. Whilst several wealth of project documents have to change hands, -conventional approaches used for managing exchange of data- do have major risks as documents move from one stage to another.

This situation renders them vulnerable to damp, fire, theft and loss. This consequently places a major economic burden on facilities managers. Currently architectural, engineering, estimating and construction, and facilities management processes still grapple with inconsistency and loss of information from one stage of a facility's life to another. Many difficult problems that would damage the project goals and clients' interests always accumulate during a facility's post-construction life. Dean and McClendon (2007) concluded that the best way to avoid this quagmire is to include effective defragmentation of information flow in both horizontal (processes) and vertical (stages) directions of project development and facilities management systems.

Building Information Modelling (BIM) combines both digital information repository capabilities and the potential of integrated technologies to overcome the limitations of conventional design tools (Lee et al. 2006; Tse et al. 2005). It also provides platforms for stakeholders and project teams to collaborate, integrate, create and share data, effectively communicate, simulate and visualize projects in different projected circumstances. The aim of this study is to explore the applications of BIM in facilities management. The objectives are:

1. To identify the applications of BIM in facilities management.
2. To establish the frameworks for the deployment of BIM in facility management processes.

This study is explained in three parts. The first reviews the relevance and framework of process improvements in managing information for effective design, construction and facilities management. The next part discusses the challenges of contemporary facilities management processes; whilst the third part maps out the relevance and applications of BIM in digital facilities management.

2 PRODUCT DEVELOPMENT PROCESSES IN CONSTRUCTION

Construction facilities are created through unique development processes and systems with regulated protocols. This phenomenon is relative to timeliness, volume and quality of graphic and non-graphic information on, at least, the basic tangible components of the proposed facilities (Kirkham 2005; Kometa et al. 1995). On the other hand, there is significant evidence that underpins the impacts of challenges which often associate with creating, sourcing, manipulation, analysis, transfer, sharing, storage and application of discipline-specific data (Maher 2008; Succar 2009). These always have compelling effects on conventional methods of conceptualising, designing, estimating, planning, execution and management of facilities (Hansen and Vanegas 2003).

Several arguments have also established the implications of overt, covert and express generation and presentation of information on project components. These have been specifically focused on the natures of risks and uncertainties, project complexity, potentials for conflict, requirements and anticipated economic and functional returns on construction projects' goals (Kagioglou et al. 2001). Some studies often regard this phenomenon as having the potential to complicate variability of clients' goals; and has always had negative consequences on the image of the construction industry (Bower 2000; Sutrisna et al. 2005). Kagioglou et al. (2000) argued that construction

facilities are developed using methods and process protocols that are delimited by limitations from project conceptualisation through design, procurement and execution of construction works. As a result, there is high tendency that fundamental challenges are likely to accumulate in facilities' lives due to inefficiencies in project development processes. Ballesty et al. (2007) concluded that the best way to overcome this problem is to map out efficient methods of storing, managing and transferring data on the conceptualization, design, procurement, construction processes all through the entire whole-life of facilities. Koskela (2000) also mentioned that construction products are better off when process protocols are value-adding and goal-oriented rather than adhering to rigid and counter-productive conventions.

To facilitate effective access and management of information, all the process mechanics in Design, Procurement, Construction and Facilities Management (DPCFM) must comply with workable and standardized models (that comply with best practices in integrative technologies). Although, the industry is sensitive to the need to simplify information documentation, Atkin and Björk (2008) opine that significant research gaps exist between the need to underpin existing process models and the unique protocols that drive these systems. Despite the ongoing paradigm shifts in the industry's thrust from manual and CAD systems into integrated technologies, DPCFM industries still grapple with challenges on how to eliminate fragmentation between project stakeholders, software and project ends (Langdon 2002). Rather than promoting process improvement strategies using mechanisms that support integration, the proliferation of independent applications has been a major disincentive. According to Akintoye and Fitzgerald (2000), the proliferation of software application, in some circumstances, might create confusion and economic disincentive when they do not communicate with other applications and are not as effective as integrated systems.

Clients' expectations and project goals extend beyond induced interactions between technical and socio-economic indicators of project feasibility. There is growing evidence which points to clients' desires to deploy best practices and innovative advancements in information technologies as a way to secure optimum performance of their facilities (Ballesty et al. 2007; Luciani 2008). Integrated techniques such as simulation of construction processes in controlled virtual environments, project visualizations, object-oriented design methods and robust information databases of project components will spur improvements in project feasibility. These techniques will be covered comprehensively in a later part in this study. However, as an overview, the benefits of these technologies have been overwhelming when measured in terms of buildability, constructability, flexibility, maintainability, sustainability, marketability, returns' potential, energy efficiency and other indices of clients' goal in facilities cycle life (Häkkinen et al. 2007).

Reviewing the applications of project goals on project performance, some researchers (Kelly and Male 1999; Kim 1998) opined that clients' desires are inexhaustible due to variations in purposes, needs, capacities, interests and backgrounds of several kinds of construction facilities. However, part of the ultimate goal of developing construction facilities is the ability to deliver anticipated returns without being vulnerable to risks and uncertainties (Wong et al. 2004). Nonetheless, the roles played by information databases on facilities life cycles are important in managing facilities in terms of space, prescribed performance specifications and application limitations. Therefore, facilities managers regularly require information on project conceptualisation, design and construction in order to be prudent in managing spaces and facilities' components. Such information is essential to optimise flexibility during conversion, modernization, extensive over-haul, cost-in-use, data surveillance and management, and challenges associated with

use of facilities, and in appropriate application of their components.

BIM processes encapsulate a variety of techniques and technologies that create and embed robust information databases on components of facilities. These processes use procedures that could enable the evolution of appropriate platforms for improvements in construction (Aranda et al. 2008b; Norbert et al. 2007). Significant evidence on the deployment of BIM in construction processes suggests a propensity for improvements on previous attempts where manual and CAD application had been put to use (Langdon, 2002). Capabilities promised in BIM include improved collaboration, value integration, project visualization, simulation, simultaneous access to project database, effective communication among project stakeholders, cost effective information management systems, and other features of object-oriented design processes. Although, several authors often refer to the adoption of BIM in the construction industry as slow, there are strong indications that this situation is likely to improve (Aranda et al. 2008b; Ballesty et al. 2007; Keller 2005).

The basis for arguments on the need to overcome the problems in, conventional fragmented processes and unintegrated flow of information across project stages and ends, has been established in this section. The next focus however, is to underpin this argument with reliable evidence regarding the technical, economic and legal feasibility of BIM adoption in facilities management. Major issues in this regard include (1) What is there for project stakeholders to gain in integrated systems? (2) How sustainable are the structural frameworks (legal, skills, technology, institutional) for enabling this paradigm shift into integrated systems? (3) How workable are existing models for the application of BIM in Facilities Management? Prior to these considerations, it is appropriate to provide an overview of the contemporary challenges of facilities management processes.

3 CHALLENGES OF CONTEMPORARY FACILITIES MANAGEMENT PROCESSES

The focuses of an integrated information system in facilities management are to overcome fragmented processes, reduce the cost of outsourcing and sustain the essence of primary data throughout the life of a project. However, these tasks are information intensive and fraught with risks. Facilities management professionals, and indeed all the stakeholders in construction development processes, need to represent the building information in different market-specific models in order to effectively capture, assess and mitigate life cycle risks of projects. Then, they need to adjust their discipline-specific inputs into integrated process models in ways that are compatible with the new order. The challenge therefore is not limited to understanding the economic incentives in contemporary facilities management processes; other issues that deserve attention include the development of integrated models which are universally acceptable. They must also encompass active protocols in conventional systems and accommodate market responses to marked changes that go with this. To understand this challenge, a review of conventional process models is required.

As indicated in the literature (Egan 1998; Kim 1998; Latham 1994), clients and market drivers activate the protocols in facilities management models. Clients require clear and reliable information and professional advice to conceptualise project goals and expectations through realistic milestones (Hansen and Vanegas 2003). As such information becomes more definitive; clients' requirements and performance expectations on project components become less fuzzy. The challenge however includes how to generate the appropriate platforms for initiating and integrating these data through design and procurement processes, and still maintain its robustness until it moves on to facilities management professionals. Although, auto-briefing and intermittent involve-

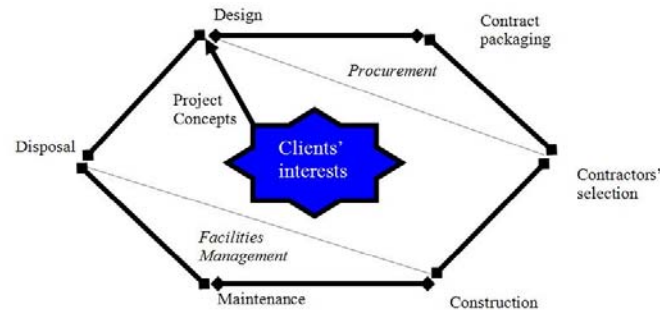
ment of clients at various stages of construction processes are possible alternatives (Kometa et al. 1995), some studies still portray clients' requirements as complex, inexhaustible, flexible and, at times, unrealistic (Gann and Salter 2000; Winch 2001).

Moreover, clients expect project teams to regularise the data provided in design briefs and close the gap between feasibility and performance. In addition to this, project teams must protect clients' interests, maximize accountability and value for clients' investments (Kirkham, 2005). On the other hand, an integral part of the challenges confronting projects teams includes the capacity to fully indemnify clients by mitigating project risks and uncertainties through feasible options across multiple arrays of project determinant matrices' variables. Such variables include flexible solutions for end-users' operational requirements, basic needs of clients, site conditions, government regulations, cost limits, culture, capacity and structure of available construction technology, environmental considerations and market forces. It is relatively easier to generate data on these indices and embed them as meta-data on integrated models rather than losing them to circumstances of life in conventional process models.

Construction processes are not always aligned with the long-term nature of construction facilities. Different teams are required to execute a different range of project-specific functions like design, contract packaging and selection of contractors, construction, facilities management and disposal of facilities. This is because processes and procedures are mostly fragmented across project stages as a panacea to mitigate specific risks and uncertainties. Figure 1 shows the structure of fragmentation in a typical project lifecycle. Frictions in business relationships often trigger dissipation of, information across systems and vital ingredients of project performance.

Despite the wealth of evidence regarding the relationships between construction process models and facilities management models, there is little

Figure 1. The structure of fragmentation in projects' whole life cycle



indication in existing research of how dynamically these links can affect contemporary facilities management models. Recent research (Abd El-Razek et al. 2007; Aibinu and Jagboro 2002; Endut et al. 2005) have explored the implications of overruns in construction processes. Fan et al. (2001) (citing Honk Kong Housing Authority, 2000), gave an insight into government's concern on the impact of poor quality of construction work and the corresponding effects on facilities life. In addition to this, Poon (2003) decried the consequences of clients' goal on facilities being jeopardized by professionals' deliberate, unwitting actions and inactions, as well as imposition of inappropriate decisions at various stages of design, procurement and construction processes. These, coupled with people issues, relationship problems and other factors (Ng and Skitmore, 2002), underlie the strains in conventional facility management models. Unfortunately, these limitations have remained relatively unchanged for centuries.

The goal of facilities management process modelling has been discussed earlier. The expectations of clients regarding facilities management are that, the investments must be recouped with returns delivered in time, the state of the facilities must be sustained, improved and be responsive to alterability. To achieve these, process models in facilities management are often regarded as largely dependent on need-based protocols that

are built on data-intensive systems. Lundgren and Björk (2004) concluded that facilities management organizations often adopt different approaches to meeting these needs. These include unstructured procedures, structured protocols or a combination of both. Arguably, unstructured procedures trigger esoteric uncertainties while structured processes need enduring frameworks and drivers. There is significant but growing evidence that modern facilities management process models support structured procedures; and on the other hand, the adoption of technical sophistication will fail in unstructured procedures, in both the short and long terms, if appropriate frameworks are not underpinned.

Facilities management process models require efficient frameworks to appropriately manage information across various stages of project development and facilities management. Information on project development processes will help facilities management professionals to model specifications on spaces, fixtures, fittings, energy consumption, procurement and other periodic necessities. Unfortunately, no two facilities are identical. Deploying data on existing facilities could trigger unnecessary concerns. Some of these data are not just likely to be cumbersome, they are also not accurate. The good way to proceed with this is the adoption of fully integrated systems where all project lifecycle data are created, managed and stored in digital

repositories. Regrettably, CAD applications lack the structure to service these because the embedding of non graphic data into graphic tools has not yet been realized in the industry since recent times. There is vast wealth of evidence showing that CAD applications comply with fragmented processes because most CAD options do not communicate with other CAD and CAD allied applications. Moreover, CAD applications are vulnerable to confusion, conflicts, omissions and errors (Tse et al. 2005).

4 BUILDING INFORMATION MODELLING AND FACILITIES MANAGEMENT

Recent studies (Aranda et al. 2008a; Lee et al. 2006; Tse et al. 2005) refer to BIM tools as the integrated design tools composed of related technologies that can be used to overcome the limitations of CAD applications – some of these limitations have been discussed in previous sections in this study. In addition to those fundamental constraints, CAD applications are limited to presenting designs with the use of ‘unintelligent features’ like lines, arc, circles, plane shapes, splines and sections. BIM, on the other hand, deploys intelligent objects that facilitate collaboration, simulation, project visualization, multi-discipline interactions, thorough integration and effective *real time* communication between stakeholders (Gu et al. 2008; Maher 2008; Norbert et al. 2007).

In BIMs object models of walls, floors, columns, windows, doors, furniture and roof etc are presented as distinct project components. These could be manipulated from higher dimensions (3D, 4D, or nD) to lower dimensions (2D) formats; and vice versa, without compromising embedded non-graphic data. Moreover, BIM also applies flexible and multidimensional capabilities that enable its applicability in various applications in architecture, engineering, estimating, construction and facilities management. Consequently, BIM

could mean different things to different users, depending on peculiarity and strategies of use. Aranda et al. (2008a) have discussed these definitions in relation to the business senses they make in professions where they are being applied.

One important attribute of BIM is the integration of both graphic and non-graphic data/meta-data on project components (Bacharach, 2009). Moreover, in the context of facilities management, object-oriented design processes are as important as the de-fragmenting conventional process barriers to information flow in projects’ whole lifecycle. This does not only provide platforms for value integration, in addition clients’ aspirations endure into designs whilst such databases are made robust, and transferred as underlying information in construction and facility management processes. Recent efforts (Barbosa et al. 2009; Maher 2008) argue that this potential provides platforms for project stakeholders to access project databases simultaneously, as well as simulate and visualize project, automate quantification, resolve design conflicts and communicate effectively in a genuine spirit of collaboration. From economic point of view, there are many benefits that are facilitated in the life of projects when designs are simulated in virtual reality models in terms of adding values to projects. This is a sharp contrast to conventional value management processes which require separate teams, longer time, and of course, more cost to achieve limited result (Barton, 2000).

Part of the economic benefits BIM provides is in integrated design systems. Design errors and delays can jeopardize project delivery in CAD’s conventional fragmented processes. Whilst integrated design systems palliate these, poor information structure is no longer an excuse in CAD systems to cause conflicts and shoddy execution of works during construction. Building Information Modelling does not only provide platform for facilitating objective creation, storage and retrieval of robust integrated data on design components, it enables comprehensive integration of maintenance and management data into

design objects. This scenario allows facilities managers to have first-hand information about the intentions and provisions of clients and designers about, end-users' liabilities, space allocation, procurement and streamlined information on use and application of project components. This is an exceptional breakthrough over conventional challenges. Commonly, facilities managers do not often have information on design intentions or such information, when made available, are too terse or at variance with realities in project life. Facilities manager are therefore left with limited options; to adopt processes that may not guarantee commensurate improvements in project life, or use available resources to compute all the needed information upon which realistic process models could be based.

According to Méndez (2006), Digital Facilities Management (DFM) models facilitate compliance with both facilities management goals and clients' interests. DFM allows facilities management professionals reduce the challenges of information dissipation across fragmented processes in DPCFM models. It uses procedures that eliminate data inconsistencies arising from *inter* and *intra* stakeholder frictions and conflicts, as information is shared or exchanged from one construction stage to the other through integrated systems. Comprehensive data on efficiency of components are developed in this process and they are based on realistic expectations of clients and end-users. These can be easily integrated into digital databases and applied in facilities lifecycle.

BIM is useful in digitising facilities management services in both new and old construction facilities. It is easier in new facilities wherein further information could be added -when due in a facility's life. However, project drawings of existing facilities could be standardized and digitalized using the process described in Khemlani (2007). Laasonen (1996) argues that on-site capture of physical data of facilities using geodetic/photo-grammetric technologies could be cheaper, better and more accurate. Nonetheless, BIM drafters and

modellers would only need to review the structures of old drawings in relation to existing state of facilities and underlay as much data as would be needed -at the present or later in the facility's life. Evidently, the applications of digital technology in construction and facilities management industries are not static. It is therefore expedient that BIM technologies improve with time to fully overcome some of the present challenges as well as break new grounds. Meanwhile, some of the specific applications of BIM in facilities management are briefly discussed as follows:

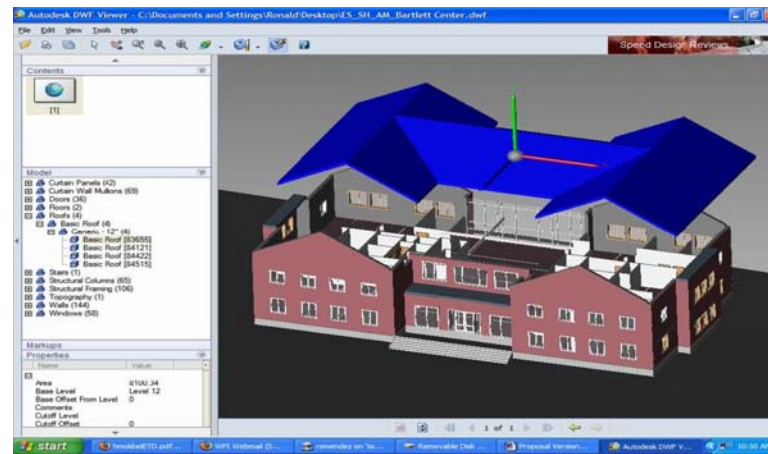
Project Visualization

BIM facilitates interactive digital reproduction of interiors and exteriors of facilities in 3D, by enabling rich photo-realistic presentations. Figure 2 shows project visualization for facilities management using a digital building model. It enables stakeholders to visualise project details in a VR environment using very reliable (i.e. architecturally accurate) resources (Laasonen, 1996). Project visualization facilitates effective collaboration between parties and promotes constructive analysis of project designs and space provisions. In addition to this, it allows clients and end-users to review their intentions using multiple options in ways that optimise, value generation in investments and flexibility in (use and) management of facilities. Moreover, design conflicts and data inconsistencies can be detected early. Furthermore, BIM-enabled project visualization adds value to communication. With this technology, it is now possible to conduct off-site training on screen for purpose-made and general-need maintenance and operations and at the same time simulate the functions of project components.

Behaviour Simulation

Simulation allows standardized models of facilities to be visualized and analysed in replicas of real life systems using 'reactive objects' to predict

Figure 2. Project visualization in facilities management using BIM (Adapted from Méndez 2006)



possible situations. The use of avatar for simulation in construction is new and rapidly developing. Maher (2008) argues that the reliability of avatar applications in predicting productivity and creativity in construction project design is increasing. The implications of BIM-based simulation in facilities management are such that components and objects are programmed to exhibit certain characterizations in varying environment. Such include visualization of presumed end-users' reactions to energy consumption, environmental impacts and sustainability variables, flexibility of use, response to emergencies, situational impacts of comprehensive maintenance operations like

alteration, conversion, modernization and so on. With this method, it is easier to reduce uncertainties and risk. Figure 3 is an example of simulation in facility management using avatar.

Auto-Alert

Building Information Modeling does not only provide appropriate platforms for stakeholders to share information, it allows all collaborating professionals to sort all information they need in the project server and input their discipline-specific information on the models. Information on intelligent objects of facilities' designs can

Figure 3. Simulation in facilities management using avatar (adapted from AMF-3D, 2008)



include lifespan data, limit of use and modification, milestones for, procurement, planning and supply chain management, inventory control and match-sequencing of corresponding alternatives. Given these variables, facility management professionals using BIM-based digital procedures are confronted with fewer challenges regarding items to change, how, where and who to execute the job. From one-point source, design components like furniture, services' equipments and fittings, lifts, wall, floors, roofs, doors etc. could tell the users and managers when they are over-stretched, underutilized or due for special attention like maintenance or replacement; and who is specifically scheduled to execute such works. This can be extended using chip technology for location tracking and security purposes.

Value Intelligence

Digital facilities management enabled by Building Information Modeling allows clients, facilities management professionals and other stakeholders to conduct analytic cost-in-use and value management routines. Cost-in-use analysis provides analysts appropriate data when deciding on economic performance of components in facilities' life, both in design conceptualization and facilities management scenarios. The procedure allows valuers to compare the relationships between immediate cost gains and value-adding compatibilities of alternative components. On the other hand, value analysis and management allows major stakeholders involved in project development in facilities' life to further collaborate and facilitate constructive patterns for justifying the relationship between components' value and functional requirements in facilities' design, use and management (Barton, 2000). In other words, while cost-in-use analysis is about creating value through optional costing, value analysis and management create pathway for defining essences that justify the choice of particular components on the basis of functionality. With the use of Building

Information Modeling in digital facilities management, alternative options for cost-in-use analysis could be generated from wider sources, thus, the gap of uncertainties between hard (well defined objectives) and soft (undefined objectives) value management approaches would reduce.

Several studies have proposed comprehensive clarifications on issues relating to the adoption and deployment of BIM in project design, estimating, planning, construction and facilities management (Aranda et al. 2008b; Gu et al. 2008; Olofsson et al. 2008). In these reports, several case studies were presented with strong evidence on business gains and performance values that all stakeholders on, facilities developments and management could benefit from. Nonetheless, going by indications from rapid changes promised in BIM, it is expedient that further studies will concentrate on concomitant appraisal of frameworks to maximise the utilization of BIM and other related technologies in facilities management (Keller, 2005).

Keller (2005) compared the procedures for process models in manual and automated processes in facilities management. The merits of Digital FM include the following:

1. Identify clients' business objectives in the relation to the state of the facility.
2. Access facility based on industry's Integrated Definition (IDEF) scorecards and Benchmarks.
3. Conduct end-users' needs analysis and project possible reaction to future changes.
4. Define system requirements and integrate real time access information.
5. Acquire integrated systems, best practices and allied technologies, to track end-users' requirements and for continuous assessment of the facilities' conditions.
6. Implement integrated protocols and access all the processes and systems involved.
7. Review project details in relation to Digital FM model processes and systems and adjust these appropriately.

Evidently, these models are vulnerable to changes in technology and systemic shifts in clients' needs and aspirations. BIM promotes better orientations to improved need identification and risk assessment towards adding value to project lifecycle. Arguably, training and system improvement procedures are expedient factors that would facilitate the needed change in facilities management professionals, stakeholders and organizations. All stakeholders in project lifecycle require exceptional skills for collaboration and teamwork to overcome the cultural and professional limitations. The earlier facilities management principles are integrated into design conceptualizations the better. Since BIM provides platforms for all stakeholders to collaborate, share and integrate their discipline-specific inputs, FM professionals' roles at project conceptualization stage could translate into meaningful benefits in projects' lives. Such roles establish the relationships between end-users' requirements and clients' expectations. This is further juxtaposed with empirical data regarding project risks, functionality and feasibility indices, environmental impacts and interface management across all process in facilities life. Consequently, there would be more reliable inferences that might assist design, procurement and construction processes. From available data at project conceptualization stages, preliminary specifications should outline clients' (and design) intentions for spaces and project components. This would enable facilities management professionals to advise design teams on the vulnerability of design concepts to certain indicators that could affect post-construction goals of the project. Such include, security assessment, response to emergency, cost-in-use and value assessment, as well as need and space analysis. Furthermore, with comprehensive information on design components, facilities managers would be able to predict susceptibility of project components to degradations; their causes, implications and provisions for alternative options.

5 CONCLUSION

Project development processes in architectural, engineering, estimating, construction and facilities management industries require clear and intensive information to minimize risks and uncertainties and meet project goals. Unfortunately, conventional CAD tools lack appropriate structures to facilitate, the integration of project information into a design database. However, Building Information Modeling is a combination of some emerging techniques in digital design, construction and facilities management processes that could close the gaps of fragmentation. BIM allows all stakeholders to collaborate, communicate, share data and integrate discipline-specific information into design/project databases. This procedure allows improved practices that could translate into major benefits in facilities' life. Opportunities promised by Building Information Modeling include project visualization, simulation, auto-alert, cost-in-use and value analysis, as well as value intelligence. Building Information Modeling enables FM professionals to manage comprehensive information on relationships between design intentions, end-users' requirements and components' use. Consequently, robust information will facilitate enduring value performance of facilities. Other benefits of BIM in facilities management include quality in training and availability of reliable data for effective planning and timely on-sourcing. To fully deploy the benefits of this study, the following are recommended as possible areas for further studies:

1. There is the need to gather and analyse empirical data on the impacts of inefficiencies in construction processes on lifecycle of facilities.
2. Since the expectations of clients and end-users are indexical, there is the need to close existing research gaps in deploying acceptable methodologies for developing

structured universal models that are workable, flexible and user friendly.

3. The adoption of BIM is either slow or not yet adopted in many countries. Also, the drivers of business incentives in DFM are not yet comprehensive, despite massive evidence that support the revolution they trigger in FM conventions. Therefore there is a need to adopt responsive framework that could monitor the relationship between BIM adoption and its impacts on Digital FM.

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KEY TERMS AND DEFINITIONS

Building Information Modelling (BIM): Building information modelling (BIM) encompasses integrative concepts being used in digital information repository systems to simultaneously create, store, share, simulate, engineer and visualize whole life information in building models.

Construction Processes: Construction process is the combination of processes or arts involved in constructing; the act of supplying, fixing, installing, fabrication, composition and other activities that are necessary in the course of executing construction tasks.

Digital Facilities Management (DFM): Digital facilities management (DFM) involves the use of integrated systems to automate facilities management functions. This includes sourcing, lease management, move management, CAD integration, auto-alert, space planning, preventive and demand maintenance, auto-reporting and management of information flow across fragmented processes in facilities life cycle.

Integrated Systems: Integrated system (IS) is a defragmented system that allows stakeholders to share common ground with access and usage of data, nomenclatures, applications, presentations and operations.

Process Models (PM): Processes models (PM) are processes of the same nature that are classified together into a model. It involves the description and/or prescription of processes by the instantiation of levels to define process procedures and fuzzes.

Project Feasibility: Project feasibility defines how a construction project exemplifies the life-cycle of a facility across an array of concepts. These concepts include sustainability, energy efficiency, maintainability, constructability, functionality, legality, social, economic viability, operability and determination of competitive advantage

Virtual Enterprise (VE): Virtual enterprise (VE) is a temporary telematic alliance between stakeholders in the development of building models to collaborate and share data, core competencies, and skills.

Chapter 12

Developing Context Sensitive BIM Based Applications

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ABSTRACT

Current Building Information Model (BIM) based applications do not integrate well with the varying and frequently changing work processes of Architectural, Engineering, and Construction (AEC) professionals. One cause for this problem is that traditionally software developers apply software design methods that aim to design software that cater to a broad range of different users without accounting for the possibility of changing work processes. This chapter theoretically introduces a different method to design software - context sensitive software development – and theoretically argues that it is poised to enable application developers to adjust BIM based applications to the varying and frequently changing work processes of AEC professionals. As a first starting point for the practical applicability of the theoretical method, first user categories that BIM based application developers can use as a starting point for the analysis of different user contexts are provided. These categories were derived from the author's experience supporting more than ten projects with the implementation of BIM based applications and from what they learned on a number of industry BIM workshops. The chapter closes by mapping out future research directions to evaluate the practical value of the method and with a theoretical analysis of how researchers can apply state-of-the-art software development methods, software development technologies, and software dissemination models to support their research.

1 INTRODUCTION

The use of BIM based applications on AEC projects is still rudimentary and fragmented (Hartmann et al.

2008). One reason for this is that their development is complicated by two characteristics of the AEC industry. For one, the AEC industry is a project based industry that organizes its workforce around projects. Companies form project teams that work detached from the formal hierarchy of the firm. Ad-

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ditionally, on projects different project teams from different companies work together. Thus, projects are quasi-organizations (Eccles 1981) consisting of different project teams from different companies that need to work together to achieve project success (Dubois & Gadde 2002). To account for this project based structure of the AEC industry, BIM based software therefore, need to account for a large number of different and often conflicting groups of stakeholders. Moreover, AEC projects are mainly concerned with the construction of unique facilities and thus, operate in uncertain, complex, and frequently changing environments (Kreiner, 1995). Thus, information from and about the environment is also conflicting and changes frequently. This further causes needs and objectives of different project stakeholders to become ambiguous and ill-defined. It is often, not even easy to formally understand the requirements of a single stakeholder group never mind accounting for the multi stakeholder perspectives. Overall, due to the above reasons it is hard for software developers to develop general use software applications to meaningfully support AEC work processes.

In general, it is of utmost importance during the development of any software program to account for the different perspectives and roles of the intended users (Checkland & Scholes 1990). This is important to ensure that these software solutions become meaningful to improve the users' work practice (Carroll 2000: 45-47). Technology developers need to focus on users and their actions instead of focusing on the technical possibilities (Carroll 57). Additionally, developers need to focus on supporting interactions between different user groups (Sato 2004; Lim & Sato 2006; Haymaker et al. 2004). It is obvious that due to the above characteristics of the AEC industry this should hold especially true for technology developers that work on BIM based applications.

Unfortunately today, many BIM development efforts do not account for specific users and their

viewpoints. Instead, currently many BIM development efforts focus on establishing standardized databases to store building related models – so called building information models (Fox & Hietanen 2007; Vanlande et al. 2008) – or they focus on how AEC practitioners can model a building to store in such a database – so called building information modeling (Eastman et al. 2008). Contrary to these efforts, this chapter focuses on the development of applications that support the work processes of AEC practitioners for which the chapter uses the term BIM based applications. The chapter defines a building information model as exactly what its name states: a model to describe information related to a building. In this way, BIMs allow storing information that is related to a building in electronic databases. Such BIM information can describe the physical shape of the building, so called product information, and the management processes to build or manage the building, so called process data. Simple storage of information alone however, cannot in itself, improve work practices. Software applications need to meaningfully access, visualize, and offer the possibility to alter the electronically stored product and process information. To account for this difference between BIM databases and applications that use such databases, the chapter therefore uses the term BIM based applications. BIM based applications allow users to understand information stored in BIMs better, by for example providing possibilities to easily access and visualize information. Further, BIM based applications enable users to generate new knowledge with respect to a building's design or related management process and to again store this data within a BIM database.

To help BIM based application developers with their efforts to purposely support the decision making of AEC professionals, this chapter introduces context sensitive software design as a method of how developers can explore and describe the context of stakeholders and theoretically argues

that the method enables software designers and developers to adjust BIM based applications to specific user and project contexts. The chapter begins with a theoretical overview about context sensitive software development. In particular, the chapter summarizes latest research efforts that are related to context sensitive software development and implementations, such as scenario based software implementations (Carroll 2000), context sensitive interactive systems design (Sato 2004), identification of software use situations (Lim & Sato 2006), and engineering viewpoint construction (Haymaker et al. 2004). In this section, it is also logically derived why context sensitive software development is theoretically poised to support BIM based application development. To give software developers a first starting point in identifying and describing scenarios for their development effort, the chapter then describes different categories and project stakeholder groups. These context categories are based on a solid empirical basis using data from past research efforts that observed the implementation of BIM on a large number of construction projects (Hartmann et. al 2008), data collected on industry workshops with practitioners (Hartmann & Fischer 2007a), and in general, on the author's knowledge gathered during participatory research and consulting work within the AEC industry. The paper closes by outlining directions for future research. These directions include the call for future empirical research to validate the chapter's theoretical claim that context sensitive design is poised to overcome the problems of developing BIM based applications for the construction industry. Further, it is suggested that future research should explore the general context and stakeholder categories of this chapter in more detail, and research ways and methods to develop software that can support multiple contexts and that is easily adjustable to changing contexts.

2 DEVELOPING CONTEXT SENSITIVE BIM INCORPORATING A MULTI-STAKEHOLDER PERSPECTIVE

In this section, it is theoretically argued that context sensitive software design has the potential to solve the problems that BIM based developers face with supporting AEC practitioners with useful BIM based applications. Context sensitive design relies on capturing the design requirements in scenarios that describe how users can potentially improve their work processes with a BIM based application. Scenarios are stories about people and their activities in a potential work environment that is supported by a new technology (Carroll 2000: 46). Scenarios should include different agents with competing goals and their actions, but also all other important information to describe a particular context that a technology can support. Scenarios should focus on the needs of the user and not on the technical possibilities.

Additionally, scenarios should be as detailed as possible and include context information that describes the environment of the user. Context information needs to account among others, for the specific environment of users, including spatial and temporal considerations, possible artifacts that users might employ within a work process or different environmental constraints that users face. In summary, using scenarios software developers can identify specific AEC project work processes BIM based applications can improve. Additionally, by describing the different BIM based application users and their actions in different scenarios, application designers can easily gain a better understanding of the users' needs. Equipped with this better understanding, BIM based application developers can then program BIM based applications that are more meaningful to support the users work processes.

Another advantage of using scenarios is that they are easily understandable by different stakeholders. Therefore, software designers can

directly discuss software design alternatives with different user groups. Such discussions will further improve the potential of the BIM based application to support the users' work processes. Additionally, the possibility to discuss different scenarios help software designers to understanding the differences in work processes between the different stakeholders. This can help developers to integrate varying viewpoints during their BIM based application development efforts.

One disadvantage of scenario based design is that after BIM based application developers have identified different user scenarios it is difficult to explore and identify the necessary interfaces between these scenarios. Therefore, it is hard at the outset for BIM based application developers to create BIM based applications and related BIM databases that can support multiple identified scenarios. While this problem at first seems to be a major problem of scenario based design, it is a general problem during each design of multi-stakeholder BIM based applications. Thus, with or without a context sensitive approach developers need to identify the information that different stakeholders require to exchange.

Moreover, context sensitive software development helps developers to search for commonalities and differences in the different scenarios. This, however, requires that developers describe scenarios in a standard way to allow for an integration of them (Lim & Sato 2001). To be able to develop such standardized scenario descriptions, developers need to describe different user scenarios in a common language (Lim & Sato 2006). To do so, BIM based system developers need to use and should be aware of a number of categories that can help to describe contexts across different scenarios. The next section describes a number of such context categories for BIM based application development. Developers can use these categories as a starting point to develop more detailed and custom tailored context categories to describe varying scenarios for the different stakeholders

that a specific BIM based application development effort addresses.

In the end, with a standardized description, developers can then represent the different scenarios within a common representation scheme. Possible schemes that allow such a standard description are, for example, use case diagrams and use case narratives that are part of the unified modeling language (UML) the standardized modeling language for object oriented software development (Dobing & Parsons 2006; Dennis et al. 2005). Based on the standardized representation of the different identified user scenarios, developers can then evaluate the required information exchange between different stakeholders within a user scenario and the required information exchange between stakeholders of different user scenarios.

In summary, theoretically, context sensitive software development seems to overcome some of the problems during the development of BIM based applications that can support the frequently changing and varying work processes of AEC professionals. Some researchers, though they do not explicitly use the term context sensitive software design, have provided first empirical evidence for this claim. For example, Haymaker et al. (2004) have developed a formal technique for analyzing the required information exchange within multi-stakeholder environments and applied it on a large scale construction project. Similar, Hartmann and Fischer (Hartmann & Fischer 2007b; Hartmann et al. 2009) have developed a process to support the constructability review by improving 4D software applications to specifically support several user contexts.

3 PROJECT CONTEXT CATEGORIES

As mentioned earlier, to enable software developers to identify and to represent scenarios, they require context categories that allow for a standard

description of different scenarios. In this section, a number of such categories that can serve as a first starting point for future context based software development efforts are presented. These categories are derived from the author's experience that was gained from supporting the BIM development for specific project contexts on eight projects in person, according to their review of BIM based application implementations on 27 historical projects (Hartmann et al. 2008), and from what they learned on several industry conferences and workshops, such as the one described by Hartmann and Fischer (2007a). Table 1 summarizes the projects that the categories are based on. However, completeness for the categories cannot be claimed. Moreover, it is believed that researchers cannot completely derive general context categories at all. BIM based application developers should and need to develop specific context categories to describe stakeholder scenarios that are custom tailored to specific BIM based application development efforts, project contexts, or stakeholder groups. Nevertheless, BIM based application developers can use the following categories as a starting point to develop more detailed categories for their specific development project. The rest of this section describes each of these context categories in detail.

State of Decision Making

One important context consideration that is currently and often omitted during BIM based application development efforts is the state of decision making a user is in. On a general level there are two main states of decision making:

- Does the respective stakeholder want to make a decision and, therefore, needs the BIM based application to support his decision making, or;
- Does the respective stakeholder want to communicate a decision to other stakeholders and, therefore, needs the BIM

based application to support him with the communication of a ready made decision.

Ewenstein and Whyte (Ewenstein & Whyte 2007; Whyte et al. 2007) use the terms fluid and frozen to describe the state of artifacts in their relation to the above described states in the decision making process. These terms are applied to the state of decision making a user is within a specific context and label contexts in which a user needs to support and help the making of decision as fluid. Contexts are further labeled in which a user needs to communicate ready made decisions as frozen.

BIM based applications within a fluid context need to support ongoing decision making tasks. BIM based applications in a frozen context need to support the communication of readymade decisions between different stakeholders. Both contexts require significantly different BIM functionality. In the fluid context, the BIM based applications need to provide the ability to collect relevant information about the project and to visualize this information to support the decision making process itself. Additionally, these applications need to provide the easy possibility to quickly change the information to develop and evaluate new alternatives for the product or the project plan that is represented by the information. In the frozen context, BIM based applications need to provide the ability to enter relevant information about a ready made decision in a simple and easy way. Furthermore, in the frozen context applications need to support the visualization of the ready made decision to support its communication to other project stakeholders.

It is also important to recognize that BIM based application users need to make two different types of decisions: decisions that are related to the physical shape of the product that is built, and decisions with respect to the process of how to build the product. These two types of decisions usually alternate with respect to their frozen and fluid status. After freezing decisions with

respect to the product it is, often it is necessary to make decisions about the process of how to build the product, including financial, resource, and schedule related considerations. During the

implementation of BIM based software applications, it is therefore, important to consider both of these two decision types and their alternating character.

Table 1. Summary of the projects used to derive the context categories

Project	Country	Year	Type	Size	Involvement
P1	USA	2004	Transportation	> \$100 Mil.	BIM Implementation Support
P2	USA	2004	Office Building	\$5 - \$10 Mil.	BIM Implementation Support
P3	USA	2005	Transportation	> \$100 Mil.	BIM Implementation Support
P4	USA	2006	Health Care	> \$100 Mil.	BIM Implementation Support
P5	USA	2007	Health Care	> \$100 Mil.	BIM Implementation Support
P6	USA	2007	Transportation	> \$100 Mil.	BIM Implementation Support
P7	USA	2007	Transportation	> \$100 Mil.	BIM Implementation Support
P8	Romania	2007	Sports Complex	> \$100 Mil.	BIM Implementation Support
C1	USA	1997	Commercial	<= \$ 5m	Review of Historical Data
C2	USA	1997	Industrial	<= \$ 5m	Review of Historical Data
C3	USA	1998	Institutional	>=\$ 100m	Review of Historical Data
C4	USA	1998	Commercial	>=\$ 100m	Review of Historical Data
C5	Finland	2000	Institutional	\$ 5-100 m	Review of Historical Data
C6	USA	2000	Commercial	>=\$ 100m	Review of Historical Data
C7	USA	2001	Industrial	>=\$ 100m	Review of Historical Data
C8	USA	1999	Institutional	>=\$ 100m	Review of Historical Data
C9	China	2001	Commercial	>=\$ 100m	Review of Historical Data
C10	USA	2003	Institutional	\$ 5-100 m	Review of Historical Data
C11	USA	2000	Institutional	>=\$ 100m	Review of Historical Data
C12	USA	2002	Commercial	\$ 5-100 m	Review of Historical Data
C13	USA	2003	Institutional	>=\$ 100m	Review of Historical Data
C14	UK	2003	Transportation	>=\$ 100m	Review of Historical Data
C15	Sweden	2002	Residential	<= \$ 5m	Review of Historical Data
C16	Norway	1997	Residential	<= \$ 5m	Review of Historical Data
C17	USA	2004	Institutional	>=\$ 100m	Review of Historical Data
C18	USA	2004	Institutional	\$ 5-100 m	Review of Historical Data
C19	South Korea	2004	Industrial	>=\$ 100m	Review of Historical Data
C20	USA	2004	Transportation	>=\$ 100m	Review of Historical Data
C21	USA	2002	Residential	>=\$ 100m	Review of Historical Data
C22	Finland	2004	Residential	\$ 5-100 m	Review of Historical Data
C23	Finland	2004	Residential	<= \$ 5m	Review of Historical Data
C24	Finland	2003	Commercial	\$ 5-100 m	Review of Historical Data
C25	Finland	2005	Residential	\$ 5-100 m	Review of Historical Data
C26	Finland	2003	Residential	\$ 5-100 m	Review of Historical Data

Level of Detail

Another important consideration during the development of BIM based applications is that the application needs to make the right information available to the right person at the appropriate level of detail (Pulaski & Horman 2005). It is therefore, important during the development of BIM based applications for a specific scenario to understand the level of detail of the available information in the frozen state and the level of detail in which the BIM based application needs to represent fluid information. On a very general level, developers can distinguish between two different detail levels of a BIM: conceptual and detailed. Again, this categorization can only help developers to understand the context of stakeholders on a general level but developers need to conduct more in-depth research about the required level of detail for a BIM based application in each of these project stages.

Techniques are available to allow the dynamic switching between different hierarchically sorted levels of detail for one kind of information, such as work breakdown structures for construction schedules (Project Management Institute 2006), cost breakdown structures for cost information (Zimmerman 1995; Usry & Matz 1980), or hierarchical decomposition functionalities for geometrical information (Gnanendran & Sundarraj 2006; Kamat & Martinez 2002; Tan & Benbasat 1990).

These techniques allow BIM base application developers to implement single applications that cater towards the needs of specific stakeholders in the process. If it comes to linking several different kinds of information, such as data in so called 5D applications (Chen 2008; O'Brien 2000) that promise to link schedule, cost, and geometrical information, then practical solutions are by and large not existing yet. This is mainly due to the fact that the hierarchical storage of data to represent the level of details for different types of information is no longer possible. For example,

to allow effective decision making about the cost and material supplies of a project, BIM based applications should represent data in different levels of detail sorted according to building materials. At the same time, to allow for effective decision making about a project's schedule information, BIM based applications need to represent information in several levels of detail sorted according to spatial zones. These two hierarchies are often conflicting as different materials can be contained within one construction zone and vice versa. Therefore, BIM based application developers need to explore specific links between hierarchies, and BIM based applications should provide automated algorithms that can convert one hierarchy into the other. To do so, BIM based application developers need to closely observe practitioners and identify their needs with respect to the level of detail of the different information types. They can then use this context information to carefully implement decomposition data structures and conversion algorithms that fulfill the needs of all necessary participating stakeholders.

Hardware/Software Environment

Further, it is important during the development of BIM based applications to realize that different stakeholders work in different contexts with respect to the availability of hardware and software. BIM based application developers should distinguish, for example, between contexts according to the availability of computing power. These contexts might range from high-end computer networks, to run sophisticated engineering simulations and renderings, to old workstations or laptops. BIM based application development has even started to support handheld devices, such as personal digital assistants (Wang 2008).

In this context, developers should also consider the different display devices available in a specific context. High end BIM visualizations that look photorealistic on a 21" monitor, might lose a lot of their representative power if showed to a

large audience using an old projector. Similar, the resolution of today's computer screens is not yet able to display complicated two dimensional construction drawings in the required level of detail. Thus, professionals still need to plot construction drawings and thus, the availability of a plotter might be an important context consideration.

Next to the consideration of different hardware contexts, it is also important for BIM based application developers to account for the specific software that particular stakeholders have access to. Many BIM based applications, for example, offer free viewers that enable stakeholders, for who it is not feasible to purchase a commercial BIM based application, to explore frozen BIMs. Hereby, it is again of utmost importance to consider the status of the decision making within a specific context and what information stored in a BIM needs to be frozen and fluid. Standalone viewers, for example, do not allow users to change underlying BIM data and thus, do not support users in fluid contexts well.

On a very general level, developers can distinguish between low and high technological environments in which respective users operate.

Local Position

Considering the local position of users within a specific scenario that a BIM based application intends to support can also be of utmost importance during development. While it is often appropriate to assume that stakeholders work in a stable office environment, this is not always the case. BIM based application developers can, for example, design applications to support users that work directly on construction sides, or users that need to travel and, therefore, will use the application on planes and trains, or in airports and train stations.

According to a user's local position, BIM based application developers need to account for different factors, e.g. the availability and reliability of internet connections and other networks, the availability of hardware devices, or the possibili-

ties for the use of sound might be restricted in non-office environments. Additionally, considerations about the security of the stored BIM data are of importance. BIMs stored on servers in office environments are much securer than BIMs that are stored on a laptop to support work on the construction site.

On a very general level, during developments of BIM based applications, developers should at least distinguish between office environments and construction site environments.

Temporary Position

The final context category this chapter discusses is temporary position which can serve to link different identified and explored contexts together within BIM based applications. In this way, users will be able to exchange meaningful project information among each other. The temporary position of each of the different scenarios that a BIM application addresses will define a specific context with respect to the above categories. BIM based application developers can use this context information to identify how and where information needs to be managed, adjusted, and changed across different scenarios according to the scenarios' temporary position. Additionally, the temporary position of a scenario can be helpful to identify possible stakeholders that a BIM based application developer needs to consider during development. On a general level, AEC projects can be divided into four major project phases. The first phase is the project shaping phase in which product but also process information is usually very fluid and changes will occur frequently. During this stage, BIM based applications will need to offer practitioners the fast and easy possibility to evaluate several design alternatives and support the definition of all stakeholder objectives. Furthermore, the modeling of BIMs needs to be relatively cheap, as in this early phase it is not clear whether the project will proceed and if stakeholders can make revenue from the project.

Table 2. High level context conceptualization of important users of BIM based applications

	Architect	Designer	Construction Manager	Owner	Facility Manager	Insurance/Law Agency
State decision making – Product	Fluid	Fluid	Frozen	Fluid	Frozen	Frozen
State decision making – Process	Fluid	Frozen	Frozen	Fluid	Frozen	Frozen
Detail Level	Conceptual	Detailed	Detailed	Conceptual	Detailed	Conceptual
Hardware/Software Environment	Low	High	Low	Low	High	High
Local Position	Office	Office	Construction Site	Office Operating Building	Office Operating Building	Office
Temporary Position	Shaping	Design	Construction	All	Operation	Shaping Operation

During the design and construction phase it is, then, feasible for users to make more and more investments into BIM based applications and thus, developers can consider modeling more sophisticated BIMs. During this phase, information will become increasingly more frozen as stakeholders make more and more final decisions. The final stage of a building project is the use or operation phase. During this phase, users can often benefit from BIM based applications to manage the ongoing operations of a building with respect to the building's heating and ventilation systems, or with respect to building security aspects. A detailed BIM can also be helpful for future renovation activities such as as-built references of the current state of the building.

4 PROJECT STAKEHOLDERS AND CONTEXTS

Different project stakeholder will operate in different contexts and thus, the above described context categories will vary from stakeholder to stakeholder. This section describes the contexts of a number of general stakeholder groups that are involved with AEC projects. Again, this categorization is derived from the author's experiences

of supporting BIM implementations on projects in person, reviewing the historical projects that implemented BIM (Table 1), and from discussions with practitioners on a number of workshops. Further, the stakeholder categories are again on a very general level and BIM based application developers should only use them as a starting point for researching stakeholder contexts in more depth. Table 2 summarizes these general contexts of possible users of BIM based applications.

Architects

Architects are involved in the early shaping phase of a project. During this phase, the decision making about the product is very fluid. Architects also make initial decisions about the processes of how to build the product in later project phases. Architects will need to frequently change information within BIM based applications. Furthermore, architects can largely benefit from BIM based applications that help them to creatively generate new knowledge. Obviously, BIM based applications for architects need to represent mainly a conceptual level of detail. In current practice, architects often work in low tech environments. They still rely heavily on sketches and scale models, and BIM based application developers should

not assume that architects, in general, will have high end software and hardware readily available. Architects might visit the construction site from time to time; however they usually work in an office environment.

Designers and Engineers

Designers and engineers convert the results of architects from the shaping phase into a feasible design within the design phase. The state of decision making with respect to product decisions for designers needs to be very fluent. However, other than architects, designers rarely make decisions about processes of how to build the facility. Thus, designers usually work with relatively frozen process decisions. Designers take the conceptual design information from the shaping phase and convert it into detailed designs. Hereby, they often use sophisticated simulation and communication technologies. Therefore, BIM based application developers can assume that designers operate in high technological environments with respect to hardware and software. Designers rarely visit the construction site and almost entirely operate in a stable office environment.

Construction Managers

Construction Managers plan and manage the actual physical construction of a project's design on site in the construction phase. Decisions about the product design in this phase are relatively frozen. However, construction managers make frequent decisions about the processes of how to realize the project and thus, the process decision making state is very fluid. Construction managers need to work with very detailed product information. They operate directly on the construction site and seldom in an office environment. This also effects the sophistication of the project managers' technical environment that is usually characterized by low technical possibilities with respect to software and hardware. Construction managers can largely

benefit from BIM based applications that run on mobile devices.

Owners

Owners are involved with a project in all phases from the early shaping phases to the final operating phase of the building. Owners prefer to have maximum influence on decisions concerning the product and processes of a project. Therefore, BIM based application developers can best support them with applications that support fluid decision making tasks with respect to product and process related decisions. Owners often lack an in depth technical understanding and additionally prefer to maintain an overview of the whole project. Therefore, BIM based applications to support owners should represent information on a conceptual level. BIM based application developers cannot expect owners to operate in high end hardware and software environments. Thus, requirements for the technical aspects of the BIM based applications need to be low. Owners seldom operate on the construction site but rather in a stable office environment.

Facility Managers

Facility managers can benefit from BIM based applications during the operating phase of the building. Decisions about the product are no longer made and thus, the decision making state is relatively frozen. To understand the operation of the building, facility managers require a very detailed information level of BIM based applications. At the same time, applications and BIMs can be quite sophisticated because, at least in modern facilities, facility managers operate in high technological environments with respect to hardware and software. Facility managers are often directly positioned within the building. Sometimes, they are also managing the operations of a building from a remote office location.

Insurance or Law Agencies

Insurance and law agencies are usually involved within the early shaping phases of a building. Furthermore, they are often involved after the completion of the building to negotiate claims of various stakeholders that arouse throughout the design and construction of the building. Lawyers and insurance agencies operate within a frozen state of decision making. Similar to owners, insurance and law agencies lack an in depth technical understanding and additionally prefer to maintain an overview of the whole project. Therefore, the level of detail represented by a BIM based application should be conceptual. Insurance agents and lawyers usually operate in stable office environments.

5 SUGGESTIONS FOR FUTURE EMPIRICAL RESEARCH

So far this chapter theoretically introduced the idea of context sensitive software development and argued that this development method has the potential to overcome the problems of the AEC industry to develop meaningful BIM based applications. Further, the chapter summarized concept categories and stakeholder groups. In this way, the chapter can serve as a starting point to initialize future research in the area of context sensitive BIM based applications. This section will suggest such research areas and a number of methodologies that can help researchers who wish to work in one of the suggested directions.

First, and most importantly, research should aim at empirically evaluating the feasibility of context sensitive software development to develop BIM based applications that can support AEC project processes. To do so, researchers need to start developing metrics and benchmarks that allow for the targeted collection of data that shows the value of new developed context based BIM applications and allows for a comparison with the

status quo. Only in this way, will it be possible to evaluate whether the theoretical arguments of this paper hold and whether context sensitive software development is able to overcome the problems of the AEC industry to design, develop, and implement meaningful BIM based applications.

Next to empirically validating the method, researchers should start to extend the chapter's context categories and provide more in depth information from specific project contexts that can inform the design of a BIM based application. One problem that researchers will face during such efforts is that they can hardly research all possible user scenarios and their respective contexts upfront. Therefore, it is advisable that researchers choose an iterative research approach (Dey et al. 2001, Hartmann et al. 2009). They need to first gain an initial understanding in the complex project context and then iteratively adjust contexts identified on one project on the same project and across several projects.

Additionally, there are a number of technical problems that researchers need to solve to enable context sensitive BIM based application development. One problem is the already mentioned difficulty to combine different contexts of different stakeholders within a consistent BIM based application environment. Different stakeholders in different contexts have different requirements with respect to user interfaces. Therefore, BIM based applications need to provide flexible graphical user interfaces that specifically support different stakeholders in their different contexts. Further, context sensitive BIM based applications need to link data from different BIM databases. Thus, researchers need to find ways that allow BIM based applications to dynamically and flexible link several databases.

Another problem that researcher need to solve to allow for context sensitive development efforts is that it is necessary to easily and flexibly adjust BIM based applications to changes in contexts across several projects. Further, contexts change even on single AEC projects because project

environments drift over time (Kreiner 1995). Therefore, BIM based application developers need to be able to quickly and flexibly change the applications' graphical user interfaces and databases.

Future research needs to overcome these three technical problems. Traditionally, BIM based applications are delivered as fixed desktop solutions that run on single workstations. Users need to install those applications on a workstation PC and a reinstallation is necessary with every change in the BIM based application or its underlying database to make the change accessible to the user. This approach does not allow developers to adjust and readjust existing user interfaces and database easily and quickly. One possible technical solution to overcome this problem is Asynchronous Java and XML applications (AJAX) (Garrett 2005; Hanson & Tacy 2007). AJAX applications reside on a central server and users can assess them through a standard web browser. However, different from traditional web applications, AJAX applications offer a similar 'touch and feel' and similar functionality as standard desktop applications. The advantage of AJAX applications lies in the possibility to update new versions of the application directly on the central server. A new distribution of the new version to users that need to install locally is no longer required. Furthermore, AJAX applications allow for the easy possibility to dynamically adjust graphical user interfaces to varying stakeholder contexts according to information from the web browser that is used to access the server. It is for example, possible for the AJAX applications to dynamically switch the graphical user interface to dynamically support the contexts' of various different scenarios. It is therefore suggested that researchers explore the technological possibilities of using AJAX to develop context sensitive BIM base applications.

Another technical problem with respect to BIM based application development is that methods to dynamically link and update data between different databases are currently missing. From

a technological standpoint, BIM environments that operate on several databases need to provide a middleware server that is able to translate between the different databases (Schreyer et al. 2006). Additionally, BIM based applications can largely benefit from technical solutions that are able to search through multiple project databases automatically and autonomously. Agent technology (Lee & Bernold 2008; Bellifemine et al. 2007) can provide such functionality. In the future, researchers should explore how agents that operate through a middleware server and automatically and autonomously search for relevant data within the network of databases of one project can help to improve context sensitive BIM based applications.

Finally, researchers need to closely integrate the above outlined suggestions for future research. Ethnographic-action research (Hartmann et al. 2009) is a strategy that allows for such a close integration of research which explores contexts in depth, develops new BIM based applications, and evaluates the utility of these applications. Ethnographic-action research is an iterative strategy of observation of practitioners within their working environment; the development of improvements of BIM based application; and the consecutive implementation of the improved application on projects to evaluate the direct usefulness of the solution in iterative research cycles. Researchers can apply the method on one project or across different projects and in this way iteratively improve the context sensitivity of the BIM based application.

6 CONCLUSION

This chapter introduces context sensitive software development methodologies and argues that the method is able to improve BIM based application development. In detail, the chapter

1. introduces and explains context sensitive software development in detail reviewing the relevant literature in this area,
2. argues that context sensitive software design can support and improve BIM based application development,
3. derives broad categories for the different contexts of possible BIM based application users that software developers can use as a starting point for context sensitive BIM based application development,
4. and closes with outlining a number of future empirical research directions.

Overall, context sensitive BIM based application development has the potential to overcome the problems of the AEC industry to widely benefit from the advantages that the use of BIM promises. The author believes that context sensitive BIM based applications will integrate well into the work processes of AEC practitioners. This, on one hand, improves the task technology fit between BIM based applications and the work task requirements on AEC projects (Zigurs and Buckland 1998). On the other hand, such a better integration into the contexts of practical work processes improves the user's perceptions of the benefits of the new application and the control that users have over the implementation. The perception of benefits and control will in turn, improve the acceptance of BIM based applications among AEC practitioners (Hartmann 2008). Overall, taking both of the above advantages of context sensitive BIM based application development into account, the context sensitive development method will allow for more sustainable BIM based applications. This in turn will enable the AEC industry to finally fully leverage the potentials of BIM.

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KEY TERMS AND DEFINITIONS

BIM Based Application: A BIM base application is a software application that offers users meaningful functionality by using information that is stored in a building information model. It is important that a BIM represents only a database that stores information about a building, while engineers still need BIM based applications to make BIMs useful to support practice.

Context Sensitive: A BIM based application is context sensitive when it integrates into a specific user context on a construction project. Context sensitive BIM based applications need to minimally consider the role of the user, his state of decision making, the needed level of detail for the respective decision making state, the hardware and software environment the user operates in, and the local and temporal position of the user. The user context also varies according to the role of the user.

User Role: Construction projects are multidisciplinary efforts that involve a large number of participants from various different backgrounds. A participant's background determines the respective role of the participant on the project. A role can be discipline spanning.

State of Decision Making: Context sensitive BIM based applications should consider the state of decision making a user is in. The main point to consider here is whether the user already made a decision and plans to use the BIM based application to communicate this decision to others, or whether the user is in the process of making

a decision and, thus, the BIM based application needs to support.

Level of Detail: Building design evolves iteratively through various design cycles during which engineer generate more and more building information over time. Levels of detail are an abstraction mechanism that allows BIM to adjust to the amount of available information at the actual planning stage of the building.

AJAX: Ajax (Asynchronous JavaScript and XML), is a web development technique that enables software developers to create interactive web applications. With Ajax, web applications can retrieve data from the server asynchronously in the background without interfering with the display and behavior of the existing page. In this way

AJAX allows the implementation of web-based applications that offer the user the same ‘touch and feel’ than a normal desktop application. AJAX web applications allow software developers to easily adjust BIM based applications to different user contexts.

Autonomous Agent Technology: A autonomous software agent is a piece of software that acts on behalf of a user or other. Such “action on behalf of” implies the authority to decide which (and if) action is appropriate. Agents have the potential to autonomously search and link the different context sensitive BIMs existing on a construction project to allow for an improved interoperability.

Chapter 13

Towards the Development of a Project Decision Support Framework for Adoption of an Integrated Building Information Model using a Model Server

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ABSTRACT

This chapter discusses an action research study towards the development of a decision framework to support a fully integrated multi disciplinary Building Information Model (BIM) using a Model Server. The framework was proposed to facilitate multi disciplinary collaborative BIM adoption through, informed selection of a project specific BIM approach and tools contingent upon project collaborators' readiness, tool capabilities and workflow dependencies. The aim of the research was to explore the technical concerns in relation to Model Servers to support multi disciplinary model integration and collaboration; however it became clear that there were both technical and non technical issues that needed consideration. The evidence also suggests that there are varying levels of adoption which impacts upon further diffusion of the technologies. Therefore the need for a decision framework was identified based on the findings from

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an exploratory study conducted to investigate industry expectations. The study revealed that even the market leaders who are early technology adopters in the Australian industry in many cases have varying degrees of practical experiential knowledge of BIM and hence at times low levels of confidence of the future diffusion of BIM technology throughout the industry. The study did not focus on the benefits of BIM implementation as this was not the intention, as the industry partners involved are market leaders and early adopters of the technology and did not need convincing of the benefits. Coupled with this there are various other past studies that have contributed to the 'benefits' debate. There were numerous factors affecting BIM adoption which were grouped in to two main areas; technical tool functional requirements and needs, and non technical strategic issues. The need for guidance on where to start, what tools were available and how to work through the legal, procurement and cultural challenges was evidenced in the exploratory study. Therefore a BIM decision framework was initiated, based upon these industry concerns. Eight case studies informed the development of the framework and a summary of the key findings is presented. Primary and secondary case studies from firms that have adopted a structured approach to technology adoption are presented. The Framework consists of four interrelated key elements including a strategic purpose and scoping matrix, work process mapping, technical requirements for BIM tools and Model Servers, and framework implementation guide. The BIM framework was presented in draft format again to key industry stakeholders and considered in comparison with current best practice BIM adoption to further validate the framework. There was no request to change any part of the Framework. However, it is an ongoing process and it will be presented again to industry through the various project partners. The Framework may be refined within the boundaries of the action research process as an ongoing activity as more experiential knowledge can be incorporated.

1 INTRODUCTION

Despite the apparent benefits in terms of information sharing and management, efficiency in information flow and associated overall anticipated cost benefits, as well as project collaboration and coordination may seem evident, the adoption of BIM in practice has been slow (Bernstein and Pittman 2004). Many factors have been identified which contribute to the slow rate of adoption including; lack of training (Khemlani 2007), low business incentives (Holzer 2007), perception of lack of rewards (London and Bavinton, 2006), technological concerns (Howard and Bjork 2008), industry fragmentation related to uneven ICT adoption practices (London and Bavinton, 2006), contractual matters and resistance to changing current work practice (Johnson and Laepple 2003). In fact, the majority of the past studies were conducted at a distance from the research participants.

The aim of this national research study was to review and analyse the current capability of Model Servers leading to open software technical requirements with special emphasis on the so-called “non-functional” specification for BIM Model Server which would cater for digital models accessible through a web interface. The approach was to conduct the research collaboratively with industry market leaders who had been early adopters of the BIM approach. The findings reported in this chapter form an important part of an action-oriented research study which seeks to explore the technological, operational and strategic factors related to adopting BIM in the AEC/FM industry. There were five major phases to the study including:

Phase 1 Literature Review: An overview of BIM model server based collaboration platform including a literature review and discussion on the BIM approach and levels of technical capabilities and technology adoption.

Phase 2 Desktop analysis: Desktop analysis of key BIM Tools and Model Servers

Phase 3 Industry needs analysis: Detailed review of industry needs based on Focus Group Interviews. Preliminary findings (based on literature review, desktop analysis and FGI data) are used to refine the research approach.

Phase 4 Case studies: Eight case studies conducted to investigate the Collaborative BIM approach. Firstly, industry based case studies include a controlled testing as a pilot study and experiences of using a BIM approach in a real world project. Second, a comparative study of different document based collaboration platforms is presented to identify the technical features for a Model Server.

Phase 5 Decision Framework: Synthesis of previous phases towards developing a non functional technical features specification for a BIM Model Server. This phase also included exploration of BIM strategic and project management requirements and approaches to support implementation.

This chapter summarises the literature review and the findings of the various focussed group interviews and the case study analysis. The focus of the chapter is the description of the Decision Framework. For a more complete discussion on the analysis of the literature review to the chapter “BIM Adoption: Expectations across disciplines”, Gu et al (2010) in this Handbook (and the final research report “Collaborative Platform Solutions Research Report”, 2007 -003 EP, Taylor et al.

2 BACKGROUND

BIM is a process of maintaining a repository of all the information relevant to a building or construction project throughout the different phases of the project lifecycle. This repository facilitates storing, integrating, checking and visualizing the entire data emerging throughout the project lifecycle. This information can be used in

combination or separately, but not in isolation, in the sense that it will always be subject to some integrity and cross-checking.

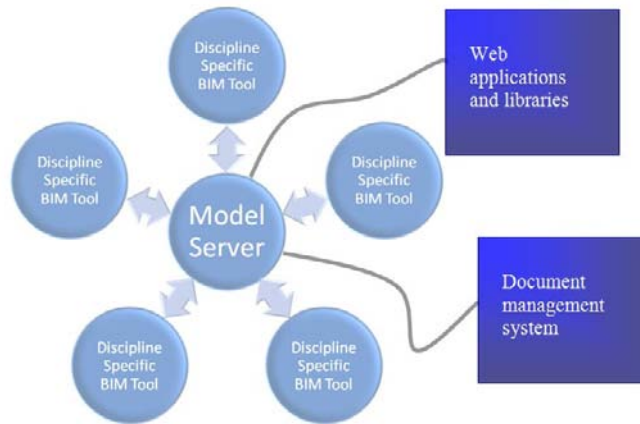
The information maintained and produced in the BIM approach includes both the geometric and non-geometric data. Geometric data comprises 2D drawings, 3D models, as well as dimensional and spatial relationships. Non-geometric data refers to annotations, textual semantic relationships, reports, tables, charts, freehand illustrations, graphs, images, audio-visual data, and any other form of representing some information generated during the project. (Taylor et al, 2009)

The implementation of BIM in general involves a client-server model. The BIM Model Server usually does not include any applications apart from the regular database management operations. Each discipline uses its own native applications to work on the data. Any changes or modifications (required to be made on the data) residing in the model server is done externally, using the native application. However, many BIM design tools support an internal database and multi-disciplinary capabilities, allowing a BIM like approach with limited applications.

A BIM model server only holds a repository of the information, and allows native applications to import and export files from the database for updating, modifying, viewing and checking the data. In general, the model server by itself has no inbuilt applications. Figure 1 shows how a model server is used along with the other BIM applications that form native tools for the collaborating disciplines. A BIM model server may also be connected to other tools such as a document management system or web applications and product libraries. Such integration can enhance collaboration capabilities facilitating a unified source of information access and sharing. (Taylor et al, 2009)

A literature review and a desktop analysis of available commercial applications was conducted by Singh (Singh et al., 2008). It is well understood that the development of Object-oriented (O-O) CAD packages has allowed greater intelligence

Figure 1. BIM model server allows import/export of data to and from BIM application tools



in the CAD models. This enables associativity, modelling constraints and relationships within the objects and the object properties (Ibrahim and Krawczik 2003, Lee et al 2003). These constraints and relationships have been used to develop tools and features for performance and cost analysis, clash detection, conflict resolution, scheduling and intelligent documentation (Bajzanac 2005, Mitchell et al 2007). Thus, at the core of BIM technology is the embedded information within the models.

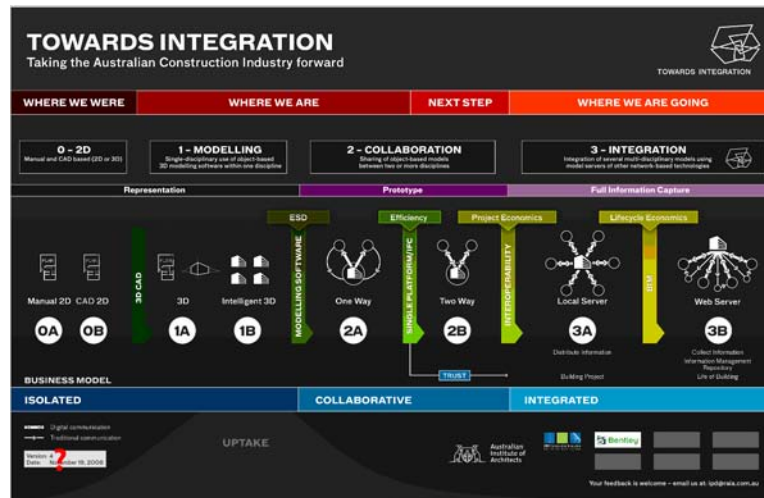
The lack of initiative and training (Bernstein and Pittman 2004), the fragmented nature of AEC industry (Johnson and Laepple 2003; London and Bavinton, 2006), varied market readiness across geographies (London and Bavinton, 2006), and reluctance to change existing work-practice (Johnson and Laepple 2003) and the problem of interoperability have all contributed in various ways to slow BIM adoption rates. In an industry where most projects are handled in multi-organizational teams the lack of clarity on responsibilities, roles and benefits in using a BIM approach is also an important inhibiting factor (Holzer 2007).

Our concern in this study was for that part of the sector of the industry, who are seeking to adopt at the highest level of integration; namely those that have already adopted BIM technol-

ogy in some form, had already worked across disciplines towards integrating submodels and who were seeking to understand the relationship between the models they were developing and online document management systems.

In Australia, the Australian Institute of Architects has developed a categorisation of Integration from Level 0 through to Level 3 with Level 3 being full integration of submodels into a 'mother' model utilising the web. Figure 2 indicates the various levels of technology available for architecture and design practice. The range of technology usage varies from 2D drafting to integrated BIM development, which entails two-way collaboration and a shared model. Refer to Figure 2 for a more complete description of the categorisations. We have adopted this categorisation for this study particularly because the results of this study are providing input to a National BIM Guideline which is currently being developed. According to the classification in the AIA diagram the BIM server technology falls under the category 3A and 3B. Thus, most of the discussions on BIM adoption refer to the capabilities for 3A and 3B. However, the decision framework proposed in the study is aimed at allowing evaluation of project partner's current capabilities and readiness i.e. which level of adoption they are capable of, and providing the

Figure 2. AIA diagram for digital design technology in architectural practice



support for a structured and informed transition from one stage to the other. The key participants on projects' adoption profiles are much less straightforward with different project team members being at varying levels which makes an explicit decision framework even more critical.

Although a wide range of commercial applications supporting BIM are available, interoperability still remains a key concern. The range of products varies from product suites (e.g. ArchiCAD, Revit and Bentley) that can be used by multiple disciplines across different phases of the project lifecycle to products for specific disciplines and applicable to a particular phase of the project.

Only a few of these products are IFC (Industry Foundation Class) compliant. This inhibits their use with other packages that cannot read the data format. There is often the debate regarding interoperability in the AEC sectors as to whether IFC is the most appropriate pathway. Apart from IFC there are other methods of data integration that allow individual applications to communicate with each other, such as APIs (Application Programming Interface), other data-oriented export formats such as ODBC, XML for Internet-based applications, and so on. (Khemlani 2007). Seam-

less integration of a suite of commercial applications based on the IFC format has not yet been demonstrated, except for carefully modelled test projects. However, IFC's integration capabilities and collaborative benefits can go a long way towards eliminating the inefficiencies and waste in the building industry.

Surveys conducted recently (Khemlani 2007b, Howard and Bjork 2008) suggest that collaboration is still based on exchange of 2D drawings, even though individual disciplines work in 3D environment and the demand for object libraries is growing. These surveys reveal that tool preference varies with firm size, and there is a greater demand for technologies supporting distributed collaborative works across all firm sizes. However, there is a lack of confidence in standards such as IFC.

In the recent years, web-based product services have increased, which can be very useful (Ibrahim et al 2004, Campbell 2007). Commercially available web-based products include product libraries, document management systems and BIM model servers.

The barriers to adoption can appear insurmountable as they include culture, industry fragmentation, existing work practices, procurement

strategies, regulation, legal and contractual issues, ownership of intellectual property, ownership and contractual responsibility associated with model ownership, data security fears, cost of implementation, client support, business processes... and the list continues - it appears overwhelming (Bernstein and Pittman 2004, Holzer 2007, Johnson and Laepple 2003). What does appear to be missing in the research literature to date is an integration of theory and practice in relation to Model Servers

Most of the earlier research on BIM adoption has focussed on specific disciplines of the AEC/FM industry where surveys and questionnaires have generally been used to collect the research data. Though surveys have been conducted which have tended to focus on barriers to adoption, there appears to be lack of comprehensive discussion with involvement of all major disciplines towards implementation.

The BIM tools and applications report was important to the industry participants in this study as the question arose:

What should we be really using when?

The report described the features and applicability of the various software applications as well as a discussion of the characteristics of two Model Servers currently available which are aimed at bringing together various disciplinary sub BIMs and integrating into a larger 'mother' BIM.

The first Model Server focussed on data storage and management for the facility management type client during operation and use phases after the sub-models had been developed and the second focussed on the creation, development and integration of sub-models during design and construction phases.

3 INDUSTRY NEEDS ANALYSIS

Two Focus Group Interviews (FGIs) with representatives from different sectors of the AEC/FM industry were conducted in the preliminary phase. The FGIs involved leading Australian organisations that have adopted BIM to some extent, and were aimed at identifying the industry perceptions of needs, concerns and expectations in relation to collaborative BIM adoption

Table 1. Key themes discussed in FGIs

ISSUES	BRIEF DESCRIPTION
Data organization	Data management, grouping, sub-sets and usability
Version management of project data	Data integrity and concurrency
Validation	Trust and confidence in CAD models and the process of design review
Standards	Data format and interoperability.
Communication and information exchange	Instant messaging, notifications, flagging and communication logging.
Security	(1) Network security (2) Intellectual Property (IP) and protection of copyrights
Data exchange between civil and architecture models	Compatibility and data exchange between a GIS (Geographic Information System) model and BIM is an issue. Users from civil disciplines expect IFC to be expanded into civil applications.
Roles and responsibilities	Emergence of new roles and responsibilities. e.g. BIM managers are employed in large-scale projects. What was "Architects and drafters" is now "Architects and modellers". Procurement strategies require different approaches along with new BIM contract clauses.
Training support	Training and awareness on BIM applications and current tool availability. Training modules for practitioners as well as curriculum in schools were discussed

The FGI involved twenty one participants in discussion for approximately 2-3 hours and these were recorded on tapes and then the comments segmented. The segmented data and background study were analyzed firstly using an open-ended approach to identify the main themes. Based on these main themes a coding scheme was developed and applied to the FGI data for detailed analysis. The design of the coding scheme reflects on the importance of various factors affecting collaborative BIM adoption. For a more complete discussion on the focus group interviews refer to the chapter “BIM Adoption: Expectations across disciplines”, Gu et al (2010) in this Handbook and the final research report “Collaborative Platform Solutions Research Report”, 2007 -003 EP, Taylor et al.

Key themes identified are listed in Table 1.

Apart from the key issues discussed by the FGI participants, the analysis of the data revealed the following:

- a) Object-Oriented model development requires a different approach than using traditional CAD packages. The importance of the initial set-up phase of the model is often not realized, leading to inaccuracies, conflicts, frustrations and disappointments in latter stages.
- b) Though there is a general agreement on the potential benefits of BIM for all disciplines, the actual benefits and usability of the approach is not clear. There is lack of clarity on how BIM can be integrated with the work practices on projects.

- c) There is a common misconception that the entire work-practice has to be changed for the BIM approach to be adopted. This is primarily because many of the users fail to realize that the BIM approach can be used for only parts of the project lifecycle. Although the ideal is full implementation, the most important aspect is that in the initial stages a clear statement of the purpose and scope of the BIM is required. That is, some users do not realize the flexible scope of BIM in an AEC project.
- d) Different business models will be required to suit varied industry needs (Wakefield et al 2007). BIM can be maintained in-house or outsourced to service providers. In the latter case additional legal measures and agreements will be required to ensure data security and user confidence.
- e) Knowledge and awareness about BIM is low across most disciplines. Discussions reveal little distinction in participants’ know-how between current capabilities of BIM applications and wishlist. Disciplinary background also skew the expectations from BIM (refer to Figure 3).

Architects and designers with CAD background see BIM as advancement from earlier CAD technology to current CAD tools such as ArchiCAD, Revit and Bentley. They expect BIM to primarily support extraction of information and drawings from the model they develop and that the model would be developed and/or supported

Figure 3. Skewed expectation from BIM across disciplinary backgrounds

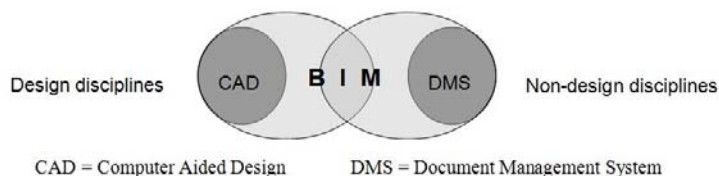
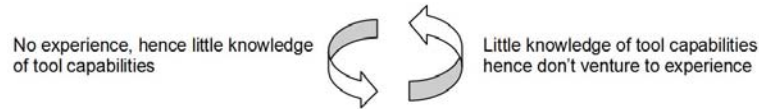


Figure 4. Industry status-quo loop inhibit technology adoption and slowing technology maturity



by the applications that they are utilising. There is a degree of design analysis as well, so it is not simply design documentation; however this is less well developed across all design consultants at this stage.

Contractors, project managers, quantity surveyors, facilities managers, who are typically participants from non-design backgrounds, expect BIM to improve the document management capabilities. In this respect, they expect BIM to be an extension of current document management systems (DMS). They expect BIM to be an enhanced DMS, where all the relevant information is appended and linked to the models. Thus their expectations from BIM go beyond the embedded information of object oriented models as in ArchiCAD or Revit.

Hence, for a widespread adoption of BIM, the scope of BIM approach should be considered to include not only models with embedded information, but also appended and linked information. Thus technologies supporting BIM, and in particular collaboration platforms such as BIM model servers, must facilitate the integration of the models and all related information generated either internally or externally of the models.

- f) Discussions in the FGIs suggest that the industry is trapped in a status-quo loop (refer

to Figure 4). The lack of knowledge and awareness about BIM has resulted in lack of confidence in, either BIM technology and/or their own organisation's and collaborators' capabilities in BIM technology and thus a lack of willingness to adopt BIM, and as a result of this inhibition to adopt and use BIM the level of knowledge about BIM continues to remain low. This phenomenon influences the rate of development of BIM technologies. Some of the BIM applications have not yet matured, which may lead to dissatisfaction among some of the potential early adopters. However, these tools can only improve with experience and feedback for which early trials and adoption are essential. Thus, for the BIM technology to mature and industry to adopt these technologies the status-quo loop needs to be reversed into a recursive development cycle (Figure 5).

In summary the implications of BIM adoption require changes to four key inter-related domains including; work processes, resourcing, scope/project initiation and tool mapping. Particularly, each of these four elements is influenced by the phase of the project life cycle, the purpose of BIM related to project requirements, stakeholder needs and collaborator capabilities.

Figure 5. Development cycle promoting technology adoption and facilitating technology maturity



For example, in relation to existing work practices, data and document version management, workflow, decision points and design and document review methods are all matters which take BIM from an idea to a reality. Resourcing is critical as it not only relates to design consultants being able to develop the models, but the level of interaction that they have and shared understanding of building models. The capability assessment does not rest with the design team as specialist subcontractors will also contribute to the building of models. Ideally product suppliers and all other subcontractors will contribute to BIM however in many cases it is more than likely that many firms involved in BIM projects will tend to use models rather than contribute to building models in the first instance. By clearly defining the scope of BIM at project initiation and thus the activities within subsequent project phases then decisions regarding tools and the connectivity between tools and phases becomes more efficient and streamlined rather than in conflict. Underpinning BIM implementation is the need, to consider the scope and purpose of the model and to embed roles and responsibilities within procurement strategy and contractual relationships as these need to support BIM implementation rather than inhibit the work environment and thus frustrate work practices.

New roles and responsibilities such as the BIM manager are emerging and an examination of current workflow and resourcing capabilities would begin to highlight whether this would be an internal or externally resourced role. There was much diversity in the first two FGIs and it was agreed that the scale and business models of the different players in the industry means that organizations need to develop strategies that suit their requirements and practices, contingent upon the capabilities of their current firms that they work with. In time if BIM is diffused more widely then the 'role' of a BIM manager may become redundant as it becomes part of the normal behaviour and work practices as knowledge about streamlined multidisciplinary collaboration becomes embed-

ded within the various clusters of organisations. However, at this early stage of adoption it appears that this type of resource is necessary to provide support, training and daily assistance.

Industry participants suggested that they did not have a structured approach to evaluating their project requirements, particularly in terms of tools, tool usage pattern, capabilities and compatibility across their project partners.

Hence, a Collaborative BIM Project Life Cycle Decision Framework was proposed to allow organizations assess their internal practice, their relationship to the clusters of firms that they typically work with, and then evaluate collaborative BIM applicability to their organization. In summary four key elements underpin the development of the Collaborative BIM Project Life Cycle Decision Framework:

- a) Work process roadmaps
- b) Tools and applications
- c) Scope, roles and relationships
- d) Resource capabilities.

The proposed framework is expected to facilitate the reversal of the status-quo loop into a recursive development cycle through:

- a) Structured analysis of a firms BIM readiness and know-how;
- b) Informed selection of BIM applications through understanding of the underlying capabilities, conflicts and limitations of the selected tools; and
- c) Ability of a firm to define the purpose and scope of BIM contingent upon the available resources and project requirements.

4 COLLABORATIVE BIM MODEL SERVERS CASE STUDIES

The industry needs analysis revealed the industry lack of experience in use of Model Servers which

has lead to the limited feedback on technical requirements and industry needs. Therefore, the project scope was expanded to proprietary software (and not only IFC compliant software) in order to relate to their familiar experience on existing collaboration tools. Use of non-IFC based tools is common and particularly relevant to civil works.

Hence, the following two approaches to elicitation of technical requirements have been adopted.

Approach One: Case Studies - Controlled Testing and Industry Use

A case study based approach is adopted, where a leading BIM model server is tested on a real world project data with the following research objectives:

- To test the current functionalities, usability and capability of the existing BIM model server
- To identify the technical limitations of the existing BIM model server in a collaborative setting while working with other BIM applications such as CAD packages, analysis tools and so on.
- To identify the gaps and missing technical functions of the existing model server.
- To compare the changes in the design and collaboration practice when using a BIM model server as against the use of other collaboration platforms such as a document management system that support traditional work processes and practices.

To compliment the controlled testing, selected industry use of the BIM approach is then presented and discussed.

Approach Two: Collaborative BIM Project Life Cycle Decision Framework

At present there is limited use and hence limited knowledge of BIM applications and integrated BIM development in the industry. The lack of awareness means that a direct feedback on technical requirements cannot be obtained from industry use. This lack of feedback is hindering the growth rate of the BIM related technologies that are yet to mature. Hence a Collaborative BIM Project Life Cycle Decision Framework is proposed as one of the research approaches with the following interrelated objectives:

- To provide a structured approach for potential and willing BIM users to understand their work practice, current tool capabilities and assess their BIM readiness.
- To allow potential users to identify the likely conflicts that would have arisen if they or their project partners had chosen incompatible tools in a given project.
- To create awareness about BIM applications and their usability in different project activities and phases.
- To generate a reflective practice among industry users such that the awareness and knowledge of available BIM applications allows them to give a feedback on what is missing in current applications and what they believe can be improved.
- To facilitate the rate of maturity of BIM applications through industry feedback. This in turn should facilitate greater adoption of BIM in practice.
- To provide a computational framework that can be developed and implemented as an interactive computational BIM collaboration management tool to assist BIM managers and similar roles.

An action oriented case study methodology (Yin, 1994) was adopted for the study which was underpinned by a grounded theoretical approach (Strauss and Corbin, 1990). Each case study contributes to informing the development of the Decision Framework in some aspect. After data was collected, the analysis was completed followed by a period of reflection and interpretation in relation to the research problem (i.e. the development of a decision framework for multidisciplinary diffusion of collaborative BIM).

This section presents case studies of both BIM based and document based collaboration platforms. BIM based collaboration platform includes Seawater Chamber – a controlled test case study conducted within the research team, in which EDMmodelServer™ is used, and the Ark Building Project – an industry case study in which NavisWorks is used to merge different discipline models. Document based collaboration platform case studies include examination of existing online collaboration applications, such as Incite, Aconex, Team Binder and Project Centre, along with inquiries and interviews at Incite, Thiess, EDMmodelServer™, Woods Baggot and Sydney Opera House. ActiveFacility, another BIM based collaboration platform was also reviewed from an application features perspective.

The intention was to review the existing processes for implementing and utilising document based collaboration platforms and investigating how they applied when employing BIM based collaboration platforms.

All the case studies were measured against the “AIA diagram for digital design technology in Architectural practice” in order to apply a common grading system throughout. Please refer to the Table 2.

The following summary presents case studies of both using BIM based and document based collaboration platform. Using BIM approach for collaboration platform includes Seawater Chamber – controlled testing case study in which EDMmodelServer™ is used as a collaboration

platform, and the Ark Building Project – industry case study in which NavisWorks is used to merge different discipline models.

Document based collaboration platform case studies include inquiries and interviews at Incite, ProjectCentre, Thiess, EDMmodelServer™, Woods Baggot and Sydney Opera House.

The discussions are categorized into user management, visualization control, data management, system management and technical support. These discussions should then combine with industry needs and decision framework to develop technical requirements of model server.

In general, to utilise EDMmodelServer™ as a collaboration platform is not mature yet and still in developing. Some issues need to be considered including

- Budget management of BIM cost, including software and hardware
- Training of using BIM
- Enrich the user manual and help function of BIM Model Server
- Hardware and software requirement
- Data management including the management of file size and running time, additional storage for storing project data and specification, and linkage of link information and external information
- Data ownership management
- Operation and Management manual (O&M) / link to detailed information of the objects in the model

User Management

- Current EDMbimManager™ user management provides users and groups controls with different authorities including create, delete, execute, private, write, read and none.
- It is suggested that
 - User management could be more flexible and applicable for different users in different project life cycle.

Table 2. Summary of case studies: Integration, software and purpose

Towards developing BIM Technical Requirements			
Case Study	Level of Integration (AIA Grade)	Software	Purpose
Seawater Chamber	Level 3 – Integration 3B:webserver	EDM Model Server ArchiCAD Octaga Modeller DDS- CAD Solibri Model Viewer	Experimental case study to test existing model server capabilities towards developing technical requirements
Ark	Level 2 – Collaboration 2A:1 way Limited elements of 3A:local server	NavisWorks INCITE ArchiCAD Revit	Marketing Presentations Development of O&M Manual to client Not as a collaboration tool during project delivery.
Towards developing an Implementation of a BIM Decision Framework			
Case Study	Level of Integration (AIA Grade)	Software	Purpose
INCITE	Level 3 – 3B:webserver [potential for BIM model server integration]	INCITE	INCITE web based server from a document management system approach
EDM Model server	Level 3 – 3B:webserver	EDM	Web based server from a CAD approach Little support for project delivery communication and information flow and current work practices
Active Facility	Level 3 – 3B:webserver	ActiveFacility	Web based server from a CAD approach. Designed to provide client/owner with BIM for facility management Little support for project delivery communication and information flow and current work practices
Woods Baggott	Level 1 – 1A: Model-ling Elements of 2A Col-laboration	Aconex/FTP Server/Archicad	Potential for Level 3 Integration
Thiess	No levels	Not applicable. In house organisation online guides	Design and construction project delivery Online Best practice project management Guide Potential to integrate work processes to build BIMs and support BIM Model Server Level 3 Integration
Sydney Opera House	Level 1 – 1A: 3D Mod-elling	Aconex/TRIM [inhouse document management system]	In house local server with BIM development from a CAD approach. Does not support document management system. Build individual discipline models for facility management Single point of control by building owner which has not moved towards Collaborative nor Integration level

- Give some users the authorities only in some specific project life cycles which are applicable to them
 - It can also provide some linked functions and extend functions, e.g. contacts and messenger, for uses of server not limited to data sharing but also online user communication.

Visualization Control

- All EXPRESS Data Manager™ products have a model-driven architecture and all functionalities in the EDMmodelServer™ can be changed.
- EDMmodelServer™ consists of two main parts, including text-based information windows and a 3D model viewer. Currently,

Octaga Modeller is plugged for instant viewing 3D model. Jotne EPM Technology is now modifying EDMmodelServer™. Other model viewers could be plugged into EDMmodelServer™ in the near future.

- It is suggested that
 - Customizability of system configurations with a flexible user interface to be suitable for and easily adopted to different needs of:
 - different users including designer, contractor, facility manager and client,
 - different building project life cycle ranging from project identification to bid, start up, design, contract, operate and manage, and
 - different scales of collaborative projects
 - User interface with drop down menus, forms, charts and so on needs to be developed to assess information in a collaboration project.
 - EDMmodelServer™ should not only be limited in an operation window. Pop out windows might be used to accompany with the main operation window. It will increase the flexibility, usability and interactivity of EDMmodelServer™.

Data Management

- Data management of EDMmodelServer™ includes object properties and Information Delivery Management (IDM). Objects of the model are presented by text-based information in repositories and 3D object-model in Model Viewer.
- Jotne EPM Technology is currently in the process of finding the solutions for GUID, IDM and scaling problems encountered in

merging different discipline-specific models using EDMmodelServer™.

- It is also suggested to provide plug-in applications or mechanisms to achieve the following functions:
 - Ownership and control mechanisms of objects and models authorities could provide more options to different users, user groups or users in different hierarchies. It is to enhance the security of data and workflow.
 - Improvement of interactivity between the text-based information and 3D models of objects to control the accurate interrelationships between objects and the model.

System Management

- Currently, EDMmodelServer™ is set up and controlled by EDMsupervisor for user control and authority settings. There are still some issues which need to be addressed in using EDMmodelServer™ as a collaboration platform, such as data back up and instant communication.
- It is suggested to:
 - Adopt industry needs with the support of specific discipline, domain knowledge and IT technique. Therefore, the industry can easily understand the tool capability and reflect its usability in practice.
 - Add “Conflict detection mark-ups” function to highlight possible tool compatibility issues, access right and information flow clashes.
 - Ensure Data back up system setting. If the system which maintains EDMmodelServer™ is crashed, the backed-up data can be utilized and uploaded into EDMmodelServer™ while reconstructing the system.

Table 3. Cross case comparison in relation to elements for a decision framework

Case	Key challenges	CAD vs DMS approach	Project scoping approach	Tool compatibility	Model server usage	Work process maps	BIM Capability	BIM Decision Framework Integration
INCITE	Integration of BIM environment with DMS Providing Training & support Creating cultural change	DMS	Yes	No	No	Yes	No	Potential
New-forma Project Center	Integration of BIM environment with DMS Creating cultural change	DMS	Yes	No	No	Unknown	No	Potential
Thiess	Integration of BIM environment with DMS Culture change not an issue as Thiess makes it mandatory for collaborators	DMS	Yes Project scoping is done but sans BIM	No	No	Yes	No	Potential– alignment with current TMS
Arup	Representative from Arup believed separate models may be needed for specific purposes. e.g. Design, Facilities management and construction. Opinion on IFC and collaboration model servers was not very positive.	CAD	No	Yes	No	Unknown	No	Potential- particularly with alignment to current KMS
Woods Bagot	Focus is at present on intra-disciplinary model. Exchange with consultants is through 2D documents. Challenge in future would be exchange of information with consultants through models.	CAD	No	No	No	Yes	No	Potential- for intra-disciplinary exchange of 3D data
SOM	Adopt KM strategies that are sustainable and accepted across the organization	DMS (more information mgt)	Yes	Yes	No	Yes	No	Potential
HEWVC	Isolated approaches to CAD and project information management Key challenge is to integrate CAD & DMS & extend to BIM	CAD & DMS	No	No	No	No	No	At present isolated efforts and integration will require a fresh effort

- It is also suggested to provide:
 - Instant direct communication, e.g. chat room and videoconference, and indirect communication, e.g. broadcasting and email, to improve the communication for project development and control.
 - Project wiki to share project information and tool usage information
 - A look-up tool capability matrix, where users can search, query and check functionalities and capabilities of all BIM supporting tools such as CAD packages, analysis tools.
 - Command to create tool-compatibility matrix to determine the scope of BIM usage in a project, based on the tools chosen by project partners.

Technical Support

- Current Jotne EPM Technology provides helpdesk through email and telephone for EDMbimManager™.
- It is also suggested to
 - Improve the help function in EDMbimManager™, e.g. interactive help window, for users to seek and obtain solutions and assistances for the problem they have in using a model server.
 - Online helpdesk in case where Model server facilities are provided by a service provider.
 - May also be applicable to large scale in-house projects, where this helpdesk service is supervised by a BIM manager.
 - Provide interactive tutorial such as Graphisoft's BIM tutorial

Table 3 compares in a summarised manner each case study in relation to key elements of Decision Framework and clearly indicate a need for each of the elements to be developed in more detail. Interestingly no case study participants appears to conduct a capability analysis and few firms conduct a specific BIM scoping step nor analyse tool compatibility. The experiences and findings from case studies then used for the development of technical requirements of a BIM model server as a collaboration platform.

5 PROJECT LIFE CYCLE COLLABORATIVE BIM DECISION FRAMEWORK

The adoption of a fully integrated multidisciplinary seamless Building Information Model to describe a construction project has not been implemented completely in the Australian property and construction industry even by early technology adopt-

ers who are market leaders. This would require a collaborative platform Model Server. The lack of adoption with market leaders is due to:

- a lack of operational technical knowledge of Building Information Modeling
 - low and/or varying levels of awareness, knowledge, skills and capabilities across disciplines
 - low levels of confidence in Building Information Model adoption due to lack of experiences
 - lack of clarity on how to develop and integrate Building Information Modeling into current work practices
- a lack of high level strategic guidance to address the varied levels of adoption across different disciplines
 - varying levels of adoption across different disciplines
 - misconceptions and fear regarding partial and full implementation
 - confusion between traditional CAD packages described as a Building Information Model and an object oriented model and poor decision making in initial project set up phase
 - lack of clarity of key stakeholders' definition of purpose and use of a Building Information Model related to project needs and requirements
 - new frontiers to be explored in relation to contractual provisions, procurement strategies, model ownership, information management, data security and model user confidence

There is a recognition of the need to develop guidelines in relation to technical (software and hardware tools, data compatibility, interoperability) operational project decision making and non technical (procurement strategies, model ownership, contractual obligations, information management) strategic project and organisational

decision making. However, the adoption of innovative technology and its diffusion throughout the industry is challenging without a starting point to guide decisions for project managers, architects, clients, facility managers, contractors, engineering consultants, specialist subcontractors and suppliers. When innovative BIM technologies have been implemented and have become more diffused throughout the industry, BIM implementation will be seamless and implicit in everyday work practices but until that time decision making and roles need to be explicit.

One of the key early decisions in developing and using BIMs which needs to be addressed for the Model Server environment is the extent to which the various software products are IFC compliant and/or interoperable when converting from the native format to IFC. This impacts on model creation primarily however it also impacts upon how the models are integrated and managed within the Model Server environment.

Limitations have been identified with the current practice in IAI's certification of IFC compatible applications (Bentley 2007). For example, the IFC specification does not cover export of certain proprietary data types that support application functions. As these cannot be exported, an IFC-file re-imported (round tripped) cannot create the original application data, thus certain features can no longer work. This leads to inefficiencies and complexities in managing an integrated database at the model server in the form of IFC files.

Given this scenario, IFC based model server may not always be the best choice. Hence, the decision support framework considers the possibilities of direct data exchange between proprietary tools using other approaches such as APIs and XML formats. Thus, assessment of the BIM tool compatibility is considered as an important step in the decision making process.

Purpose of Decision Framework

A Project Life Cycle Collaborative BIM Decision Framework is proposed to facilitate fully integrated BIM adoption using a model server, through informed selection of tools based upon project collaborators' readiness, tool capabilities and workflow dependencies. The Decision Framework is cognisant of the potential to integrate and collaborate across all phases of the project life cycle. The focus of the Decision Framework tends towards the technical requirements, however early and concerted attention to the non technical strategic project and organisational decision is critical to provide the necessary supporting cultural and business environment for adoption of BIM technologies.

The Project Life Cycle Collaborative BIM Decision Framework provides the information aimed at those who are BIM 'ready' or actively implementing BIM including those industry participants who would tend to be at Level 1, 2 and 3 according to the following levels (refer to Figure 2 AIA diagram for digital design technology in Architectural practice)

1. **Level 0:** CAD based [2D and 3D] - design disciplines who are designing, documenting and creating visualisations, but who have not yet fully embraced object modeling and the concept of embedded information and/or appended/linked object information
2. **Level 1:** Modeling – single disciplinary use of object based 3D modeling software within one discipline
3. **Level 2:** Collaboration - sharing of object based models between two or more disciplines
4. **Level 3:** Integration – integration of several multi disciplinary models using model servers with the ultimate aim of moving from local servers to a web based environment

The Decision Framework is primarily aimed at multi disciplinary industry participation at Level 3 Integration; however there are varying levels of adoption and on projects where a Model Server is being utilized it will be necessary to move participants at lower levels towards Level 3 Integration.

The Decision Framework provides a project life cycle view to support all industry participants including design and non-design discipline. The aim is to present a way forward to bring together the CAD and DMS perspectives of BIM technologies to attempt to realise the full potential of BIM implementation by including models with embedded information, and also appended and linked information. The Decision Framework provides information for clients and facility managers to understand the full resource implications of BIM technologies on projects and the impact of their decision making on BIM implementation. The diffusion of innovative technologies is influenced by the positive experiences of adopters and the ability to modify the technologies to suit individual organisational (i.e. own) needs to successfully maintain and/or enhance business competitive advantage. This means that the Decision Framework needs to be customised for individual organisations or unique projects. There are Model Owners, Developers and Model Users.

As such, the Decision Framework is intended to be adapted by the following organisations to suit both their organisational requirements and project requirements:

- architects, engineering consultants, quantity surveyors, design managers, etc. who may not make project decisions but create, update, review, collaborate and integrate models
- clients/project managers/facility managers - those who make project decisions about BIM implementation on a project and who can influence resourcing for project teams

- senior technical managers senior managers and executives of organisations who make decisions about technology investment, human resourcing, project bidding and organisational strategic direction

Project Life Cycle Collaborative BIM Decision Framework

The four sections of the Project Life cycle Collaborative Building Information Model Decision Framework for Model Server Implementation and a brief overview are now provided:

1. *Defining scope, purpose, roles, relationships and project phases:* critical early decisions in the Model Server environment are required at the outset to enable a supportive business and cultural environment for streamlined data flow and information management within a knowledge enterprise.
2. *Developing Work Process Roadmaps:* guidelines for developing Model Server implementation roadmaps
3. *Identifying technical requirements of BIM Model Servers:* A comprehensive knowledge of the available commercial BIM applications and their capabilities is important. Tools and levels of interoperability, is dynamic and therefore project specific requirements need to be defined at the outset. To reach Level 3 Integration stage of BIM implementation, requirements regarding tool compatibility for multidisciplinary model sharing and model servers is necessary.
4. *Implementing the Decision Framework:* guidelines for implementing the framework Evaluating skills, knowledge and capabilities a definition of skills, knowledge and capabilities required mapped against current status

Table 4. Scoping activities, purpose and phase matrix- non technical requirements

CHECKLIST FOR MODEL SERVER MANAGER												
Scoping Activities: 9 NON TECHNICAL STRATEGIC STEPS Identify purpose[s], extent of BIM and map to project phases Define Model Server Ownership Risk Management parameters Define model ownership, funding source, owner requirements, management structure, & boundaries of responsibilities for model and/or sub-models for all project phases including; contractual roles obligations and protocols for model management Inter relationships between collaborators Develop Business Plan for BIM Integration including financial & time constraints & appropriate resourcing for training and support Define level of integration between Model Builders and Model Users i.e. design consultants model developers with document management systems managers within the Model Server environment Undertake scoping analysis of collaborator competencies according to capability Levels 0-3; Conduct BIM Integration Adoption workshops for selected senior executive and project level participants towards developing a collaborative culture and creating a BIM Model Server Communication Strategy to raise awareness and identify conflicts Develop BIM Technical Support Levels for collaborators: Level 1: Start up Training for inexperienced collaborators Level 2: Tool & model server support for collaborators Level 3: Long term education related to Knowledge Management Strategy Develop Knowledge Management Strategy for capturing learning for future BIM Integration projects	Purpose	Project Initiation	Concept Design	Developed Design	Bid documentation	Tendering	Construction	Commission	Occupation	Refurbishment		
	Community Marketing	H	H	L	L	L	H	L	H	H		
	Client Presentations											
	Discipline Design Sub-Models											
	Inter disciplinary design collaboration											
	Multi disciplinary design collaboration											
	Design Review											
	Design Analysis											
	Subcontractor Tendering											
	Construction Information Mgt.											
	Facilities Management Operations											
	Facilities Management Maintenance											

Defining Scope, Purpose, Roles, Relationships and Project Phases

In the early stages of consideration of set up for a Model Server it is advisable to consider the 9 Scoping activities that are outlined in Table 4. This forms a Checklist for a BIM Model Server Manager.

The first strategic scoping activity is to identify the purpose[s], extent of BIM and map to project phases. The purpose of developing an Integrated Building Information Model using a Model Server needs to be clearly defined at the outset. There can be a spectrum of implementation from, a complex fully integrated multidisciplinary Building Information Model (with online collaboration with real time updating across every phase of a project's life cycle) to individual discipline Building Information Models (as stand alone models specific to phase, sub phase or activity within a phase). Each project will have different requirements and thus, if Level 3 Integration has been decided for the project, it is necessary to develop a specification of the purpose that is required, so that it is fully supported by a well thought out business plan. The following matrices forms a guide and need to be adapted to suit individual project procurement strategies. The matrix can be developed from a project perspective or from an individual collaborator's perspective. For example, if the client funds the BIM they may wish to receive a fully operational Facilities Management model which they can use for operations and maintenance and community marketing, whereas a contractor funded model, may focus on detailed design analysis, design review, alternative construction methods, construction information flow, safety features. The Matrix can be customized to suit individual project needs. The first step is to identify the purposes for which the model will be used for as this impacts upon the Model Server requirements. The next step is then to determine phases of a project where this is a high or low priority and then communicate that throughout the

project team including model developers, model funders and model users.

The second strategic scoping activity involves defining Model Server Ownership Risk Management parameters. Table 5 outlines 6 key factors which influence the management of risk in relation to Model Server setup and implementation. It is intended that the matrix would be customised to suit and sit within the framework of risk management systems and strategies which have already been developed for the projects and organisations. However this provides a guide to key issues for the Model Server Manager and the model server owner to consider at the outset.

Developing Work Process Roadmaps

Describing and developing Work Process Roadmaps in relation to Model Server management and implementation is important to enable a shared understanding, within and across organizations of key decision points. Typically organisations have documented key processes within their organisation as a form of quality assurance exercises and/or accreditation or simply as, good business practice. This takes many formats ranging from formal and well communicated maps to simply accepted understandings of 'What we do'. If an organisation is at the stage of being engaged in a project that shall use a Model Server they would typically have some BIM capacity, either as a Model Owner, Developer and/or User. For good project management in relation to Integrated BIM implementation and associated Model Server management, it is highly desirable that both strategic and operational roadmaps are developed for projects. Organisations should individually customise their work process roadmaps to suit their involvement in a project that requires a BIM Model Server. The following is an indicative checklist for the BIM Model Server Manager in relation to Work Process Roadmaps:

Integrated BIM requiring Model Servers will require strategic workflow process maps to sup-

Table 5. Model server ownership parameter

Model Server Ownership Risk Management Factors					
Model Server structural organisation					
Centralised					Distributed
Model Definition Stage					
Static Phase Defined Completed Models					Dynamic Phase Ill defined Real time evolving Models
BIM Management Skill Sets					
Internal In-house					External Sourced
Data Protection Classification					
Low level/Barrier Simple security	2	3	4	5	High level/Layered Multi-Security levels
Model Ownership scope & Server Capacity					
Integrated Model working size is small Hosting capacity required is low	Small			Large	Integrated Model working size is large Hosting capacity required is high
Data and Information Regulatory & policy framework					
Public Full disclosure					Private Confidential

Table 6. High level roadmaps checklist

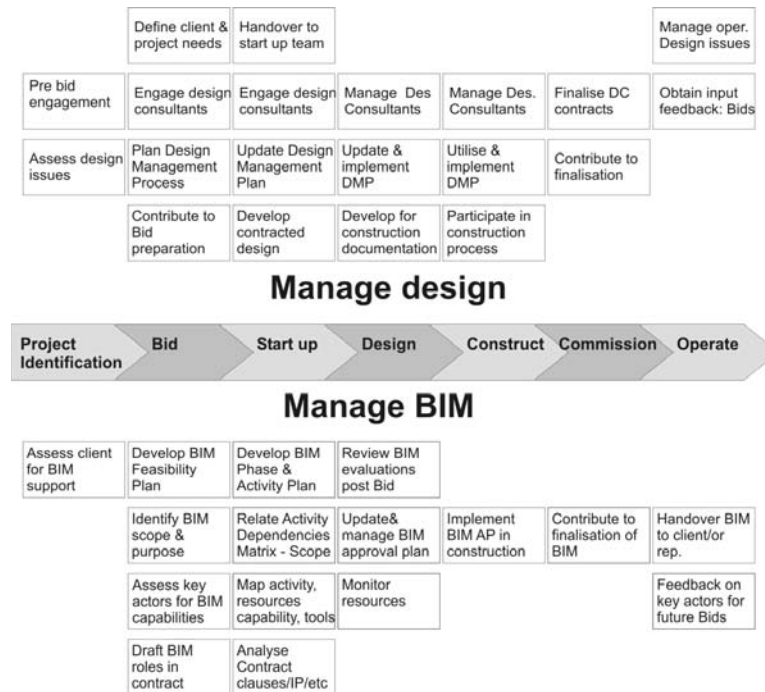
Roadmap Activity	Description	Actioned	
1	Schedule of Roadmaps for each Phase		
2	Develop Roadmaps as required for Project Specific needs: refer to BIM Purpose and Phases decisions made in Scoping Activities Checklist: 9 Non Technical Strategic Steps		
3	Distribute roadmaps to project team participants		
4	Upload Schedule and Roadmaps within BIM Model Server environment		
5	Develop Model Server Handover Process Roadmap		

port project (operational) information exchange and data transfer workflow processes. Figure 6 is an example of a high level roadmap on BIM implementation for the BIM Manager working on a project, whereby a contractor has taken the lead for the Model Server environment (and has employed a BIM Manager who is responsible for design review processes). The roadmap illustrated in Figure 6 is specifically suited to a contractor led BIM Model Server scenario, however there

will be various other scenarios whereby BIM Management may be assumed by government clients, facility managers, asset owners, project managers or architectural consultants. There are two key issues to consider;

- First that other project champions and actors would have their own process map depending upon their involvement and the type of procurement relationships

Figure 6. Manage design process roadmap: Integrated BIM implementation



and associated roles and responsibilities required.

- Second that there are additional layers of detail for each individual project phase major processes identified in the roadmap in Figure 6 which would involve descriptions of step by step activities, players, deliverables, resources and tools, risks and indicators for success.

Figure 6 is generic and would appear to be applicable for lower levels of BIM adoption; however it is critical that such an explicit BIM Manager ensures that each of these steps is taken for a fully integrated BIM using a Model Server. In the early stages of BIM adoption it may be necessary to develop explicit work process roadmaps. If learning is transferred from project to project, an organisation will gradually diffuse BIM adoption systemically and in time these will more than likely become normal behaviour and may not be necessary.

Key questions that a Model Server Manager needs to ask to develop such a roadmap includes:

- What are the project phases the organization is involved in?
- What are the activities in each of the phases? e.g. modelling, visualization, detailing, design review, etc.
- What actors are involved and what are the authority relationships between actors, i.e. model owners, developers and users? How does the BIM Model Server Manager control workflow?
- What are the dependencies between the activities?
- What information is required to be exchanged? What is the data transfer?
- What are the decision points for updating, reviewing, checking, signing off and uploading?
- What the sign off points?

- Who has authority to conduct review, update, check, sign off and upload?

The roadmap in Figure 7 illustrates a sample Design Management Review process as a flow-chart indicating the relationship between Model Developers, Owners and Users and the central role of a BIM Manager. It is a Work Process Roadmap for the “Implement BIM Approval Plan (AP) in construction” activity from Figure 6.

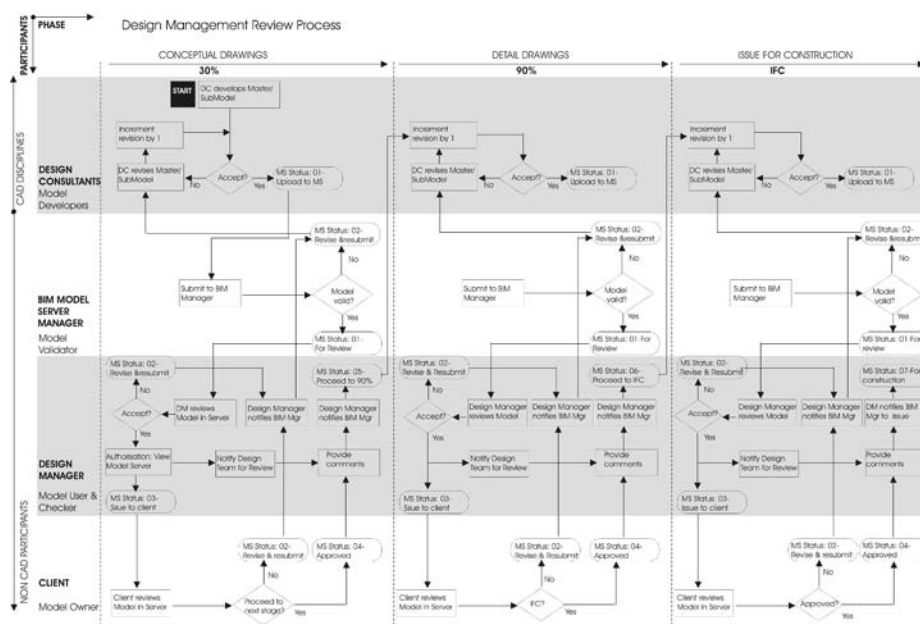
In the section: Technical Requirements Model Servers, more specific guidance describes how project activities relate to the development and analysis tools that are used by integrated BIM users and developers. In the Model Server environment one of the key issues is exporting and importing of data from various file formats and therefore, Tool Compatibility and its impact on the workability of the Model Server with regards to efficiency and effectiveness is critical.

Project collaborators would have their own process map depending upon, their involvement and the type of procurement relationships and asso-

ciated roles (and responsibilities) required. There are more roadmaps which can be developed at each phase which would involve descriptions of step by step activities, players, deliverables, resources and tools, risks and indicators for success. It may be necessary to develop explicit roadmaps in the early stages of implementing BIM initiatives. In the time when learning from each project has been sufficiently diffused throughout an organisation, various activities will become accepted behaviour and part of normal work practices, and roadmaps may not need to be so detailed or they may be changed to suit the needs of the organisation.

A fundamental principle towards achieving a fully integrated BIM (to Level 3 using a Model Server) is the efficient compatibility of tools. Although this is important for BIM development at any level, it becomes critical at Level 3 Integration. Therefore the following section is concerned with providing guidance on identifying compatibility of tools to support Level 3 Integration and the use of Model Servers so that the technical requirements for Model Servers is contextualized.

Figure 7. Design management review process for integrated BIM model server environment



Identifying Compatibility of Tools

A comprehensive knowledge of the available commercial BIM applications and their capabilities in relation to interoperability is important. Tools are constantly evolving and tool compatibility is dynamic. Firms can hire consultants to perform desktop audits. Alternatively, government agencies who are inclined to promote BIM adoption may have maintained such audit reports which can be easily accessed.

Given that 100% interoperability across the various proprietary tools is unlikely, in the near future, knowledge of the degree of compatibility between the different tools will be useful in tool selection. Importing and exporting capabilities from native file formats into other file formats and associated metrics or efficiency indicators would be useful. Import and export efficiency indicators can guide BIM Managers' decision making in the early setup stages. Early consideration of tool compatibility will typically avoid conflicts mid-way through the project. It is also useful to have a summary of conflict resolution strategies between tools, links to online tutorials on tool usage, and contact details of tool experts. A comprehensive Tool Compatibility Matrix was developed, but has not been included in this chapter. This can of course be customised to suit individual project and/or organisational needs.

This research primarily focused on the technical requirements of a BIM -Model Server and hence technical requirements for other BIM applications are not specifically explored. Since, a wide range of the BIM requirements exist, as reflected in the variety of BIM supporting applications, this research assumes that differences would exist across similar proprietary tools in their technical capabilities and approaches. However, some technical features that are generally found to be absent in most BIM supporting applications were listed and explained, these include:

- Ability to export/ import information appended to objects
- Alignment of product libraries to actual product manufactures catalogues
- Design rule editors
- Standard names and labels for features and tool capabilities

This is an indicative list and other similar features and technical requirements for BIM supporting applications need to be explored.

Technical Requirements for BIM Model Servers

In terms of their importance, the technical requirements for a model server can be categorized as operational technical requirements and support technical requirements. Operational technical requirements refer to the features needed during usage of the model server. Some of operational technical requirements relate to user log-in and access, data import and export, data management and organization, version management, user interface, navigation and visualization, and so on.

Support technical requirements such as help menus, tutorials, FAQs, and so on are required to facilitate usage of the model server. Support requirements have traditionally been a part of all technological tools and have been critical to technology adoption and user support. In collaboration-based tools such as some of the DMS (e.g. Aconex, Team Binder, Project Centre, Incite) templates, assessment matrices are other support technical requirements that have been included to facilitate set-up and implementation of the collaboration platform for project needs. Hence, one of the important support technical requirements of a BIM -Model Server designed to function as a collaboration platform includes project decision support features and functionalities.

Based on the features, the technical requirements for a model server can be broadly grouped into the following categories:

1. *BIM server based collaboration platform set-up assistance related requirements:* The technical requirements within this group are expected to facilitate set-up, implementation and management of the model server at systems level. Some of these technical requirements are operational, while some other technical requirements in this group are support technical requirements.
2. *BIM -Model Management related requirements:* The technical requirements within this group are related to the usage of the model server. These technical requirements directly affect operations on, and maintenance of the stored data such as model, documents, and related information. Hence, all the technical requirements in this group are operational requirements.
3. *Distributed/ virtual design review related requirements:* The technical requirements in this group are specifically related to design review activities. In general, depending upon project team and the planned design review process, these requirements can either be considered operational or support technical requirements.
4. *Data Security related requirements:* The technical requirements in this group are related to network security and prevention of unauthorized access into the system. These are operational technical requirements.

In general, the technical requirements related to Groups 2, 3 and 4 have more or less been included and partially or fully developed in the model server studied in this research. However, only a few of the technical requirements related to Group 1 has been considered thus far in the existing model servers.

A summary of the technical requirements for a BIM model server that can be used as a collaboration platform is provided in Table 7. Technical requirements for each of the categories 1, 2, 3 and 4 are detailed elsewhere and are not included

in this chapter (Taylor et al, 2009). Column 2 provides a description of the requirement and sub-requirements. A check in column 3 suggests that this requirement is completely met (M) in existing model servers. A check in column 4 means the requirement is partially met (P). If neither of column 3 and 4 is checked, it means the requirement has not been considered in existing model server, as tested in the case studies.

Integrating the Decision Framework

This section is presented to stimulate discussion and thought about how best to integrate the Decision Framework into existing work practices. It is primarily a tool for reflection of practice. Clearly our challenge with BIM Model Servers is that it is not just a technical solution, it is a business process, an education program, a changing of work culture, and a procurement and contractual dilemma. It is a combination of elements which will facilitate the move to collaborative Model Servers. At the core of the Decision Framework has been the Technical Specification for a Model Server. However it is the non technical contextual environment to support and facilitate Model Server implementation that should also be considered by clients and industry participants as model developers, owners and users in practice have many decisions to make along the way towards achieving Level 3 Integration.

Online collaboration and web-based services are increasing. The scope of BIM applications in such a scenario is bound to change. In order to achieve the goal of Integrated BIM development, BIM supporting technologies should be able to manage all the information related to the project. This includes information stored within the object properties, communication exchanged during the project development, mark-ups and comments, and other data linked to the project and the model at different phases of the project development. Thus, BIM approach of the future will not only include information embedded into

Table 7. Non-functional requirements for BIM model server

Non-functional Technical Requirements	M	P
BIM server based collaboration platform set-up assistance tool	x	X
Project BIM decision support application Software Tool compatibility matrix Project- BIM scoping support	x	X
Server administrator support System configuration manager System configuration layout viewer System status viewer	x	√
Training and support	x	√
Legal and contractual	x	√
BIM -Model management	x	√
BIM -model organization model repository sub-models and objects at different levels of details Public and private model space GUID, Information Delivery Manuals and problems encountered in merging different discipline-specific models	x	√
IDM related specifications	√	√
Model access and usability secured log-in with access rights Hierarchical model administration structure Download/Upload model/ Check- in/ Check-out/ Check-out with lock Version lock and archiving Model viewing and screenshots Documentation and reports	x	√
Interface Customizable window layouts and interface On line viewing, printing and markups On-click object property check/edit/modification	x	√
Distributed/ virtual design review	x	√
Interaction and communication	x	X
Navigation	x	√
Data Security		
Certified network security	√	√
Encrypted passwords and access	√	√

the models but also the information appended and linked to the models. BIM approach of the future will require integration of the experience and technologies from CAD as well as document management systems. BIM -Model Servers are likely to emerge as the future collaboration platforms for integrated digital design development and management. The BIM -Model Servers will combine the capabilities of object-oriented CAD

packages and document management systems or at the least support bi-directional link between object-oriented models and all related and appended information, which can come from a set of plug-ins and add-on tools.

A number of BIM supporting tools have already emerged and this number is likely to increase. In such a scenario, a variety of tools will co-exist with specific capabilities and limitations. While

ideally, interoperability can be achieved at some point but market competitiveness and business alliances may prolong the goal. In the meanwhile, the AEC industry will continue to be dependent on proprietary tools. Hence, amid this growing number of specific applications with varied capabilities and compatibility the selection of the right tools will be critical to project effectiveness.

With more distributed design and greater inter-firm specializations the need for coordinating project resources and capabilities is likely to increase. As can already be seen, some of the ad-hoc processes in technology integration and selection may prove detrimental to project success. The higher role of technology will necessitate better decision making for technology and tool management across the firms and specific to project requirements. This is where a Project Life cycle Collaborative BIM Decision Framework will be useful. However, given the increasing number of tools and factors dependent upon tool selection this framework itself should develop into a BIM management tool, preferably accessible to project partners with a web-based online interface. A technical implementation of the decision framework is envisioned as the BIM managers' tool that can interact with other project information management tools to support collaboration set-up and coordination for integrated digital design development.

Business Process

In general it is expected that the Collaborative BIM Decision Framework can be implemented through one or more of the following business channels:

- **Client as the driver:** The client may identify the benefits of a structured BIM project management approach to implement a Model Server and require, a report on strategy and analysis of the project collaborators capacity to operate within Model

Server environments. In such a scenario, the decision framework will prove to be a useful tool in assessing, project implementation risks and opportunities at a very early stage of the project.

- **Leadership of parent/dominant organization:** large firms involved in design and construction that have to manage the project complexities will benefit from the decision framework. The Thiess Management System is an example of such a detailed framework and as mentioned earlier, discussions with representatives from Thiess was the initial encouragement for the BIM project decision framework.
- **Application vendors and market opportunity:** A number of project information management tools have evolved in the market (e.g. Newforma Project Center) with some success and acceptability. From the recent developments it is evident that new roles such as BIM -Model Managers and BIM -Model Server Managers are emerging. Analogous to project management tools (for project managers) a BIM management tool (for BIM model/server managers) implementing the BIM project decision framework is a very likely possibility. Such applications may eventuate as plug-ins to existing project management tools, embedded in Model Servers or be developed as standalone applications.
- **Government regulation:** Government agencies intending to promote BIM usage and adoption may promote and/or require an initial BIM project plan as part of the project assessment and approval process. This will be particularly useful for government projects requiring project participants to deliver BIMs and to work at high levels of integration and use Model Servers. The BIM project plan would become a necessary part of the project bidding stage. For such strategic and significant projects a

BIM project decision framework in some format will be critical to development of such a BIM project plan.

- **Requirements for loans, insurance and financial agencies:**
- Financial agencies that approve and finance construction projects may consider a BIM project plan to assess the inherent risks and opportunities in project collaboration and development. 4D- 5D models are desired because they provide greater cost estimation and detail before the construction phase. Thus, an understanding of the project collaborators BIM capabilities will allow such agencies to judge if such expectations of detailed and accurate models is realistic or not.

Evaluating Skills, Knowledge, Behaviours and Capabilities

The use of BIM -Model Server as a collaboration platform requires various levels of skills, knowledge and capabilities. Some of the indicative roles and responsibilities are listed here with the expected skill, knowledge and capabilities:

- Server feature developers and technicians
 - Intermediate/ advanced programming and coding skills
 - Advanced internet and networking skills
 - Familiarity with project management processes and approaches
- Server management and administration
 - System administration and troubleshooting skills
 - Basic programming and coding skills
 - Project management and organizational skills
 - Advanced internet and networking skills
- Model management and administration
 - Project management and organizational skills

- Familiarity with 3D and CAD packages
- Familiarity with design development processes and regulations
- Basic internet skills
- Model users and model developers
 - Modelling skills and competence in 3D/ CAD packages
 - Domain expertise and knowledge (e.g. thermal analysis, structural analysis, etc)
 - Basic internet skills
- Document users and model viewers
 - Basic internet skills
- Others: e.g. on-site workers, tradesman, etc
 - Basic technological skills such as handling Cell phones, SMS texting, etc

Support, Training and Education

Support, training and education for BIM Model Server implementation is required at various levels including:

- Formal courses in schools
 - Designers
 - Modellers
 - Project managers
 - Analysis tools within various disciplines
 - BIM experts e.g. BIM manager
- Training of project staff and new recruits
- Continuing education and professional development programs for existing users
- Information sessions and briefings for decision makers
 - Clients and senior executives
 - Stakeholders and suppliers
- Online resources and collective learning through blogs, discussion forums and open source development

The Framework has concentrated on the specific technical requirements for Model Server implementation. It is too large a topic to deal specifically with support and training, however suffices to say that the appropriate level of training and support is required and after a skills audit some plan should be developed. It is also worthwhile to note that as most participants [model builders] would be operating at a reasonably high BIM knowledge level and so it is only that specific training that is required to move into a collaborative environment. Model users may require a certain level of training and support with Model Servers and the Model Server manager would need to ensure that this happens. Finally a certain level of ‘education’ and awareness is necessary for the client, but only to the level that is necessary, and this is probably one of the next challenges for the future.

Steps to Customise the Framework

When working through this Decision Framework organizations should consider how it can best be incorporated into their project. There are so many different scenarios on projects that it is nearly impossible to account for all the different decisions that would be needed to implement a Model Server. Figure 8 displays a flow chart of the process that an organization charged with the responsibility of setting up a Model Server should follow, when integrating the material in this Framework.

‘What to implement?’, ‘How to implement?’, ‘Who pays?’ etc are all questions that model owners will need to grapple with. Many of the activities discussed in this framework are common sense – whilst some are not and are quite technical. Regardless of whether or not it is common sense, it is surprising how often we “jump in the deep end” with poorly thought out plans of how we will swim to the other side or whether we can. Leadership is required in the early stages of a project. We have suggested that a BIM Manager is required and strong support from senior executives and the client – in time such

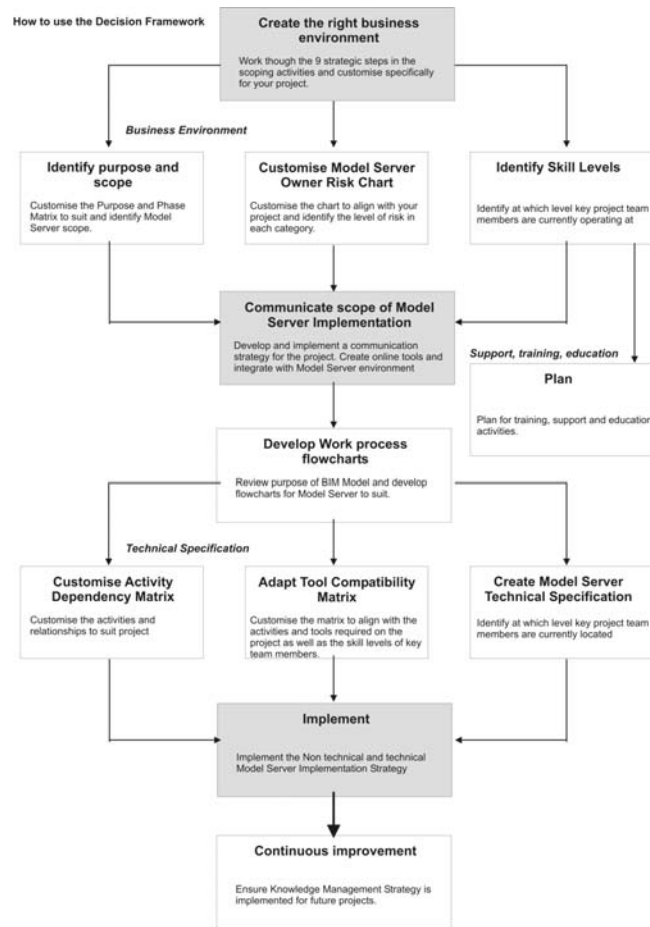
an explicit role may not be necessary. One of the challenges we face is that there is little experience to draw from in the industry and so with many innovations it takes time to become more widely adopted. Such a step wise and systematic approach advocated in this framework will more than likely not be necessary once Model Servers have been in use and have become an accepted practice. Further to this, it is strongly advised that the Decision Framework is incorporated online as an additional tool within the Model Server environment and various charts/forms/matrices are customized to suit specific project and/or organizational needs; along with any national guidelines and/or codes of practice that have been developed. With increased knowledge will come increased diffusion of the use of BIM -Model Servers.

6 FUTURE TRENDS AND CONCLUSION

Online collaboration and web-based services are increasing. The scope of BIM applications in such a scenario is bound to change. BIM approach of the future will not only include information embedded into the models, but also the information appended and linked to the models. BIM approach of the future will require integration of the experience and technologies from CAD as well document management systems. In such a scenario, a variety of tools will co-exist with specific capabilities and limitations. While ideally, interoperability can be achieved at some point but market competitiveness and business alliances may prolong the goal. In the meanwhile, the AEC industry will continue to be dependent on proprietary tools. Hence, amid this growing number of specific applications with varied capabilities and compatibility, the selection of the right tools will be critical to project effectiveness.

With more distributed design and greater inter-firm specializations, the need for coordinating project resources and capabilities is likely

Figure 8. BIM collaborative model server decision framework customisation flowchart



to increase. As can already be seen, some of the ad-hoc processes in technology integration and selection may prove detrimental to project success. The higher role of technology will necessitate better decision making for technology and tool management across the firms and specific to project requirements. This is where a BIM decision framework will be useful. However, given the increasing the number of tools and factors dependent upon tool selection, this framework itself must develop into a BIM management tool, preferably accessible to project partners with a web-based online interface.

Future research on the BIM project decision framework is required to develop it into a more comprehensive decision tool. At present, the deci-

sion framework gives a layout of the minimum requirements for such a BIM project decision tool. Case studies with industry-based projects and inputs from other project management tools will be useful.

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KEY TERMS AND DEFINITIONS

BIM Approach: A practice adopts a BIM approach for a building project if the project applies a BIM as the base model for the design and/or construction processes.

BIM -Model Server: An information repository that will hold the building information sub-models and allows native applications to import and export files from the database for updating, modifying, viewing and checking the data.

BIM Project Lifecycle Decision Framework: A project decision framework developed by the author team to assist the design and implementation of a suitable BIM approach for a building project.

Collaboration Platform: A computer-based platform that provides a centralised unit (i.e. a server), for supporting collaborative projects and coordinating team activities.

Document Management Systems (DMS): A collaboration platform developed specifically for managing documents shared by multiple parties in a project.

Object-Oriented Modelling: Object-oriented modelling is a programming paradigm that uses objects as data structures to design computer-based applications. In an object-oriented building model, building elements are represented as objects that can contain both geometric and non-geometric information.

Work Process Roadmap: Formal documented maps of key processes of an organisation developed as a form of quality assurance and/or accreditation or simply as, good business practice including activities, events and key decision points and relationships between these entities.

Section 5

Green Building

Chapter 14

The Idealization of an Integrated BIM, Lean, and Green Model (BLG)

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ABSTRACT

Idealization, “a very high level view,” is defined here as looking at the possibilities of integrating Green socially responsible requirements with Lean principles of construction practices with well-developed Unifying Models, such as Building Information Modeling (BIM). BIM, Lean, and Green (BLG) will allow a rapid prototyping of design and construction, the integration of drawings, specifications, and manufacturing in a Green best practice ambient that employs benchmarked Lean principles. This chapter explains our propositions on Green as a concept that gives direction on what to do right (effectiveness), on Lean that captures how to do it right (efficiently), and on BIM as an enabling platform that will facilitate the implementation of this effort. The integration of this concept addresses the quest for economically viable construction projects with the purpose of finding the best optimum performance. We consider the design as a theory, the project as an experiment, and the resulting products as a test that validates the theory. BLG allows for multiple executions of a theory to find the best option, and then test it against the final product. This chapter contributes to the body of knowledge but does not cover all aspects of the subject.

1 INTRODUCTION

According to Garcia-Bacca (1963, 1989), one invention does not necessitate the next logical invention; that is, inventions and creativity are not predestined (Mitcham, 1994). However, the fact remains that

past inventions, innovations and technologies created the current background of tools, knowledge and practices in the construction industry. In particular, the advent of Computer Aided Design (CAD), first in two dimensions, then three dimensions, and now in n^{th} dimension axiomatic design (Suh, 2001) capabilities has improved design aspects (Fowler, 2003; Iansiti, 1995). If Garcia-Bacca is correct, Building

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Information Modeling (BIM), defined as: 3D, object-oriented, Architect-Engineer-Contractor (AEC) specific CAD (Tang and Ogunlana, 2003), or Building Product Modeling (Eastman, 1999; Eastman et al., 2008), and now BIM-Lean-Green (BLG), are not predestined from CAD by necessity but by human intentionality.

The construction industry's needs are different than they used to be and require tracking an ever increasing number of parameters in a robust platform that can interoperate among multiple actors such as suppliers, vendors and the entire organization of a construction firm. The industry has focused its attention on Unifying Models that are rich in parameters to supply its needs. The unifying models prescribe product design and performance requirements (Foliente, 2000) through parameters, a concept known as Building Information Modeling (BIM) in the industry. BIM is a well-developed Unifying Model that can be understood as a model developed to support interoperability, which is the sharing, exchanging, and integration of information among project stakeholders and possibly during the entire project lifecycle in a collaborative fashion (Mutis 2007a). BIM unifies within a single model the information that is going to be shared, exchanged, and integrated among stakeholders from the design to the commissioning. Functions of the Unifying Model can be extended to facility management of the project.

The problems of interoperability remain significant at this point in time and is therefore an issue that cannot be brushed aside or minimized. Gallaher et al. (2004) in the National Institute of Standards and Technology (NIST) Report to the U.S. Department of Commerce estimated that approximately \$15.8 billion (US Dollars) in annual interoperability costs were quantified for the capital facilities industry. Respondents also indicated that significant inefficiency and lost opportunity costs exist but were beyond the scope of the NIST report. The International building SMART efforts, processor of the International

Alliance for Interoperability, are part of an IT culture dedicated to the interoperability problems and issues. European interoperability experts generated a STANDINN report and developed a handbook on interoperability between BIM and Green. Part of the problem is the rooting of platforms that do not have an open architecture. An open object format that can support the industry, such as an open architecture that allows Life Cycle inventory data to support sustainability and the proper measurement of embodied energy in accurate 3D representations with rich data describing key physical, performance and commercial properties, is relevant to the idealization of BIM, Lean and Green.

Multiple benefits have been attributed to BIM such as early and more accurate visualizations (Forsberg et al., 1996), lower levels of design corrections, earlier collaborations with other disciplines, energy efficiency, and sustainability evaluations (Eastman, 1999; Eastman et al., 2008; Krygiel et al., 2008; Kymmell, 2008), among others. The model captures however, only *some* aspects of design, materials, and *few* of the construction processes (Slaughter, 1993, 1998, 2000). Although BIM methods have motivated architects, owners, engineers, and other construction project actors to evaluate the traditional methods of working with architectural designs (drawings and specifications) and contractors' tools (estimating, scheduling project management, cost controls and tracking requests for information change orders), the industry must be aware of the limitations of the unifying models. BIM is trying to redress the current lack of collaboration between planning, design, construction and operations with sustainment practices and inefficient construction processes due in large part to the systemic nature of the industry (Fernández-Solís 2008).

Our examination of BIM, as a well-developed Unifying Model proposes the association of critical design information (working drawings and specifications) along with contractor tools (estimating, scheduling, project management, cost control,

tracking requests for information and change orders to name a few) within a robust platform. In other words, our proposition associates the project components and project processes.

Due to the implications in handling variability and complexity, BLG have the potential to become industry wide paradigm shifts (Fernández-Solís, 2007f; and Williams 1999). The importance of this is that when implemented by a critical number of practitioners, the construction industry will be radically different from what we have in 2008; a paradigm shift (Kuhn, 1962; 2000) will have occurred.

Cost / Time / Quality Paradigm Shift

Project delivery systems are devised as solutions to construction's changing needs. Design-bid-build (D-B-B) arose as a solution to cronyism and inflated costs, as it provided a mechanism to attain the least cost by a qualified service provider. When D-B-B least cost led to confrontation, change orders and litigation (supported by the Spearman Doctrine that says documents have to be buildable and not a design intent), the industry created Design-build (DB), or a single contract agreement and project delivery system. Design-build allowed fast-tracking of projects, and time (early completion) became another form of lowering cost by speeding up the moment when the capital asset becomes productive. Time, as a surrogate of cost, and lower cost have been the ruling paradigms even when selection processes emphasized Request for Qualification followed by a Request for Proposal. Construction Management at Risk and Integrated Project Delivery are variants with time and cost as alternating main criteria.

Sustainability and the Green movement have shifted the project delivery main concern from cost and time to a high-performance project, that is, a shift toward a particular type of quality — a new Green paradigm. This shift is a nascent paradigm shift in the industry from cost and time of delivery to high-performance building. High performance

is achieved not by fine-tuning component performance, but by looking at systemic performance, that is, the whole building's performance. This requires an understanding of systems integration that is much more sophisticated than its appearance and common understanding dictates. Therefore, it can be said that the driver of future project delivery systems will emphasize quality of design and achievement of high performance in the areas of sustainability and the relationship of the built to the natural environment.

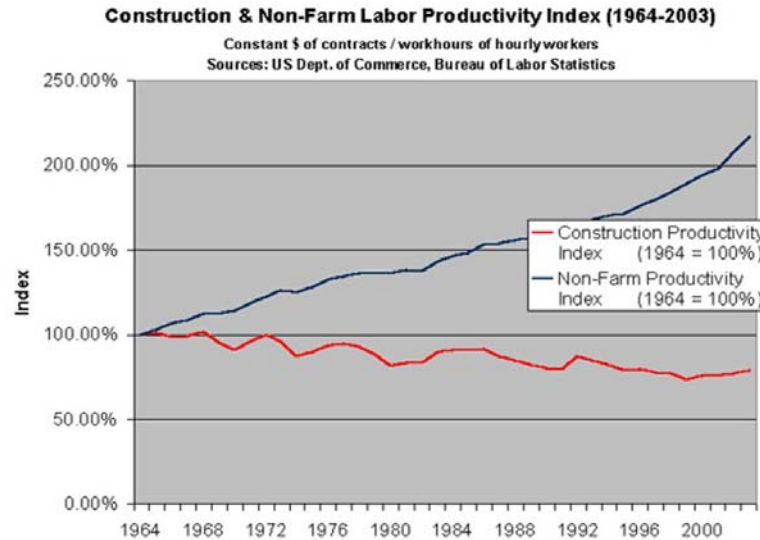
BIM and Lean, by themselves, will have limited achievement outside this new Green paradigm. In other words, outside Green the paradigm remains low cost or faster time to market and both BIM and Lean strive to achieve those ends independently and concurrently. However, when BIM and Lean are utilized in the context of achieving high-performance building as required by a Green imperative, the three have a synergistic potential, that of maximizing performance and not cost or time alone.

Efficiency in Construction, a Paradigm Shift

Practitioners insinuate that we have achieved and can continue to achieve respectable construction efficiencies (Bowley, 1966; Bennett et al., 1998a; Berger, 2005; Bertelsen, 2005; Forsberg et al., 1996). Latham (1994) and Egan (1998, 2002) have, over the past ten years, challenged the industry to improve its efficiency as well as the quality of its output. Failure to achieve these efficiencies points to a lack of understanding of the systemic nature of the industry. Regarding productivity in construction (Oglesby et al., 1989), US Labor Department statistics show that construction productivity has decreased over the last 40 years, while other industries have more than doubled their productivity (Fig. 1).

However, Rojas and Aramvarekul (2003) argue that the raw data used to calculate construction productivity values at the macroeconomic level

Figure 1. Labor productivity index for US construction industry and all non-farm industries from 1964 through 2003



and their further manipulation and interpretation present so many problems that the results should be deemed unreliable. “The uncertainty generated in the process of computing these values is such that it cannot be determined if labor productivity has actually increased, decreased, or remained constant in the construction industry for the 1979-1998 period.”

Furthermore, Rojas and Aramvareekul (2005) indicate that microeconomic studies suggest that labor productivity in construction may have actually increased in the above mentioned period. Construction trends during this period favored moving elements that can be pre-assembled to off-site production. In this case, productivity gains are attributed to and accounted for by the manufacturing sector of the industry (Fisher, 1993; Gann, 1996), leaving the less productive tasks on-site, therefore biasing the construction data toward less labor productivity. While overall the construction process may have gained in productivity, the US Labor data continues to show construction productivity as declining (Ranta, 1993).

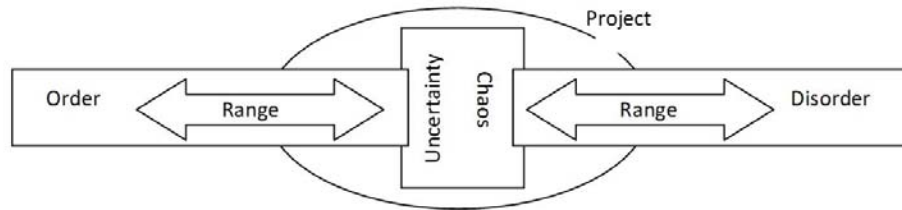
The US Labor data, if accepted as a valid indicator, portrays the construction industry as

suffering from structural productivity problems that need to be corrected. According to Rittel and Webber (1973a, 1973b), the potential areas for improving productivity are:

- Use of IT/IS (BIM, which is also referred to as Visual Design and Construction - VDC)
- Project Delivery Systems - PDS (Lean Construction, Design-Build or Integrated)
- Industry consolidation (fewer small firms, more large players)
- Increased R&D spending (currently it is less than 0.5%, while the average for all industries is 3.5%)

However, productivity efficiencies in the absence of technological changes are dismal (Syben, 1993). Proposals have been made to link design and automated construction (Howe, 2000; Simon, 1969; Tabatabai-Gargari and Elzarka, 1998; Tang and Ogunlana, 2003) with the automation of construction (Johnson, 1995; Howe, 2000), design and robotics (Warszawski, 1990, Sangrey and Warszawski, 1985). However, others point out that construction, because of its nature and complexity

Figure 2. Conceptual boundary of the complexity of a construction project (adapted from, Vanegas 2008)



(Waldrop, 1992; Fernández-Solis, 2007a; Gidado, 1996) exists between order and disorder at the boundaries of uncertainty and chaos (Bertelsen and Koskela, 2002; Crichton, 1996; Gleick, 1987; Lewin, 1993; Lorenz, 1993; Scott, 1933; Tavistock, 1966; Thiétart and Forgues, 1995). Fig. 2 illustrates where waste and variability are embedded and are not obvious to the practitioner. The innate complex nature of construction (Sebestyén, 1998) frustrates all current attempts at increasing its efficiencies in a systematic and predictable manner, like that evident in other industries such as manufacturing. Fernandez-Solis (2007e) argues that attempts at increasing efficiency add exterior complexity, with the paradoxical result of “sand-bagging” efficiency improvement efforts.

In Lean Construction (LC) thinking, local efficiency is achieved at the expense of the whole project, a net result that may negate any local efficiency improvement. Systemic thinking is needed where local performance is fine-tuned but not necessarily optimized, when considering that total project flow is anchored on what constitutes final value for the client.

Other researchers have observed how far the construction industry needs to improve in its quest to become like manufacturing (Egan, 1998; Fisher, 1993; Fox et al., 2002a, 2002b; Gann, 1996; Groák, 1994; Miozzo and Ivory, 2000; Syben, 1993; Strassman, 1997). In this quest, some suggest that structural changes may be required (Koskela, 2003a; Koskela and Kazi, 2003) and argue that a theory of construction is needed (Koskela, 2002;

Whetten, 1989), because the underlying theory of project management is obsolete (Koskela and Howell, 2002a, 2002b; Lillran, 1995). Furthermore, some question if construction, as currently practiced, is sustainable (Nootebom and Teisman, 2003; see the seminal work of Pearce, 2006 and Fernandez-Solis, 2008). Construction productivity and efficiency is in what could be safely called an “identity crisis”; that is, it reflects the need to find a theory that can address internal and external complexity in the systemic nature of the industry (Seaden, 2000; Seaden et al., 2000).

Pre-Paradigmatic Present (2008) Conditions

The state of the art indicates that there is no single application (Sneed, quoted by Kuhn, 2000) and there is definitely no single theory in the construction industry. However, Masterman, critiquing Kuhn, argued that a paradigm “can function when the theory is not there,” in the case of the construction industry, and Kuhn (2000) agreed: “*paradigm is what you use when the theory isn’t there.*” In this sense, paradigm and heuristics are closely related and close descriptors of BLG as an idealized metaphor, at the present moment in time.

Kuhn (1962) observed that in a pre-paradigm situation, a paradigm shift, or in a crisis, the professions resort to philosophy (Williams 1999; Thompson, 1993; Titus et al., 1995; Koskela, 1992) for clarity of ideas (we can infer direction

such as what is effective) and then to science and technology for implementation (such as what is efficient), which underscores the purpose of this paper. According to Kuhn (1962, 1976), there have been a few periods in history that deserve the label of “transforming eras”, during which circumstances changed sufficiently in response to challenges to warrant a major shift of assumptions in what he calls a paradigm shift. This transforming era paradigm shift occurs when people depend on working assumptions that become so inappropriate that they break down, to be replaced by a more appropriate set.

Likewise, building construction history has been affected by internal and external forces that are characterized by long periods of stability in a paradigm, punctuated by relatively short periods of high instability (pre-paradigm shift or crisis). This exemplifies history as a staircase rather than a ramp (Kanter, 1983). The current building construction industry crossroads, when considering the magnitude of the challenges, is at a historical pre-paradigm threshold, a time during which surmounting the crisis will require an exponential step. Again, what are the arguments underlying our position that we are at a pre-paradigmatic stage, on fertile ground toward a major paradigm shift of exponential consequences in the construction industry?

Previous advances in project management (Hillebrandt et al., 1974; Hofstede, 1978) and in project delivery systems (Bertelsen and Koskela, 2002; Riis et al. 1992; Briscoe et al., 2004; Parker and Oglesby, 1972) have failed to deliver expected or projected efficiencies in a reliable and consistent way (Egbu, 2004; Fernández-Solís, 2007e; Gann, 1996; Koskela and Vrijhoef, 2001; Saxon, 2002; Woudhuysen and Abley, 2004). The quest can be stated as:

How can the industry achieve consistent continual improvement in waste reduction, value creation, labor productivity increases, etc. within the sys-

temic nature of the construction industry with its unique defining characteristics?

Three independent forces, along with many others, such as performance buildings (CIB, 1997a; Foliente, 2000) and studies revaluing construction (CIB, 2005; CIB, 2000, CIB, 1997b; Miozzo and Ivory, 2000), are currently working their way through the construction industry: BIM, LC and Green initiatives (Koskela et al., 2002, 2003; Koskela, 1992, 2000, 2003b; Koskela and Ballard, 2003; Koskela and Kagioglou, 2006). Each is trying to affect or even change the paradigm that drives the industry. However we argue that:

1. Even if BIM, Lean and Green are practiced by individual firms and each initiative is practiced in isolation from the others, as in the current scenario, the necessary critical mass will not be realized and a significant industry wide paradigmatic change will not take place.
2. As multiple sources in the industry pursue BIM, Green, and Lean initiatives, there is an opportunity to integrate these initiatives through the understanding of their purposes and their philosophies.
3. A clear argument of the “why” needs to be articulated so that we know we are headed in the right direction (effective) before increasing speed (efficient).

This chapter, a *tour de force* in literature search, establishes the state of the art research about the long-term horizon of BIM, especially concerning the possibility of integrating BIM’s platform with LC practices and with Green initiatives (BLG). BIM is simply the starting point. In a parallel analogy with the state of the art from the 1960’s, BIM is at the slide rule level, when considering its future potential (even though it is not yet imagined because R&D investment is lacking for theoretical future studies) for addressing project complexities

and variability while achieving effectiveness and efficiencies.

The objective of this chapter is to showcase how the envisioned BLG platform captures the fundamentals of cooperation and integration between BIM, LC and Green performance indicators.

2 BACKGROUND: THE PROBLEM STATEMENT

Construction is a complex process with multiple variables in a dynamic setting (Ranta, 1993; Chu et al. 2003, Fernández-Solís, 2007; Dubois and Gadde, 2002; Baccarini, 1996). Consequently, parametric models and their poor prescription of situations are neither efficient nor practical for implementation. They require extraordinary effort for different actors to collaborate on *interpreting* the described geometry, the simulation or prescription of situations (Carassus, 1999; Mutis, 2007). Additional endeavors are required by other project actors, as the model cannot be mapped to multiple situations within the construction process, to interpret the model. In consequence, highly intensive sessions for interpretation of the models, within a shared space, such as a trailer or a technology room, are required with multiple actors who participate in the construction project. These sessions then require human participation and manual mapping of the models' objects to other applications employed by project managers, engineers, mechanical engineers, subcontractors, etc. For example, mappings, which require an actor's interpretation of the model between the parametric model design and the engineering application, are required to link the modeled element and the application (Mutis and Issa, 2007). The interpretations and mappings are cumbersome, onerous activities, and they are a source of inefficiencies when project actors require exchanging, sharing, or integrating the resulting parametric models (Butler, 2002; Mutis et al., 2007).

BIM, as a well developed Unifying Model, is a concept that supports the interoperability (or

generation), sharing, exchanging, and integration of information, among project stakeholders and possibly during the entire project lifecycle in a collaborative fashion. In this sense, BIM is an idealization that simplifies the most crucial components of a building into a three dimensional model with parametric attributes. BIM isolates the building components, which are defined by parameters, represents them visually, and assigns other values to the components. These visual representations are *symbolic* abstractions created and generated for construction product designs, with the purpose to have a world characterization that should satisfy particular world-states (Mutis, 2007; Mutis et al., 2007). BIM's parametric attributes allow the building components not only to link to one another in a self awareness of time, space, and connectivity, but also to other attributes not currently modeled, such as: (1) upstream: project financial pro-forma; site specific codes such as zoning, building and fire; geo-technical information and site historical data; (2) instream: tracking the entire process of fabrication transportation, storage and material placement; determination of sustainable, green product and system characteristics; (3) downstream: the life cycle of the building, including all aspects of maintenance, renovation and decommissioning (dematerialization or recycling).

Interoperability remains a major obstacle and an issue that is being addressed by experts in major research laboratories such as Building Research Establishment (BRE), Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia, Collaborative Research Centre in Construction Innovation (CRC-CI), Centre Scientifique et Technique du Bâtiment (CSTB) in France, Lawrence Berkeley National Laboratories (LBNL), National Institute of Standards and Technology (NIST), Pacific Northwest National Laboratory (PNL) SECOM Co. Ltd., Nederlandse Organisatie voor toegepast-natuurwetenschappelijk, (the Netherlands Organization for Applied Scientific Research), Valtion

Teknillinen Tutkimuskeskus (VTT), Technical Research Center of Finland, among others. There are numerous educational institutions dedicated to solve the problem of interoperability such as the Georgia Institute of Technology, University of Salford, and Texas A&M University, among others. Several research books have been published on the subject of interoperability such as McGraw-Hill (2007) *Construction SmartMarket Report – Interoperability in the Construction Industry* and Jernigan (2007) *BIG BIM little bim*, Eastman (2008) *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, and Krygiel (2008) *Green BIM: Successful sustainable design with building information modeling*, among others. This body of literature, which has been consulted by the authors of this chapter, indicates that although great progress has been made, we have a long way to go before the ideation espoused in this chapter and in this Handbook, will be a reality. According to Garcia-Bacca (1989), the idealization reality is speeding towards us at a quicker pace with each passing day due to sheer number of talent and resources that are dedicated to the problem.

What is interoperability? McGraw Hill (2007) defines interoperability as the ability to manage and communicate electronic product and project data among collaborating firms. What is the problem behind interoperability? BIM, loaded from Revit/Archicad/Bentley/ etc... is just another Computer Aided Design and Drafting (CADD) software program and with each release a new version needs to be loaded in. Simulations are run locally, in a shared platform within the organization (Local Area Networks – LAN) or even shared with other stakeholders through the net. However, DProfiler and what Jernigan (2008) calls BIG BIM, the software is linked with manufacturers, supplier, vendors, with the marketplace that has informational access of the product characteristics, costs, shipping availability, tracking of shipment, connectivity requirements, erection requirements,

etc. In other words, the entire product specifications for all the available products in the market place become a source of information. With Green, embodied energy and a multitude of other parameters become embedded in the data that now has valuable information. For this to take place, the interoperability of all parties in a single platform becomes critical. A protocol has to be followed that allows standardization of the information. It is like if all the grocery stores had their one bar code standard, manufacturers would not be able to have the current efficiencies in production and delivery if they had to accommodate differing standards. Interoperability then goes beyond data communication between firms, it is between the entire construction industry.

BIM employs a parametric modeling approach in the design of construction building projects. The advantages of this approach have motivated architects, owners, engineers, and other construction project stakeholders to evaluate the traditional methods of working with architectural designs. Multiple benefits have been attributed to BIM, such as early and more accurate visualizations, lower levels of design corrections, earlier collaborations with other disciplines, energy efficiency, and sustainability evaluations (Eastman et al., 2008; Krygiel et al., 2008; Kymmell, 2008), among others. The problem is a lack of idealization of the future after BIM (Scharmer, 2007). This is probably due to (1) the current focus on making BIM work, and (2) the lateness of CAD acceptance by construction companies, the most entrenched traditionalists of the service industries (Fitchen, 1986; Groák, 1992, 1994; Latham, 1998; Fernandez-Solis, 2007e; Fox et al., 2002a; Koskela, 2003a). Idealization is a critical tool in understanding processes, and as such, it is used mostly by architects, engineers and some constructors. There are four identifiable obstacles to this idealization:

- (1) Companies need to stop using BIM as a marketing differentiation tool and start working

toward the adoption and integration of BIM into the industry at all levels. Individuation and competition are major stumbling blocks to realizing efficiency potential and a higher industry-wide optimum. In the US, companies such as The Beck Group from Dallas, TX, and Linbeck from Houston, TX, have come to this conclusion and are devoting time and resources to reach out to the industry. Why? Perhaps when companies maximize themselves, it is at the expense of systemic maximization, a meta version of project LC thinking, explained later.

- (2) Companies also have difficulty transitioning from using CAD, the traditional tool of individual and corporate visualization of a project, to using a systematic self-directed tool capable of doing everything typically done by general contractors. This is a stumbling block to making lessons learned permanent and applying them consistently in a virtual reality capable of generating multiple scenarios as a decision support system. The idealization itself is so real that it scares practitioners the way that CAD scared architects, causing them to think their profession would vanish and become a commodity rather than a personalized artistic service to the community, a guardian of the safety and welfare of society.
- (3) Companies should investigate using BIM, not on top of drawings, specifications, and agreements (an addition to the current set of contract administration documents) but as the singular contract administration tool. When this takes place, BIM will have matured and achieved the same objective that CAD did when it replaced Mylar's and layering by hand of the 1970's.
- (4) Firms should understand that parametric models, such as BIM, are a family of *propositions* that constitute *approximations* that resemble instances or events of the world. A geometric model of a construction beam, for

example, does not reflect all sets of conditions of the world where the model is to be applied or used. The designer describes all the possible geometry and components within the geometrical model of the construction beam, adds additional attributes, and complements the model with documentation that specifies the required standards such as the material properties. The described components are simplifications of the complexity of the construction beam. However, the modeled components represent a novel tool that engages collaborative work to facilitate understanding of the designs amongst project participants.

BIM and Project as a Heuristic

Idealization, according to Wimsatt (2007) and Papert (2000), within the context of the philosophy of science, is a partial, multiple and plastic approximation based on heuristics, a precursor of theory, hypothesis and scientific research. Theories, Wimsatt argues, are the result of scientific reasoning, such as theories of complexity in construction (Fernández-Solís, 2008; Baccarini, 1996; Bertelsen, 2003, 2004; Bertelsen and Emmitt, 2005; Chu et. al., 2003; Lucas, 2000, 2004, 2005; Nightingale, 2000), effectiveness and efficiencies (i.e. LC theories), and Green construction (sustainable theories).

Bayesian approaches are currently in vogue, but many practicing scientists are more familiar with the Popperian model of the scientist as an ideal refutation engine that we shall examine later. Within all these models exists fallible, context-dependent heuristics, which are central to the success of science (Koen, 2003). Therefore, a good model, one that idealizes reality, must focus on understanding construction and the use of heuristics. According to Koen (1985, 2003):

- Heuristics does not guarantee a solution,
- It may contradict other heuristics,

Figure 3. Project as a theory

Traditional		
Design + Constructability	=	Hypothesis
Construct	=	Experiment testing the hypothesis
BLG		
Design + Constructability	=	Hypothesis
BLG - Heuristics	=	Local optimum hypothesis model and testing
Construct	=	Experiment testing the hypothesis

- It reduces the search time for solving a problem,
- Its acceptance depends on the immediate context instead of an absolute stand.

What we are discussing is transferring the heuristics from all the stakeholders (strategic planning and especially those in tactical and implementation areas) into contract documents, now contained in a three dimensional model, a model with the parameter of time, and a model with infinite number of parameters that not only encompass the product but the entire process, on its way to becoming a model that includes the entire life cycle of a project. Such a model remains an approximation at best (Sternan, 2002), fallible and bounded in a messy complex ambient, that is organized around the idea of heuristics (how to best achieve effectiveness and efficiency), that is, to minimize waste in the transformation and flow, and create value for the owner and stakeholders. What is gained in BIM and BLG platforms is the reduction of the search time for anticipating and solving problems.

Project as Experiment Testing the Design Hypothesis

Traditionally in a project, the design can be idealized as a hypothesis, construction as the experiment that tests the hypothesis, and performance as the comparison between what was intended and the test results when the project is completed (Kohler and Hassler, 2002). The idea of viewing

aspects of a project as a hypothesis and the construction as an experiment is not new; for example, the project has been idealized as an economic hypothesis (Carassus, 1998, 1999; Hillebrandt, 1974). BLG introduces the option of a virtual building hypothesis that encompasses finance, sustainability, construction, operation and maintenance, which can all be manipulated to obtain the local optimum of the project before testing it through actual construction (see Fig. 3).

The possibility of finding a local optimum through a virtual project that encompasses not only the design but also the production, benchmarked best practices (as in LC thinking), and best practices in green building, along with a holistic understanding of sustainability and emissions generation, is a step to capture suggested waste in the industry (Hillebrandt, 1974, 1975, 1984). What is the magnitude of this waste? LC claims that all construction related waste in a typical project approximates to 50%. The Beck Group in a white paper in 2000, identified readily available construction waste to be approximately 27%. There are multiple attempts at capturing this waste and converting it into value for the owner, one of which is LC.

Waste reduction (Coventry and Guthrie, 1999) and value generation are the landmarks of LC (Howell and Ballard, 1994a, 1994b, 1997; Howell et al., 1993a, 1993b; Howell and Koskela, 2000) and the holy grail of the construction industry (Allen, 1985). It is estimated that changing project delivery systems would bring significant reduction in waste. For example, going from the litigious,

Table 1. Value Opportunities range to minimize waste and maximize value in construction based on heuristics.

Project Delivery System	Minimum	Maximum
Design-Bid-Build (DBB)	Base-line	Base-line
Design-Build (DB) Construction Management at Risk	0%	5%
Integrated (Virtual Organizations)	5%	10%
Lean Construction (individual)	10%	15%
Lean Construction (regional)	15%	20%
BLG (individual)	20%	35%
BLG (regional)	25%	40%

but least cost by a qualified service, Design-Bid-Build (DBB) to Design-Build (D-B), with all its variations, and Construction Management at Risk (CMAR), with its fast-tracking potential, are ultimately cost related movements (Cox and Townsend, 1998). Notably, none of the project delivery systems have achieved efficiencies consistently, that is, in a predictable, repeatable and reliable way.

However, D-B has generated an average 5% improvement over DBB. Integrating project delivery in a virtual organization (Lundin and Söderholm, 1995; Lundin and Steinhórrsson, 2003; Eccles, 1981) of all stakeholders with the use of Project Definition Rating Index (PDRI) (Durmont, et al., 1997; Cho et al., 1999), Partnering (Baden, 1995; Bennett and Jayes, 1998b; Larson, 1995; Godfrey, 1996; Rackman et al., 1996), and a plethora of other initiatives in a D-B type of agreement reaches at best, an additional 5% efficiency increase. However, this is sporadic and depends on the project type, team and all the customary variables. See Table 1 for a heuristic posed for future research verification. LC (Alarcon, 1997; Ballard and Howell, 1994; 1998a; 1998b) adapted to the peculiarities of construction, has benchmarked best practices from the manufacturing industry with the concepts of transformation, flow and value, waste minimization and value maximization, pull techniques (Ballard, 1999), last planner (Ballard, 1994; 2000; Ballard and Howell, 2003b), and

lean project management (Ballard and Howell, 2003c). This has brought another possible 5% improvement to the project delivery (Ballard and Howell, 2003a; 2004; Ballard et al., 2002; Ballard, 2005).

However, a glass efficiency ceiling has been reached because companies are doing LC individually, but the industry has not caught on downstream: some companies do it one way, other companies do it another, and the majority, a large number of very small companies, do not practice LC in any way (Abdelhamid, 2004). If the industry at large were to implement LC, an estimated 20% waste elimination / value generation would be reached -a hypothesis to be tested. However, with a BLG platform, first at the individual company level, a 25% waste elimination and value generation is hypothesized, and if the industry at large adopts a BLG platform, the probable local optimum of 40% could be reached in a consistent and predictable way, using DBB as a benchmark. In other words, the current paradigm is about company differentiation and a lack of systemic thinking of the industry as a whole, a kind of company maximization at the expense of industrial efficiency (Williams, 1999). This type of critical thinking parallels the LC observation that maximizing a part or a process is done at the expense of the whole. To achieve waste minimization and better levels of value creation, the industry needs to have meta-systemic thinking.

Lack of Meta-Systemic Thinking at the Industry Level

The construction industry at large has no clear understanding of the difference between effectiveness (doing the right thing, the why, a philosophical and qualitative question) and efficiency (doing the thing better, continual improvement, change, a quantitative issue). Without a clear understanding of the nuances implied by effectiveness and efficiency, the industry may be moving faster on the train of change, but in the wrong direction. Effectiveness and efficiency are two sides of the same coin -vectorial elements with an emphasis first on the direction, then the why, and finally the magnitude, whose origin is taken for granted. Lack of an understanding of the problem has led to the current state of there being a multitude of improvement initiatives with increased complexity in the project delivery process and with decreasing results such as:

- **Organization related:**

- Project Management (Miozzo and Ivory, 2000; PMI, 1999);
- Project Management Body of Knowledge (PMI, 2000);
- Partnering (Baden, 1995; Bennett and Jayes, 1998b; Godfrey, 1996; Rackman et al., 1996); Slaughter, 1998);
- Project Definition Rating Index, (PDRITM) (Cho et al., 1999; Durmont, et al., 1997);
- Learning Organizations (Edmondson and Moingeon, 1998);
- Knowledge Management (COM, 2000);
- Open Building (Kendall and Teicher, 2000; Van der Werf, 1990; Vrijhoef et al., 2002)
- Virtual Organization (Winch, 1998);
- Innovation in Construction (Slaughter, 1991, 1993, 1998, 2000; Tatum,

1996; Tushman and Anderson, 1996; Widén, 2002);

- Comparison with other industries (Vrijhoef and Koskela, 2005a, 2005b, 2005c; Green et al. 2004; Voodijk and Vrijhoef, 2003);
- Emergent Change (Weick, 2000)

- **Performance related:**

- Total Building Commissioning (USGSA, 1998; NIBS, 1999);
- LC (Alarcon, 1997; Ballard and Howell, 1994; Santos, 1999; Howell and Koskela, 2000; Ballard et al., 2002; Koskela et al., 2002; Vrijhoef et al., 2002);
- Concurrent Engineering and Fast Tracking (Ballard, G., 1999);
- Just in Time Production (JIT) (Gilbreths and Gilbreth, 1922; Hopp and Spearman, 1996);
- Total Quality Management (Shewhart, 1931; Shewhart and Deming, 1939);
- Continuous Improvement Theories (Wortmann et al., 1997);
- Theories of Integration (Wortmann, 1992a; 1992b);
- Robotics (Sangrey and Warszawski, 1985; Warszawski, 1990);
- Re-Engineering (Winch, 2003);
- Last Planner (Ballard, 1994; 2000; Ballard and Howell, 2003b);
- Constructability and Buildability (Ferguson, 1989; O'Connor, 1986; Shin, 1992)
- Value Engineering and Management (Kohler, 2006; Allen, 1996);
- *Life Cycle Costing*
- *Critical Path Scheduling*

- **IT related:**

- nD CAD - parametric oriented, web based real time multi-user platforms (FIATECH, 2004; Koskela and Kazi, 2003; Fenves, 1996; Johnson, 1995; Ladevéze and Zienkewicz, 1992)

- Digital Building Process and As-built Documents (Tabatabai-Gargari and Elzarka, 1998)
- **Codes and Standards related:**
 - Performance Based Building Codes, Standards and Specifications (Foliente, 2000)
- **Contract and Structure related:**
 - Integrated Project Delivery Systems (such as: Design-Build and similar variations) (Bowley, 1966; Bennet et al., 1996);
 - Construction Management @ Risk and multiple variations;
 - Subcontractors and Vendors Alliances (Cox and Townsend, 1998; Pyke, 2002).
- **Environmentally related:**
 - LEED® (US Green Building Council)
 - SPiRit (US Army)
 - Green Globes (USA)
 - BREAM™
 - GBTool™ (UK)
 - BASIX (Australian)
 - Green Star (Australia)
 - HQE2R (CSTB - France)
 - CASBEE (BEE Japan)

Each of the above listed initiatives was created in response to an identified problem. However, these individual and collective initiatives have increased project delivery complexity, failed to achieve a permanent, reliable, consistent increase in efficiency and have come up short in providing an answer to the original question: *How can the industry achieve consistent continual improvement in waste reduction, value creation, and labor productivity increases within the systemic nature of the construction industry with its unique defining characteristics?*

Proliferation of Initiatives without Corresponding Efficiency Synergy

Koskela et al. (2003) developed, or elucidated, the issues surrounding increasing complexity of the proposed trends and initiatives without significant results. This brings to mind Kuhn's (1976) paraphrased statement: When complexity increases far more rapidly than its accuracy or benefit and when a discrepancy corrected in one place is likely to show up in another, it may lead to a similar proclamation as that of Alfonso X that if God had consulted him when creating the universe, he would have received good advice, or Copernicus' comment in *De Revolutionibus* that the astronomical tradition he inherited had finally created only a monster. Proliferation of versions of theories is a very usual symptom (or concomitant) of crisis.

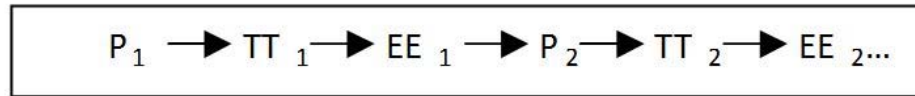
This crisis is a lack of focus on effectiveness and a proliferation of efficiency techniques that complicate and exponentially increase the complexity, resulting in a dramatic decrease in efficiency, exactly the opposite of its intent.

A literature search indicates an obsession with change in the industry toward achieving greater efficiencies (Dubois and Gadde, 2002; Egan, 2002), as in manufacturing. However, first we must ask the question: Is what we are doing effective (the correct thing to do – environmental, sustainable, using the right paradigm, waste reducing, value generating) and then we can ask: are we doing “it” efficiently (doing the thing right -least cost, fastest, better quality) (Fairclough, 2002; Atkin, 1999; Pries and Janssen, 1995; Pries et al., 2004;) within the systemic nature of the construction industry (Nam and Tatum, 1988).

3 BUILDING THE ARGUMENT: SEPARATE KNOWLEDGE DOMAINS

BIM, LC practices and Green, or sustainable, eco-friendly initiatives are typically taught, practiced

Figure 4. Popper's (1972) Analytical process of conjectures and refutations



and thought of as separate knowledge domains. For any project for an owner, different disciplines assign management teams, to which we now add LEED certification requirements along with partnering, PDRI and commissioning requirements, and ask that LC practices be implemented using CAD 3D or nD models, for example. It is also possible to have other dimensions associated with the construction product designs that have their own definition and set of constraints and rules. Our research embraces Green and Lean concepts by associating them with additional dimensions in the design of a construction product. We argue that in the near future, we will have an integration of Lean and Green initiatives centered on a BIM platform due to continued improvement in processing capabilities, increased bandwidth and the industry's need to achieve higher levels of efficiencies and effectiveness in a consistent and predictable manner. The capabilities of a BLG platform are showcased in a future scenario based on current technologies and practices.

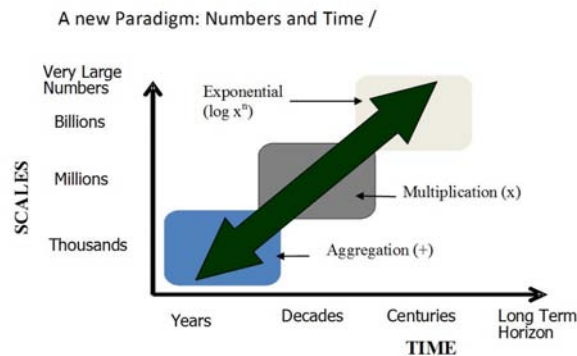
Following the established logic that we first need to identify the “effective why” and then the “efficient how” we propose that: Green should provide the effective reasoning behind the “why” we need to do things differently, Lean provides the body of knowledge, the “how” the intended levels of efficiency can be modeled, and BIM is the platform that captures the why and how in a consistent, predictable virtual reality. This process allows for scenario playing until the stakeholders buy into the proposed strategic action plan along with its tactical controls and feedback loops.

Green - Effectiveness

The Bruntland Report (WCED, 1987) provided a mission statement focusing on sustainability but it did not elaborate a vision of how to get there. Fernández-Solís (2008) has proposed a working definition of sustainability, whereby sustainability is the force that tames an exponential growth. This definition offers a more concrete direction toward establishing metrics that can be translated into objectives, strategic planning and tactical execution, that is, a plan for how to tame an exponential growth (resource consumption, emissions generation, etc.). However, a deeper philosophical understanding of the problem is necessary. In short, everything that we create solves a problem but, according to the Popper (1959, 1972) method of conjecture and refutation, also creates a problem. See Fig. 4, where P_1 is the original problem, TT_1 is a tentative solution and EE_1 is the error elimination, but the result is P_2 , a new problem.

For example, the automobile solved the problems of distance and speed limitations of the horse and buggy by adding speed and range, but it created new problems: the need for roads, service centers, etc. Success in individualized transportation created a very large number of vehicles in operation -in the short term; they are a benefit to the economy. Those numbers are increasing exponentially in the global market: one car per person in this six, going on nine, billion people on planet Earth, is not a viable option and cannot be sustained in the long term. A new paradigm is needed where everything that is proposed needs to be both scalable (from micro to mezzo to macro numbers; it must be able to grow without creating

Figure 5. Scales of number in a time line (Fernandez-Solis 2007)



new, bigger problems) and sustained in time from short term to medium to long term horizons (the growth can be projected into the future without causing a new, bigger problem). See Fig. 5 and Fernández-Solis (2008).

Sustainability is the application of this new paradigm that filters how we see the ultimate consequence of our actions in numbers (scales) and time, which is the same as space (matter, scales) and time (continuum)-the two constitutive characteristics of the universe (Hawking, 1996). Sustainability needs to be scalable and sustainable in time, over the long term; therefore sustainability must be effective (doing the right thing) before it is efficient (doing the thing right). Green is a movement towards sustainable construction in the sense that unbridled resource consumption and ever increasing emissions generation need to be tamed. That is, the exponential growth rate must be tamed in order to create a way of life that can be sustained in the long term and at ever increasing scales (Fernández-Solis, 2007a).

BLG is then a platform that captures this paradigm of scale and time and filters all aspects of construction through a philosophical construct with the hope that the problems we are solving are not creating even bigger problems... our current predicament. The primordial aspects of the universe are space and time, and space and time are also the critical elements of construction. In a virtual model, BLG captures the changing

possibilities of space and time, with all of their intrinsic complexity, until an optimal change pattern (of materials and processes) is agreed upon for implementation by the stakeholders.

Sustainability initiatives follow the Rene Descartes' dictum, which is also known as the environmental precautionary principle: "Situations in life often permit no delay; and when we cannot determine the method which is certainly best, we must follow the one which is probably the best... if the method selected is not indeed a good one, at last the reasons for selecting it are excellent" (Descartes, quoted by Koen, 2003). We propose that all Green and sustainable initiatives should be viewed and scrutinized under the aforementioned new paradigm of scales and time. Can the proposed practice be scaled up in very large numbers and at the same time be carried out continuously on a long term horizon? Passing this litmus test indicates that we are doing the right thing, according to state of the art science, and that, according to Popper's Theory of Conjecture and Refutations, we anticipate solutions that do not create a bigger problem, that is, when the solutions are effective.

Lean - Efficiency

The process of constructing a building uses separate strategic and tactical approaches, that is, a strategic approach for planning and a tactical

approach for executing. LC™ employs a set of techniques borrowed and adapted from manufacturing in order to address the complexity and peculiarities of the industry (Fernandez-Solis, 2008). It looks at the execution to better inform the planning, using such tools as LC, Critical Path Method (CPM), Last Planner System (LPS), and Just in Time (JIT) movements, among others. To increase efficiency, Project Delivery Systems have been created, such as Design-Bid-Build (DBB); Design-Build (DB); Construction Manager at Risk (CM@R) and Lean PDS, among others.

LC is based on specific values that an owner establishes. To achieve this, the project stakeholders need specific product, capabilities, price and time data, all items that a BIM platform can readily provide. From the owner's side, a project can be design-specific or performance-specific, because from the manufacturing side, the products have design-specific information as well as performance-specifications. We envision that all items of a project will be bar coded using FIATECH (2004) protocols of information that have embedded in the bar code both design and performance specifications. BLG will embed the information that Lean requires in order to:

- (1) Maintain a value stream with a capacity to rapidly prototype scenarios to
- (2) Achieve and maintain continuous flow in a
- (3) Pull ambient, while
- (4) Striving for perfection.

Both *kaikazu* (radical improvements, Gann, 1996) as well as *kaizen* (continuous incremental improvements, Imai, 1986) can be rapidly prototyped within the BLG model. Pull scenarios can be played out within a decision support matrix that evaluates the local optimum for the project (Fernandez-Solis, 2008).

BIM – Designer's Hypothesis and Interpreters' Virtual Project (Experiment) Testing

BIM is a collaborative approach that produces a sophisticated digital model of a building that is linked to a database of information about all aspects of its design and components. The building construction industry, governments, owners and other stakeholders in capital creation through construction have identified BIM as an accelerated technological initiative (FIATECH, 2004), leading to an increase in efficiency and effectiveness.

BIM is expected to help practitioners in the AEC industry achieve higher levels of efficiency (by doing things right, Emerson, 1917), generate and exchange information, create digital representations of all stages of the building process, and simulate real world performance. BIM, as a concept, demands intensive collaborative efforts, and its purpose is to overcome inefficiencies produced by disruptions in construction activities when multiple actors interoperate (Butler, 2002). BIM represents imaginary situations created by designers. . A designer's hypothesis then is generated through the Unifying Model that is intended to overcome inefficiencies particularly within interoperability and to support businesses processes. The hypothesis is a prescriptive model of the components of the design, the contextual relationships of the components, and other parameters as attributes of the components. The Unifying Model should supply the need of stakeholders' information for decision-making and for data management for interoperability.

As BIM represents imaginary situations created by designers, other actors must understand these situations. However, BIM cannot characterize all situations and all contextual conditions during all the stages of the project through formal representations. Other stakeholders, different from designers, must interpret imaginary situations represented in the model within the sharing and exchanging of information process. The stakeholders are inter-

preters of the Model. They are interpreters of the virtual project. They map the perceived condition of states of affairs of the world to the represented situation in the model. They map the assumed conditions of the designer's imaginary world to existing conditions. In imaginary domains, such as design creations, the characterizations' situations are extremely complex to represent. They are only possible through the use of poor metaphors that are created or assembled from representations (Mutis, 2007). Templates and rules for describing situations in a model serve as poor descriptions of the complexity of states of affairs because of the situation's incommensurability nature. The stakeholders interpret the model and test it against the current, project state of affairs of world.

At a deeper philosophical level, the adoption of BIM by the construction community implies an orientation toward the rationalistic tradition that regards systems of representation as patterns that stand for things in the world.

4 FUTURE TRENDS: GLOBAL PUSH

We stand at a historic moment where increases in global population and affluence (Von Weiszäcker et al., 2007; Strassman and Wells 1988; Varon, 1975) are creating an exponential demand on resources (Barnett and Morse, 1963; Barnett, 1979; Strassman, 1988) and an equal exponential increase in the generation of Greenhouse Gases (GhG)(Fernandez-Solis, 2007b). The construction industry is bracing for a prolonged inflationary period. Business as usual in the construction sector (Carassus 2004) will not be possible in the near future.

However, BIM, Lean and Green will not be achieved to their full capacities if we do not have the basic understanding of what it takes to have sustainable and best practices to deliver projects. The basic premise of this paper is that it takes an integration of all three to create the synergies required to tame the exponential growth in

resource consumption, emissions generation and inflationary forces.

Our examination of BIM, as a well developed Unifying Model, proposes the association of critical design information along with contractor tools in a robust platform (BIM) with full visualization capabilities. In other words, the translation of the project components and the processes into a "how to" that facilitate the understanding of what needs to be done when, where and how.

The outcome of a visualization model throughout the industry in the United States have 10% cost reduction average, 25% time reduction, minimization of Request for Information (RFI) and change orders (Jacobs Construction in the US informally reports that a repetitive project achieved zero RFI and zero change orders in 2008). Although comparing project efficiencies is extremely difficult due to the inherent nature of construction (Fernández-Solís 2007, 2008; Bertelsen, 2004), time, RFI, and change orders translate to cost reductions. For example, cost and construction time reductions are achieved when BIM performs conflict detection that points where parametric objects occupy the same space or when they are not aligned with design requirements. The early identification of conflict resolutions not only affects cost and time but also minimizes RFI and change orders.

In other words, not only can conflict resolution be achieved through normal model visualization practices, but also we are adding the expert knowledge of LC and the direction of Green sustainable practices to performance indicators in order to optimize the use of resources and generate value.

Visualization: A Single Piece of the Model

The execution of simulations through visualization with the parametric models is limited to the geometry and the modelled context of the design product. All aspects of production of that design

product, from upstream to downstream of the supply chain, have to be executed by employing other applications. Simulations through visualization require extraordinary effort to collaborate with what the human analysis of the visualization can provide. Visualization of architectural products designs for clash detections and 4D modeling is an example of such simulations. Different actors interpret the described geometry, and visually perform simulation or prescription of situations. However, a production analysis cannot be performed within the parameters of geometry of the product that is contained within the Unifying Model (Shin, 1992; Mutis, 2007). This process is highly inefficient and is based mostly on human intensive activities, which are interpretations of the visualizations and manual mappings. Simulations of construction processes require analytical tools or software applications to be executed.

Incorporating the Lean Construction Concept into the Unifying Model

When a simulation of construction processes such as BIM is executed, it is limited to a visualization of the architectural products designs. All aspects of production of the construction of the designed products are left out of the visualization. The visualization supports the anticipation of problems in the design, some aspects of the product constructability, as well as an early analysis of the impact of decisions, such as the effects of changes in the design. However, elements of the construction process such as productivity efficiencies (waste minimization, Coventry and Guthrie, 1999; Howard and Ballard, 1994a, 1994b, 1997), transformation of employed resources into products cannot be deduced from the visualization. There is a need to investigate local efficiencies and accountability of waste and value of material and resources employed to build a product.

This chapter proposes the generation of a richer model where actors in the construction project and along the supply chain collaborate and participate

with more accurate variables of the construction process. The architecture of the model connects the parametric model design that is employed for visualization and the variables to the metrics used for production systems. The parametric model design is enhanced with parameters of the construction process.

LC (Abdelhamid, 2004; Alarcón, 1997; Ballard, 2000, 2005; Ballard and Howell, 2003b, 2003c; 2004; Ballard et al., 2002; Koskela et al., 2002) proposes an alternative for understanding production as a flow rather than a transformation of substance. This alternative leads to a re-conceptualization of construction products where future conditions of the construction process are involved. It is a concept that will facilitate the analysis of design realization from the design creation. LCTM (Howell and Koskela, 2000) employs a set of techniques borrowed and adapted from manufacturing in order to address the complexity and peculiarities of the construction industry (Fernandez-Solis, 2008; Ballard, 1999; Ballard and Howell, 1994, 1998a, 1998b; Chu et al. 2003). It looks at the execution phase to better inform the planning among other tools such as Critical Path Method (CPM), Last Planner System (LPS), and Just in Time (JIT) movements, among others (Watson, 2001). The construction industry's needs are different and require tracking an ever-increasing number of parameters in a robust platform that can operate with suppliers, vendors and the entire organization of a construction firm, especially in exchanging, sharing, and integrating information to make decisions. The co-authors propose connecting the resulting variables of production employed in LC to the parameters of the designed product of the parametric model.

One significant contribution of this research is that we propose the association of the design to the specific values that the owner provides, as Lean is based on values that an owner establishes. To achieve this, the project stakeholders need specific product, capabilities, price and time data, and all items that a well-developed Unifying Model, such

as a rich BIM, can provide. From the owner's side, a project can be design-specific or performance-specific, because from the manufacturing side, the products have design-specific information as well as performance-specifications. Lean's variables are framed within a philosophy that emphasizes maintaining a value stream with the capacity to rapidly prototype scenarios to achieve and maintain continuous flow in a pull ambient, while striving for perfection. The basic premise is that relating variables of production to a priori parameters of the design will create the synergies required to tame the exponential growth in resource consumption, and inflationary forces.

In other words, not only can conflict resolution be achieved through normal BIM practices, but we are adding the expert knowledge of LC in avoiding waste and thus generating value. The integration of BIM and LC will be novel to this project and the state of the art in Information Modeling platforms.

Incorporating the Green Construction Concept into the Unifying Model

Our proposed Unifying Model captures the changing possibilities of space and time, with all of their intrinsic complexity, until the stakeholders agree upon an optimal change pattern of materials and processes for implementation. Green construction concept and sustainable initiatives are captured in the Unifying Model in providing stakeholders a rich model the option for selection of materials and processes. The stakeholder's ability for selecting materials and process is a practice that can be scaled up as the model is enriched in a continuous basis. For example, the accommodation of the design to the specific Green (Pries and Janssen, 1995) rating system values that the owner designates (Nootebom and Teisman, 2003) can be provided through the model in a continuous fashion. In this scenario, the stakeholders have the ability to perform analysis of parameters provided by

the model simulations and interpretation of the resulting prescribed situations in space and in time. The unifying view of a real project not only including LC principles but also Green building initiatives and performance criteria (CIB, 1997; Foliente, 2000; Pearce, 1989, 2003, 2006; Pearce and Turner, 1990; Pearce and Warford, 1993) are tracked through the unifying model.

Sustainability initiatives follow the Rene Descartes' dictum, which is also known as the environmental precautionary principle: "Situations in life often permit no delay; and when we cannot determine the method which is certainly best, we must follow the one which is probably the best... if the method selected is not indeed a good one, at last the reasons for selecting it are excellent" (Descartes, quoted by Koen, 2003). We propose that all Green and sustainable initiatives should be viewed and scrutinized under the aforementioned new paradigm of scales and time. The proposed Unifying Model provides an opportunity for implementation of this view.

5 THE PROBLEM CONCLUSIONS

LC concept and Green sustainability initiatives marry a parametric modeling technology with a promise that has caught the interest of the construction industry (albeit a technology in its infancy and an interest at the individual company level). The resulting integration of these initiatives is the BLG proposition, which transfer manufacturing best practices through LC (albeit with limited results because of the individual company scale of implementation), and combines sustainable initiatives and benchmarked systems of best practices that promise a reduced energy and material footprint along with quality and performance improvements (albeit in its early stages).

When looking at these concepts from a wider perspective, it becomes even more vital to understand how these three knowledge domains can merge throughout the building's service life. The

increasing number of Green initiatives that deal with buildings after they have been constructed, such as LEED-EB, implies that facility management is considered at a similar level of importance as AEC. BIM itself must still be studied to figure out the benefits of utilizing it for post-occupancy phases, rather than merely for design and construction, as it is used today. Also, LC's concepts may be used for Lean maintenance and Lean operation of buildings. We envision that BLG has a long way to go from its current role in the design and construction phases to a wider role in the design, construction, and operation of buildings throughout their entire service life.

The employment of parametric models to perform simulations of energy consumption is a practical strategy that significantly supports designers in optimizing their architectural designs and materials selection for their creations. LC proposes an alternative for minimizing waste, while maximizing value in the transformation of prime matter into objects and eventually projects, and in minimizing waste in the production understood as a flow. This alternative leads to a re-conceptualization of construction products and processes, which require an understanding of the embedded energies in both product and process.

Currently we have bits and pieces of embedded energies but not to the level necessary to create a correct, complete and timely accountability of a building footprint (Wackernagel et al., 1997; 2002; Venetoulis and Talberth, 2005; Van Vuuren and Bouwman, 2005). Such a footprint could be used for benchmarking and establishing an energy economy (Pearce, 1989; 2003; Pearce and Turner, 1990; Pearce et al., 1989; Pearce and Warford, 1993) where value is based on building performance.

Regarding Green practices, we have a rudimentary sustainability mission statement, and an early understanding of embedded energies. However, we do not have at this time the necessary information to create a correct, complete and timely accountability of a building footprint that

could be used for benchmarking and establishing an energy economy, where value is based on a building energy footprint and achieving increasingly exigent performance requirements. A BIM would include sustainability parameters in detail, such as how to achieve Factor 10, footprint and rucksack reduction, Life Cycle Analysis, as well as accounts for all embodied energy for a better diagnosis of the sustainability state of building design and construction.

Ultimately we are visualizing a BIM as well as developing a Unifying Model that will incorporate LC and Green sustainability parameters that allow: (1) rapid prototyping of design proposals for decision making; (2) rapid prototyping of construction alternatives; (3) total visualization of a project process that imbeds cost, schedule project controls, tracking RFI's and change orders, applications for payments, subcontractor information, among other tasks; and (4) the development of a robust platform that captures lessons learned. Such a platform has the possibility of accelerating the paradigm shift in the construction industry.

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KEY TERMS AND DEFINITIONS

BLG (BIM, Lean and Green): The conscious and elaborate integration of BIM, Lean and Green into a Unifying Model that provides visualization of a project throughout all of its phases. See Mutis, and Fernández-Solís.

Chaos: The effect whereby minor deficiencies or miniscule changes occurring in any phase of the project, but particularly in the beginning of a process, create significantly different outcomes. See Bertelsen, Gleick, Lewin, Lorenz, Scott, Thiétart and Waldrop.

Effectiveness: The primary quest for finding what is the right thing to do; a qualitative issue that is philosophical in nature answering the why within the context of the benefit to the whole. See Fernández-Solís.

Efficiency: The secondary quest for finding how to do a thing right, better, faster, cheaper; a quantitative issue that is scientific in nature answering the when, where, how and by whom a process or product takes place. See Emerson and Fernández-Solís.

Heuristics: The theory that all is heuristics or rules of thumb; based on Heidegger's notions and the Popperian principle of three worlds where we as a subjective world only know the world of reality through the world of symbols. See Heidegger, Koen and Popper.

Idealization: The process of looking at possibilities before the considerations of probability and actualization are investigated. Ideation is based on heuristics and the theories of Garcia-Bacca that one invention does not necessarily pre-determine the next. Ideation looks at what the next invention may look like based on the integration of disparate disciplines based on scenario playing. See Gunderson.

Lean Construction: An alternative to traditional construction methods with the aim of minimizing waste (embedded in all processes and products) and maximizing value to the owner (understood as the value of final product) (nCRISP 2004). Lean Construction re-conceptualizes construction processes and products with techniques borrowed from the manufacturing industry, especially systemic thinking for maximizing the whole rather than maximizing the parts of a process. See Alarcón, Ballard, Bertelsen, Coventry, Howell, and Koskela.

Local Optimum (of a project): Construction project performance comparisons are difficult, if not impossible, due to the complex and innate nature of construction that has multiple variables in a dynamic setting. In this sense there is no project type optimum. However, a project's own local optimum and chaotic conditions at the start may have major effects on the local optimum. A scientific way of finding the project local optimum is to have a model that rapidly prototypes different versions and issues a comparative report for a decision support system, what BLG aims to provide. See Fernández-Solís.

Meta-Systems: A system of systems. The construction industry, because of the variability and number of suppliers and providers is akin to a meta-system more than are other industries, such as automobile and aircraft where suppliers and providers are more integrated into a system of production. See Palmer and Fernández-Solís.

Sustainability: There are multiple interpretations of sustainability. In this chapter sustainability is defined as the force that tames an exponential growth that is not sustainable. The exponential growth is composed of one resultant force which translates in a simple algorithm but actually is much more complex, as it is composed of multiple forces vectorial in nature that conspire to create the resultant exponential unsustainable growth. Therefore if this unsustainable force must be

tamed, it can only be done by re-aligning the multiple forces that create it. These forces need to meet one or preferably two requirements: whatever we do has to be scalable, that is, be able to be done in very large numbers without detriment to the environment and depleting resources and second, it has to be able to be carried out for a long time horizon. See Fernández-Solís dissertation, based on Garcia-Bacca.

Systemic Thinking: The concept applied to construction by the Lean Construction movement where optimizing a part or a process is done at the expense of the whole. Therefore we need to optimize the whole so that a continuous flow is achieved with value creation as its landmark and objective. All transformations are analyzed from the whole rather than the part. Systemic Thinking accepts the meta-systemic theory and searches for a local optimum in value generation. See Lean Construction and Meta-systems.

Unifying Model: BIM platforms have evolved from the evolution of two, three and multiple dimensions with parametric object-oriented information. However, this platform is now required to adapt an open architecture where other disciplines and areas of interest can be integrated in a resultant unifying model. The Unifying Model proposed has economic, accounting, design, constructability and maintenance characteristics that are driven by green sustainability performance requirements and lean principles of project delivery. See Lean Construction and Mutis.

Visualization: The process of translating typical design documents, drawings and specifications into the Unifying Model that allows a smart cockpit view of the process in detail and as a whole, according to the needs of the inquiring party. A virtual reality of all the phases, systems and subsystems, and processes for the project, with real data and in an information rich context. See Mutis.

Chapter 15

A BIM Based Application to Support Cost Feasible ‘Green Building’ Concept Decisions

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ABSTRACT

The client's role in leading the change in the construction industry has been widely perceived as crucial and, on the theme of sustainable building, it is advocated that clients must play their role to lead in engaging industry stakeholders in managing sustainable performance of construction projects. In essence, it is the client that makes the initial decision to procure construction works and the way in which procurement takes place. This influences the degree of environmentally-friendly (or sustainable) practice that is implemented in a project. For most building owners and property developers, this decision is affected by cost. A proposed rule-based system that contains decision-support rules pertaining to the assessment of (whole-life) cost implications for building projects is described in this chapter. The system is to be developed to meet the assessment criteria of Singapore's BCA Green Mark Scheme and to support the use of BIM for designing energy efficient buildings and beyond.

1 INTRODUCTION

In order for the Building Information Modeling concept to fully work and benefit for the all stakeholders of the construction industry, it is vital that all needs and requirements of the different stakeholders be considered in the aim of developing enabling applications that support the BIM's goal of allowing interoperability (between the various

different applications used in the industry throughout the lifecycle of the building). While many existing applications have mainly focused on a few key areas such as CAD, visualisation and simulation, the proposed rule-based decision support tool, as described in this chapter, is applicable to clients and their consultants during the initial briefing stage. This tool is relevant to the Green Building concept, as well as the whole-life costing.

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2 BACKGROUND

Client's Role in the Green Building Concept

In the Green Building concept, any structure is designed, built, renovated, operated or reused with objectives to protect occupants' health, improve employees' productivity, use natural resources wisely and reduce the environmental impact. Analogous with industrial ecology which is the starting point for applying ecological principles to human systems, Kibert and Schultmann (2005) proposed that;

"Construction ecology would imply a built environment that is readily deconstructable at the end of its useful life, whose components are decoupled from the building for easy replacement, comprised of products that are themselves designed for recycling, whose bulk structural materials are recyclable, whose metabolism would be very slow due to its durability and adaptability, and that promotes health for its human occupants".

Understandably, applying this concept requires changes in the client's traditional approach and a clear change program established for other project stakeholders. In the aspect of design, sustainably designed buildings can lessen their impact on the environment and improve environmental quality through minimisation of consumption of non-renewable resources, elimination or minimisation of the use of toxins, and reduction of energy consumption. The main principles of sustainable design stress on the understanding of four elements - place, natural processes, environmental impact and people; and the connection with nature through embracing co-creative design processes (Manoliadis et al., 2006).

The client's role in leading change in the construction industry has been widely perceived as crucial. Studies of potential drivers of change towards sustainable building have emphasized

the leadership role of clients and that the key is to ensure, their commitment (Egan, 1998; Addis and Talbot, 2001), their demand for better value and improved performance from suppliers, and their demonstration as good employers by procuring work in a way that allows best value to be delivered, as well as providing fair rewards for good performance (United Kingdom National Audit Office, 2001). Similarly, the introduction of client-orientated performance indicators has been recommended as an important driver for change (Winch and Courtney, 2001).

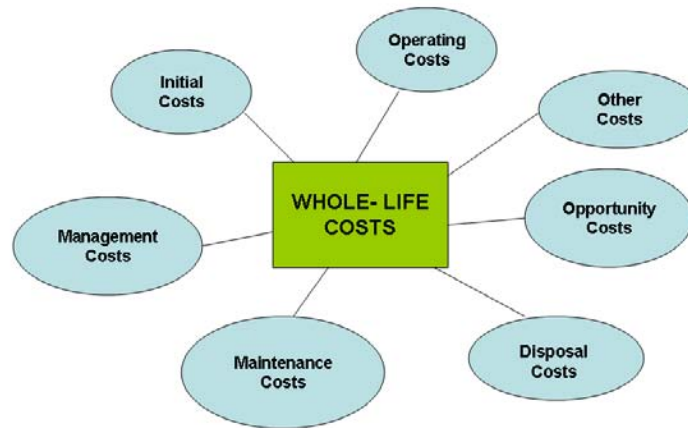
The general notion that clients are key drivers of construction performance improvement and innovation can be explained by their expected role as primary decision makers, especially during the initial stage of project conception and feasibility, that is, when deciding to procure construction work (Briscoe et al., 2004). Therefore, as they decide the way in which procurement takes place, they must also lead in engaging other project stakeholders in managing sustainable performance of the projects.

Client's Interest in Whole-life Costing

The whole-life cost of an asset is defined by Addis and Talbot (2001) as "the present value of the total cost of that asset over its operational life. This includes initial capital cost, finance costs, operational costs, maintenance costs and the eventual disposal costs of an asset at the end of its life. All future costs and benefits are reduced to present-day values by the use of discounting techniques". The main components of whole-life costs are shown in Figure 1.

The use of whole-life costing in the assessment of project proposals has been identified amongst the most important drivers of change for construction (Winch and Courtney, 2001). Incidentally, Kirkham (2005) has been witnessing a rapidly increasing application of whole-life costing within the construction industry. He views this change as industry acknowledges the benefits 'decision-

Figure 1. Components of whole-life costs of an asset (Source: adapted from Addis and Talbot, 2001)



making based on whole-life costs' can bring to the design and operation of building assets. He thinks that perhaps this change is indicative of the wider desire of the industry's focus for sustainable design.

Traditionally, clients of the construction industry have been classified by their interest and motivation for initiating a building development. Clients can develop for, profit, use or social purposes. But clearly, all development arises from a consumer demand and this demand must always be an economic one as there must be someone willing to finance the project (Ferry et al., 1999). In addition, if the client's objective is broadened to encompass sustainability, applying whole-life costing becomes a logical means in assessing and achieving the best value of the design and procurement for the development. In essence, it is the client who makes the initial decision to develop and the way in which design and procurement takes place. This influences the amount of environmentally-friendly (or sustainable) products and practices that will be used in a project. For most developers, decisions are guided by cost and most of these decisions are made during the preparation of the budget at the project feasibility stage.

From a review of the literature that aims to draw logical assumptions on types of clients,

their interests in sustainable building as well as whole-life costing (Bathurst and Butler, 1980; Seeley, 1981; Addis and Talbot, 2001), a mapping of the 'degree of importance of sustainable building' and 'whole-life costing' onto 'different types of clients' is carried out. The outcome of this mapping is shown in Table 1.

Based on the generic definition of value and applying it to construction, the client should be thinking of obtaining worth, desirability or utility from the completed building. Otherwise, he would be over-emphasizing on price, i.e. for obtaining the lowest tender price instead of the value. Moreover, in the context of whole-life costs, he would be simply looking at initial costs of the development while overlooking the other components. However, -value for money- in procurement is the optimum combination of whole-life costs and quality (or fitness for purpose) to meet the customer's requirement. Therefore, clients (who are owners) must realize that in order to attain best value for their building projects, there has to be a fair balance of consideration for both initial costs and future costs (i.e. costs that would be incurred from operating the premises over their physical or economic life). More often, practice shows that an increase in capital expenditure on certain building elements can translate into longer run savings, in

Table 1. Theoretical mapping of interests in sustainable building and whole-life costing onto different types of clients

	Public-Sector Clients	Private Occupiers (e.g. Private Individual)	Private Occupiers (e.g. Private Companies)	Private Property Companies
Type(s) of Development	Institutional Residential Industrial Commercial	Residential	Industrial Commercial	Residential Industrial Commercial
Client's Interest in Sustainable Building/ Best Value Concept	Yes	Between No and Little	Between Little and Yes	Residential – No Industrial & Commercial – Yes
Client's Interest in Whole-Life Costing	Yes	Between No and Little	Between Little and Yes	Residential – No Industrial & Commercial – Yes

terms of operating and maintenance costs. Some applicable elements include roof systems, air-conditioning and mechanical ventilation systems, lifts and electrical installations.

Global Developments in Green Building Design and Performance

Green Building Rating Systems

In the area of measurement rating for green buildings, some countries have started to develop their schemes in the nineties. Among those that are used in the world, three of the more widely known standards will be described in this section. These are the U.K. BRE Environmental Assessment Method (BREEAM), the U.S. Leadership in Energy and Environmental Design (LEED) and Japan's Comprehensive Assessment System for Building Environmental Efficiency (CASBEE).

The BREEAM was established by the Building Research Establishment (BRE) in 1990 as a tool to measure the sustainability of new non-domestic buildings in the UK based on a scoring system. The building types covered by the standard are retail, offices, education, prisons, courts, health-care, industrial and specialised buildings. Since 2008, the new version of BREEAM has incorporated a two-stage assessment process to look at the design stage and post construction stage,

introduced mandatory credits, and a new rating level -BREEAM Outstanding-. The BREEAM standard is now being adopted beyond the UK and specific versions are also available for the Gulf and Europe. In addition, the BREEAM tools available are the LCA environmental profiles, the Green Guide to specification and the Envest software. The Envest is a web-based tool that simplifies the complex process of designing buildings with low environmental impact and whole life costs. It allows both environmental and financial tradeoffs to be made explicit in the design process, enabling the client to optimise the concept of best value according to their own priorities.

The LEED green building rating system was developed by the U.S. Green Building Council as a set of standards for environmentally sustainable construction. The scheme started in 1998 and had since grown in use worldwide. Besides the U.S., there are 30 countries that have adopted the standards for assessing sustainable green building and development practices of construction projects. In essence, the LEED promotes a whole-building approach to sustainability by recognising performance in the areas of sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation and design process. The rating system offers four certification levels for new construction, namely, Certified, Silver, Gold and Platinum.

These levels correspond to the number of credits accrued in the six assessment areas.

Similarly, the CASBEE is an assessment tool developed in Japan for rating the environmental performance of buildings. The scheme started in 2001. It was developed on the principle of the building lifecycle, starting from the pre-design stage through to the design and post-design stages. In line with the building lifecycle, the CASBEE 'family' of assessment tools are created to serve each of the stages of the design process, namely, CASBEE for Pre-design, CASBEE for New Construction, CASBEE for Existing Building and CASBEE for Renovation. These tools are designed to accommodate a wide range of uses, such as offices, schools and apartments, of the buildings under evaluation. The core concept of the method of assessment is based on the building environmental quality and performance (Quality), as well as building environmental loadings (Loadings). And 'Quality' corresponds to assessing the 'internal space' of the building, while 'Loadings' corresponds to assessing the environmental impact on the 'external space' or outside the building in terms of emission of air pollutants, noise and heat from the building. There are four assessment fields covered by the scheme, and they are energy efficiency, resource efficiency, local environment and indoor environment. A five-point scoring system is used and a score of 3 points indicates an average standard.

Green BIM Tools

In parallel with the rise in the number of green building certification systems implemented around the world, a few green BIM tools developed for sustainable design and performance analysis exists in the global marketplace. The use of these tools can range from conducting general assessments of building's energy usage and carbon dioxide emission to specific evaluations of energy, carbon, daylight, solar, heating and cooling loads and their respective impacts on the green rating credits.

It has been noted in the U.S. that the '2030 challenge' and the rise of LEED and other green building certification systems are evidence of the building industry's commitment to sustainable design. Hence, it can be envisaged that with the widespread adoption of similar certification systems by more countries, it should raise global awareness of the Green Building Concept, as well as give CAD vendors a greater incentive, for the creation of new products or customisation of existing products to better serve prospective clients' needs and requirements.

Currently, the products offered by the Integrated Environmental Solutions (IES) are their range of toolkits, namely, Sustainability Toolkit Version 2, LEED Toolkit Version 2, BREEAM Toolkit Version 1 and Greenstar Toolkit Version 1 (IES, 2009). For product compatibility, the toolkits can be accessed via its Google SketchUp and Autodesk Revit plug-ins, or via its gbXML import function for other BIM design tools.

Focusing on the initial design of a building, Autodesk's Ecotect (2009) currently offers a full range of design visualisation tools, including simulation and analysis functions, to enable its users to interact with data in real time while in the process of evaluating different shading and lighting designs, conducting solar, acoustic and thermal analyses, as well as simulating the patterns of ventilation and air flow. The early design focus allows users of Ecotect to get certain design fundamentals right, such as the building's basic forms and orientation, internal layout, external façade materials, window size and position.

As a web-based tool with XML connectors, Autodesk's Green Building Studio (2009a) can integrate with major BIM design applications, including Revit Architecture, AutoCAD Architecture and AutoCAD MEP to perform energy analysis based on early stage building design schemes. With this capability, testing of building performance and validating design options can be conducted over the Internet to generate, energy statistics, as well as recommendations on how

to improve the design based on local standards for different building types, climatic conditions and others. As such, the Green Building Studio relies on a large network of relational databases containing design information, default building characteristics, common energy codes and performance standards.

In addition to the energy analysis, the Green Building Studio (2009b) plug-in for Revit enables the whole building water and carbon emission analyses to be performed on a Revit-based building design i.e. to provide users with a more complete assessment of sustainable building designs by extending its analysis beyond energy consumption.

Proposing a Decision Support Tool for Clients (as a BIM-Based Application)

The proposed rule-based system contains decision-support rules concerning the assessment of (whole-life) cost implications of the development of environmentally-friendly buildings. The system is designed and developed:

1. to aid clients and their consultants in the general understanding of value (versus cost) in relation to the design, construction and operation of buildings; and
2. to support clients in making capital investment and operation decisions relating to budgeting and design.

In the following sections, a case study of Singapore is explained and different stages of building the rule-based decision support tool are described. The methodology consists of the activities of applying a standard classification of elemental cost, developing a framework for classifying the elective requirements under the Green Mark Scheme, developing logical rules with fuzzy variables, establishing fuzzy membership func-

tions, creating *if-then* rules, testing and application of the rules to build the system.

3 A CASE STUDY OF SINGAPORE

Singapore's Green Building Masterplan

The Singapore Economic Review Committee, set up in December 2001, had envisioned to remake Singapore through “new challenges and fresh goals”, with the aim of transforming her into a dynamic global city (MTI, 2003). Among the goals set for the construction industry to upgrade capability, a new possibility was identified for its domestic enterprises to develop niches in eco-efficient design, environmental technologies, and green products and services. These areas come under Singapore's Green Plan 2012, which is a blueprint for achieving environmental sustainability. In view of the strategic plans, the signal was clear that in order for Singapore to achieve and maintain its position as a global city, the construction industry must among its other goals be able to produce and offer high quality and environmentally-friendly buildings as a demonstration of sustainable development. Responding to the calls for the construction industry to build up expertise in environmental and ecological technology, the Building and Construction Authority (BCA) had developed the Green Mark Scheme as a strategic program to encourage property developers, building owners, designers and contractors in Singapore to adopt “green building” practices. The Scheme was launched in January 2005 and it would apply to new and completed buildings. In 2006, the Green Building Master Plan was launched to encourage more building owners and developers to own and develop more environment-friendly buildings. The areas of focus of the Masterplan were incentives, regulations, industry training and public education. Since April

2007, all new public-sector buildings and those undergoing major retrofitting work would have to be environment-friendly.

The BCA Green Mark Scheme

The BCA Green Mark Scheme is a green building rating system used to evaluate a building, new or completed, for its environmental impact and performance. In each case, the assessment is based on five key criteria (or parts) looking at levels of energy efficiency, water efficiency, site or project development and management (for new buildings) or building management and operation (for existing buildings), good indoor environmental quality and environmental protection, and environmental innovation. Details of the five parts are provided in Table 2.

A point scoring system for the BCA Green Mark for Residential Buildings is shown in Table 3.

In particular, the Scheme places strong emphasis on energy efficiency and renewable energy

(Fig. 2). For the elective requirements of energy improvement, a maximum of 50 points can be obtained for compliance with areas of efficiency in Part 1 on 'Building envelope', 'Dwelling unit indoor comfort', 'Natural ventilation in common areas', 'Lighting', 'Ventilation in car parks', 'Lifts' and 'Energy efficient features'. A bonus of up to 20 points can be obtained for compliance with the area on 'Renewable energy'.

Singapore's Plan for the Use of BIM

The formation of the Construction and Real Estate Network (CORENET) in 1993 as a major IT initiative led by the Ministry of National Development and driven by the Building and Construction Authority (BCA) in collaboration with other public and private organisations has demonstrated a joint government and industry effort to prepare the Singapore's construction sector for the IT age of the 21st century. The goal of CORENET is to re-engineer the business processes of the construction

Table 2. The BCA Green Mark elective requirements – 5 key criteria (or parts)

<u>Part 1 – Energy Efficiency</u>	<u>Allocated Points</u>
1-1 Building envelope – RETV	15
1-2 Dwelling unit indoor comfort	16
1-3 Natural ventilation in common areas	2
1-4 Lighting	15
1-5 Ventilation in carparks	8
1-6 Lifts	2
1-7 Energy efficient features	7
1-8 Renewable energy	20 (Bonus)
<u>Part 2 – Water Efficiency</u>	<u>Allocated Points</u>
2-1 Water efficient fittings	10
2-2 Water usage	1
2-3 Irrigation system	2
<u>Part 3 – Environmental Protection</u>	<u>Allocated Points</u>
3-1 Sustainable construction	12
3-2 Greenery	6
3-3 Environmental management practice	9
3-4 Public transport accessibility	2
<u>Part 4 – Indoor Environmental Quality</u>	<u>Allocated Points</u>
4-1 Noise level	1
4-2 Indoor air pollutants	3
4-3 Waste disposal	1
4-4 Indoor air quality in wet areas	1
<u>Part 5 – Other Green Features</u>	<u>Allocated Points</u>
5-1 Green features and innovations	7

Table 3. BCA Green Mark award rating for residential buildings

Green Mark Score	Green Mark Rating	Pre-requisite Requirements
90 and above	Green Mark Platinum	RETV of 20 W/m ² or lower
85 to < 90	Green Mark Gold ^{Plus}	RETV of 22 W/m ² or lower
75 to < 85	Green Mark Gold	
50 to < 75	Green Mark Certified	

Note: RETV stands for 'Residential Envelope Transmittance Value'.

industry to achieve a quantum leap in turnaround time, productivity and quality. In order to achieve this, CORENET revolves around developing IT systems and key infrastructure to integrate the four major processes of a building project life cycle i.e. design, procurement, construction and facility management.

Currently, a few major projects have been developed with the aim to provide Government to Business infrastructure to facilitate electronic building plans submission, and checking and approval processes. The use of BIM by building professionals to prepare their design is advocated on CORENET's e-Plan Check project (Cheng and Teo, 2006). It is an artificial intelligence checking system that automatically checks electronic plans for compliance with regulatory requirements over the Internet. Designs that are prepared using BIM tools are uploaded onto the e-Plan Check system for automatic on-line or batch processing. The system would generate a report to highlight areas of non-compliance when the automatic checking process is complete.

In terms of BIM implementation in Singapore, the Industry Foundation Classes (IFC) has been adopted as the standard. In light of this adoption, the BCA has been working closely with the International Alliance for Interoperability Singapore Chapter (IAI (S)) to steer the industry towards wider use of the IFC-based BIM. A few commercial design BIM tools that have been certified as complying with the e-Plan Check requirements for the architectural view include Autodesk's ADT, Autodesk's Revit and Graphisoft's ArchiCAD.

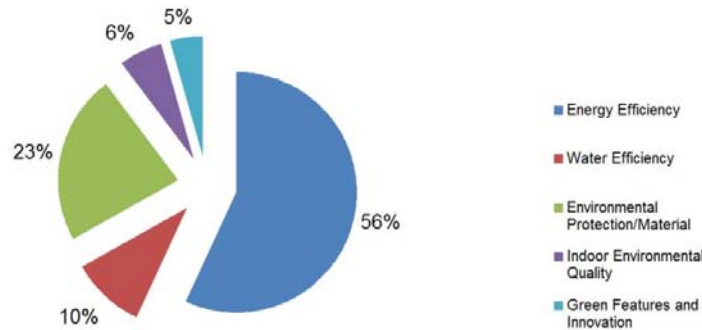
Singapore's National Efforts on Construction Information Standards Development

In Singapore, the Singapore Productivity and Standards Board (PSB) (now known as SPRING Singapore) is the national standards authority. PSB co-ordinates the 'National Standardisation Program', and the Singapore's participation in the international standardisation efforts. One of the nine Committees appointed by the Singapore Standards Council in August 1990 is the National Information Technology Standards Committee (NITSC) which is responsible for IT standardisation. This is a collaborative effort supported by PSB and the Infocomm Development Authority (IDA), with IDA serving as the secretariat to the NITSC.

In line with the mission of NITSC, the formation of the Construction Industry IT Standards Technical Committee (CITC) in 1998 is an industry effort to prepare the Singapore's construction industry for the IT age of the 21st century. The CITC's mission is to establish an industry-wide framework for the development and adoption of IT standards in the construction area.

CITC tracks, adopts and promotes construction industry specific IT Standards. It ensures that the national standards are aligned with international standards, as well as other industry de facto standards. To deploy strategic IT systems, CITC works closely with the IAI (S) which focuses on 4 main thrusts, namely, design, procure, build and maintain, covering the entire life cycle of a

Figure 2. The BCA Green Mark places a strong emphasis on energy efficiency and renewable energy (Source: Adapted from BCA)



building project. The main Singapore Standard Codes of Practice (SS CP) are:

1. SS CP80: 1999 – Classification of Construction Cost Information.
2. SS CP83: 2000; 2004 – Computer-aided design (CAD) Standards
 - a. Part 1: Organisation and naming of CAD layers
 - b. Part 2: CAD symbols
 - c. Part 3: Organising and naming of CAD files
 - d. Part 4: CAD drafting conventions
 - e. Part 5: Colour and Linetype.
3. SS CP93: 2002 – Classification of Construction Resources Information (and Amendment No.1).
4. SS CP97: 2002; 2003 – Construction Electronic Measurement Standard (in parts).
5. SS 517: 2005 – Information Exchange and Documentation at Handing/Taking-Over of Buildings upon Completion.
6. SS 527: 2006 – Building Project Document Control System.

Singapore Standard Code of Practice for Classification of Construction Cost Information (SS CP80: 1999)

This national standard was one of the first initiated by the CITC in January 1999. The development of the first draft involved two main stages. They were: (i) a review of international standards; and (ii) an adaptation of the chosen overseas standard to suit local use. In the review process, five overseas approaches were considered for the elemental classification, while two for work sections. They are:

1. The Royal Institution of Chartered Surveyors' Building Cost Information Service (BCIS) standard list of elements for cost analysis (UK-based);
2. CI/SfB Table 1 elements (UK-based);
3. Unified Classification for the Construction Industry (Uniclass) Table G elements for buildings (UK-based);
4. Mastercost construction element categories (US-based); and
5. National Public Works Conference (NPWC) list of elements (Australian-based).

Owing to the predominance of the UK practice in Singapore, especially the quantity surveying

(QS) profession, the BCIS approach was chosen on the basis that it is the most widely recognised. Modifications were made to incorporate parts of the other four methods, as well as some local conventions during the process of verifying the first draft against industry practices.

For the work-sections classification, the reviewed approaches were:

- i) The Standard Method of Measurement (SMM) for building works (UK & Singapore-based); and

- ii) Uniclass Table J work sections for buildings (UK-based).

The SMM method was chosen on the basis that the UK version would serve as the proposed standard's framework while the local SMM would provide the content. Again, the pervasive use of the SMM for classifying work sections in the local industry was the key reason for its choice.

In the second stage, a project-based approach was used to adapt the first draft to suit local use. The Building and Construction Authority (BCA)

Table 4. Classification of group elements and elements in SS CP80: 1999

Group Element	Element
1. Site Preparation	a. Demolition b. Site clearance c. Earthworks d. Soil investigation
2. Substructure	a. Piling b. Foundation c. Basement d. Ground slab
3. Superstructure	a. Columns and structural walls b. Upper floors c. Roof d. Staircases e. External walls and cladding f. Internal walls and partitions g. Doors
4. Finishes	a. Wall finishes b. Floor finishes c. Ceiling finishes
5. Fittings, Fixtures and Furnishing	a. Sanitary wares and fittings b. Fixtures and furniture c. Artworks and sculptures d. Soft furnishing
6. Services Installations	a. ACMV b. Sanitary and plumbing c. Electrical installations d. Transportation e. Communications installations f. Security systems g. Fire protection systems h. Gas installations i. Maintenance equipment j. Pool and water feature installations k. Special installations
7. External Works	a. Surface treatments b. Drainage c. External services d. Minor building works

Awards and Certificates of Merit for Construction Excellence formed the basis to select a few industry-representative (or model) projects for the adaptation. The rationale being that effective information exchange would have contributed to the success of these projects. The projects should also be high-rise developments with a basement and a high mechanical and electrical (M&E) content. This essentially narrows the choice to development types such as high-rise residential, office, retail and hotel to allow for a comprehensive coverage of the list of elements of a building. Interviews were also conducted with clients (or property developers), QS and M&E consultants, and contractors to tailor the drafts more closely to current industry practices. The final stage involved a validation of the developed standard by the whole industry via a public forum organised by the BCA.

Essentially, in terms of SS CP80: 1999, the purpose was to develop a classification format to allow the exchange of data and information for communicating design, construction and contractual matters relating to cost. In order to achieve this, cost information needs to be structured and stored in a way that is consistent and reliable within and across different disciplines of construction. The standard can be used by property developers, architects, M&E engineers, civil and structural (C&S) engineers, QS and contractors. The standard comprises the following parts:

1. an elemental classification (as shown in Tables 4 and 5);
2. a work-sections classification (as shown in Table 6);

Table 5. Elemental classification of 'Superstructure' in SS CP80: 1999

Group Element	Element	Sub-element
Superstructure	Columns and structural walls	Columns Structural walls (Vacant)
	Upper floors	Slabs Beams Steps and ramps (Vacant)
	Roof	Roof structure Roof coverings Roof drainage Roof lights (Vacant)
	Staircases	Staircase structure Staircase finishes Handrails and balustrades (Vacant)
	External walls and cladding	External walls Cladding Curtain walls Windows (Vacant)
	Internal walls and partitions	Partitions Acoustic walls (Vacant)
	Doors	Internal doors External doors (Vacant)

3. a mapping dictionary for elements and work sections
4. a set of guidance notes.

The potential benefits of adopting the standard by industry players are, more efficient information exchange between different parties, reduction of (unnecessary) duplication of work between the different disciplines, increased familiarity with a uniform standard (which leads to an overall increase in the firm's productivity, as well as the industry's).

Over time, the pervasive adoption of national classification standards will bring about productivity gains via a common language for communication. It will also help firms to embrace IT more easily with a unified information classification system. A common language for effective and efficient communication is fundamental to achieving integration for construction where diversity and fragmentation exist between different industry players, and different project phases and their activities.

Methodology of Systems Development

The proposed fuzzy rule-based system adopts the elemental classification of SS CP 80:1999 as the framework to map the respective elective requirements of the assessment criteria, as specified in the BCA Green Mark Scheme, onto the framework. From this classification, the elective requirements

are individually transformed into logical decision rules and be assigned a linguistic term (i.e. High; Very High; Low; Very Low) for each applicable whole-life cost component. The developed system demonstrates a systematic approach of appraising alternative design and technology that will meet the respective ratings (i.e. Certified; Gold; Gold^{Plus}; Platinum) of the Scheme that can be applied by clients and their consultants. It is aimed to improve the decision-making process as knowledge has been acquired from nine industry experts to develop the system. These experts are mainly in senior management positions in well-established property development companies or design, engineering and cost consulting firms. As there are many elective requirements under the BCA Green Mark Scheme, it is only possible to illustrate the stages of development for a few group elements in the following sections.

Developing a Framework of Elective Requirements

The elemental classification in the SS CP80: 1999 is adopted as the framework for the elective requirements of the Green Mark Scheme. In essence, a classification based on building elements achieves standardisation across all types of buildings. This is because the Building Cost Information Service of the Royal Institution of Chartered Surveyors has defined an element as a component that fulfils a specific function or functions irrespective of its design, specification

Table 6. Worksections classification of 'Wall and Ceiling Finishes' in SS CP80: 1999

Work section	Type of work	Sub-division 1	Sub-division 2
Wall and ceiling finishes	Internal in-situ finishes External in-situ finishes	Rendering Plastering Screeded backings Sprayed or thrown on finish Special or patent applications (Vacant)	Ceilings Sides and soffit of beams Sloping or flewing soffits of stairs (Vacant)
			Cornices, coves, ceiling ribs and enrichments Mouldings (Vacant)

or construction. Hence, it will be applicable to develop the rule-based system by adopting a standard definition for building components. In order to illustrate the classification of requirements, Table 7 shows a mapping of the respective elective requirements onto two group elements, namely, ‘Superstructure’ and ‘Services Installations’.

Developing Logical Rules with Fuzzy Variables

A decision rule can be crafted from each of the elective requirements. Two examples of how a logical rule with fuzzy variables can be formulated are provided as follows. The concept of designing

Table 7. Elemental classification and mapping of BCA Green Mark elective requirements

Group Element and Element	Elective Requirements and Green Mark Points Allocation (Version RB/3.0)
SUPERSTRUCTURE Columns and structural walls Upper floors Roof Staircases External walls and cladding Internal walls and partitions Doors	<u>Elective Part 1 – Energy Efficiency:</u> <u>1-1 Building Envelope – RETV:</u> Max permissible RETV=25 W/m ² ; 3 points for every reduction of 1 W/m ² in RETV from the baseline. <u>1-2 Dwelling Unit Indoor Comfort:</u> (a)(ii) Design for natural ventilation (applicable to development where air-conditioners are not provided) (0.6 point for every 10% of units with window openings facing north and south directions; 0.6 point for every 10% of living rooms and bedrooms designed with true cross ventilation) <u>Elective Part 3 – Environmental Protection:</u> <u>3-1 Sustainable Construction:</u> (a) More efficient concrete usage for building components (0.1 point for every % reduction in the prescribed Concrete Usage Index (CUI) limit for residential buildings). <u>Elective Part 5 – Other Green Features:</u> <u>5-1 Green Features and Innovations:</u> Self cleaning façade system (2 points for high impact item; 1 point for medium impact item; 0.5 point for low impact item).
SERVICES INSTALLATIONS ACMV Sanitary and plumbing Electrical installations Transportation Communications installations Security systems Fire protection systems Gas installations Maintenance equipment Pool and water feature installations Special installations	<u>Elective Part 1 – Energy Efficiency:</u> <u>1-2 Dwelling Unit Indoor Comfort:</u> (a)(i) Use of energy efficient air-conditioners that are certified under the Singapore Energy Labeling Scheme (at least 90% of air-cons used in all units; 2 ticks – 2 points; 3 ticks – 6 points; 4 ticks – 12 points). <u>1-4 Lighting:</u> (a) Artificial lighting in common areas baseline as stated in SS 530 (0.3 point for every % improvement in the lighting power budget). <u>1-5 Ventilation in Car parks:</u> (b) CO sensors are used to regulate the demand for mechanical ventilation (fume extract – 6 points; Mechanical ventilation with or without supply – 4 points). <u>1-6 Lifts:</u> (a) AC variable voltage and variable frequency (VVVF) motor drive or equivalent (for all 100% lifts – 1 point). <u>1-6 Lifts:</u> (b) Sleep mode features or equivalent for all 100% lifts – 1 point). <u>1-7 Energy Efficient Features:</u> Heat recovery devices; Motion sensors at staircase half landing; Heat elevators; Gas heaters (2 points for high impact item; 1 point for medium impact item; 0.5 point for low impact item). <u>1-8 Renewable Energy:</u> (a) Solar energy (1 point for every 3 kWp of solar energy). <u>1-8 Renewable Energy:</u> (b) Other renewable energy (1 point for every 1% replacement of electricity by renewable energy). <u>Elective Part 2 – Water Efficiency:</u> <u>2-2 Water Usage:</u> Provision of sub-meters to monitor the major water usage such as irrigation, swimming pools and other water features (1 point). <u>Elective Part 5 – Other Green Features:</u> <u>5-1 Green Features and Innovations:</u> (a) Pneumatic waste collection system (b) Dual chute system (2 points for high impact item; 1 point for medium impact item; 0.5 point for low impact item).

these rules is based on the cost implications of satisfying the elective requirements, i.e., a logical increase in initial capital cost and a corresponding decrease in operating cost, as compared to the normal situation. The fuzzy variables used in both examples are 'High', 'Low', 'Very High' and 'Very Low'.

Example 1

If your company plans to meet the pre-requisite requirement of RETV of 22W/m² or 20W/m², what are the corresponding percentages (%) as higher initial capital cost of the building envelope and lower operating cost per year of energy consumption that are considered as acceptable for a typical residential development?

1. For Green Mark Gold^{Plus} Rating, where RETV is set at 22 W/m² or lower:
 - a. High Initial Capital Cost _____%
 - b. Low Operating Cost per year _____%
2. For Green Mark Platinum Rating, where RETV is set at 20 W/m² or lower:
 - a. Very High Initial Capital Cost _____%
 - b. Very Low Operating Cost per year _____%

Example 2

If your company plans to secure 6 points or the maximum of 12 points, what are the corresponding percentages (%) as higher initial capital cost of the artificial lighting system and lower operating cost per year of energy consumption that are considered as acceptable for a typical residential development?

1. For 6 Green Mark points (i.e. 20% energy efficiency improvement):
 - a. High Initial Capital Cost _____%

- b. Low Operating Cost per year _____%
2. For 12 Green Mark points (i.e. 40% energy efficiency improvement):
 - a. Very High Initial Capital Cost _____%
 - b. Very Low Operating Cost per year _____%

Establishing Fuzzy Membership Functions

The fuzzy membership functions are developed by applying a modified horizontal approach (Ng et al., 2002) which is based on an amalgamation of the horizontal approach (Bharathi-Devi and Sarma, 1985) and the graphical approach (Bandemer and Gottwald, 1995). This modified approach consists of five main steps and they are:

1. Normalising fuzzy whole-life cost components.

The fuzzy whole-life cost components have to be transformed from linguistic terms into mathematical formulae. The normalisation of 'Initial Capital Cost' and 'Operating Cost per year' is illustrated for two decision rules (as shown in Table 8).

2. Quantifying fuzzy whole-life cost components.

Based on the formulae defined in Table 8, experts have been asked to provide a numerical value (in %) that best described a linguistic variable (e.g. High or Very High) associated with a fuzzy cost component. The reference to be made for describing 'High' or 'Very High' is the 'Normally Expected' situation. For instance, if 5% has been indicated with reference to the 'Normally Expected' situation for 'Initial Capital Cost' to describe 'High', while 10% is for 'Very High', then in situations beyond the normal, the client

may expect an increase by those percentages, respectively, for this cost component.

3. Deriving the X values of the membership functions.

In a fuzzy set, a membership function uses X to represent the value in the universe of discourse that defines it. The X_i values are defined according to the minimum and maximum numerical values (in %) provided by the experts for each linguistic variable (fuzzy set) and the number of bands (k) is defined as:

$$k = 1.87 \left(N - 1 \right)^{\frac{2}{5}}$$

where, N is the total number of responses to the respective fuzzy whole-life cost components.

Also, X_i values are defined as the means of bands B_i ($i = 1, 2, \dots, k$) where, B_i ($i = 1, 2, \dots, k$) are the bands of the numerical values (in %) provided by the experts to the linguistic variables (fuzzy sets).

4. Deriving the A values of the membership functions.

The value of the membership function A_i is obtained from using this formula:

$$A_i = n(B_i) / n_{max}$$

where, $i = 1, 2, \dots, k$, $n(B_i)$ is the number of responses that have the numerical values (in %) belonging to a certain band B_i , and n_{max} is the maximum value of all the $n(B_i)$ with $i = 1, 2, 3, \dots, k$.

5. Formulation of fuzzy membership functions.

For each membership function, X and A are calculated by using the stated definitions and for-

mulae and the derived values are plotted in a scatter diagram with the horizontal axis representing the X values and the vertical axis representing the A values. The scatter diagrams for the membership functions are shown in Figures 3 to 6.

Creating *if-then* Rules

The rule-based system is developed using the ILOG *JRules* software. It involves applying a set of pre-established vocabulary (see the underlined words) to define the rule's conditions and actions, as well as present the rule in a readable language. This generic *if-then* structure of a rule is illustrated for the ‘building envelope design’ as Rule 1 and Rule 2. They are shown below.

Rule 1 (with reference to Figures 3 & 4):

- If *building envelope design* meets “RET_V requirement which is set at 22W/m² or lower”,
- Then set *initial capital cost* to “high” and *add the message* “the initial capital cost is 5% to 17% higher than normal”,
- And set *operating cost per year* to “low” and *add the message* “the operating cost per year is 1% to 6% lower than normal”.

Rule 2 (with reference to Figures 3 & 4):

- If *building envelope design* meets “RET_V requirement which is set at 20W/m² or lower”,
- Then set *initial capital cost* to “very high” and *add the message* “the initial capital cost is 17% to 45% higher than normal”,
- And set *operating cost per year* to “very low” and *add the message* “the operating cost per year is 6% to 62% lower than normal”.

The generic *if-then* structure of a rule is illustrated for the ‘artificial lighting system design’ as Rule 3 and Rule 4. They are shown below.

Rule 3 (with reference to Figures 5 & 6):

Table 8. Normalisation of fuzzy whole-life cost components

Area of Energy Efficiency Assessment	Mathematical Formula
Building Envelopes - RETV:	Initial Capital Cost (%) $= \frac{ActualCost - NormallyExpectedCost}{NormallyExpectedCost} \times 100\%$ Operating Cost per year (%) $= \frac{ActualCostperyear - NormallyExpectedCostperyear}{NormallyExpectedCostperyear} \times 100\%$ where, • 'Normally Expected Cost' is the cost of the building envelope designed to meet the mandatory requirement of RETV of 25 W/m². • 'Actual Cost' is the cost of the building envelope designed to meet the pre-requisite requirement of RETV of 22 W/m² or 20 W/m².
Artificial Lighting Systems:	Initial Capital Cost (%) $= \frac{ActualCost - NormallyExpectedCost}{NormallyExpectedCost} \times 100\%$ Operating Cost per year (%) $= \frac{ActualCostperyear - NormallyExpectedCostperyear}{NormallyExpectedCostperyear} \times 100\%$ where, • 'Normally Expected Cost' is the cost of the artificial lighting system designed at the maximum lighting power budget that complies with SS 530. • 'Actual Cost' is the cost of the artificial lighting system designed to meet the energy efficiency improvement that is equivalent to 6 or 12 Green Mark points.

Figure 3. Scatter diagram of the membership functions for high and very high capital cost of building envelopes that meet RETV of 22W/m² and 20W/m² respectively

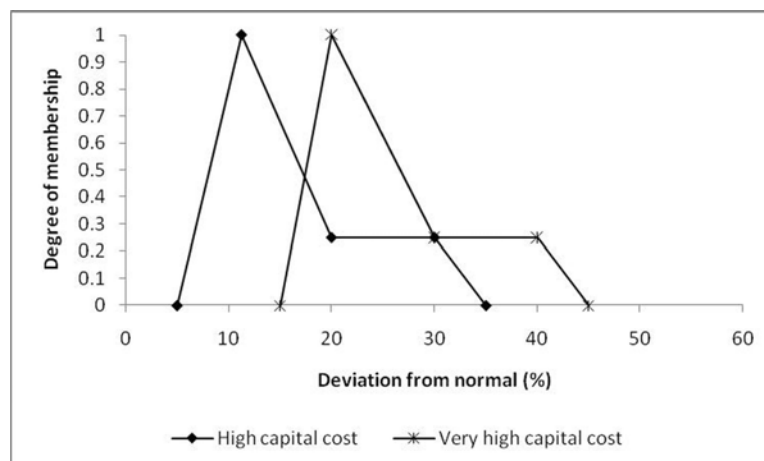
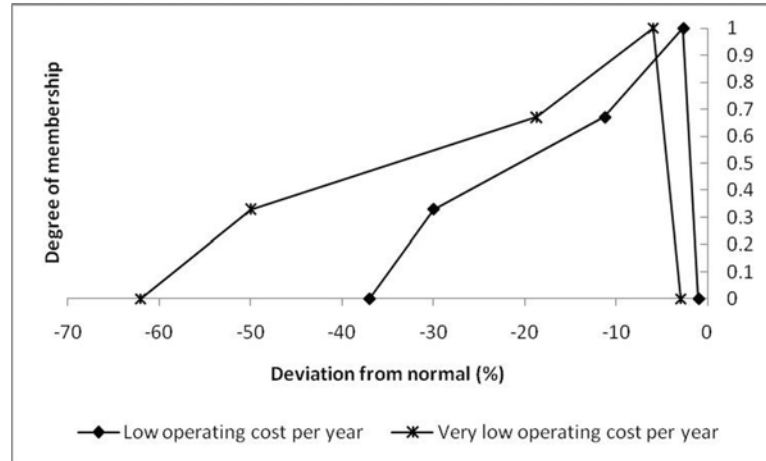


Figure 4. Scatter diagram of the membership functions for low and very low operating cost per year of building envelopes that meet RETV of 22W/m² and 20W/m² respectively



If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 6 Green Mark points”,

- Then set initial capital cost to “high” and add the message “the initial capital cost is 5% to 15% higher than normal”,
- And set operating cost per year to “low” and add the message “the operating cost per year is 2% to 24% lower than normal”.

Rule 4 (with reference to Figures 5 & 6):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 12 Green Mark points”,
- Then set *initial capital cost* to “very high” and add the message “the initial capital cost is 15% to 45% higher than normal”,
- And set *operating cost per year* to “very low” and add the message “the operating cost per year is 24% to 59% lower than normal”.

Figure 5. Scatter diagram of the membership functions for high and very high capital cost of artificial lighting systems that meet energy efficiency improvements that are equivalent to 6 and 12 Green Mark points respectively

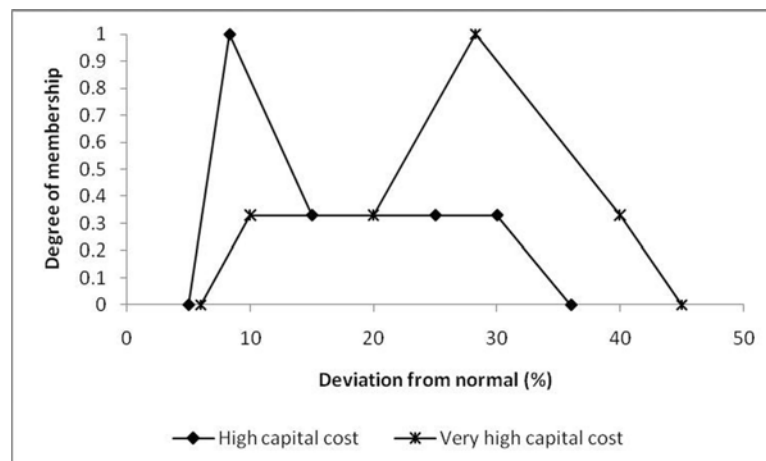
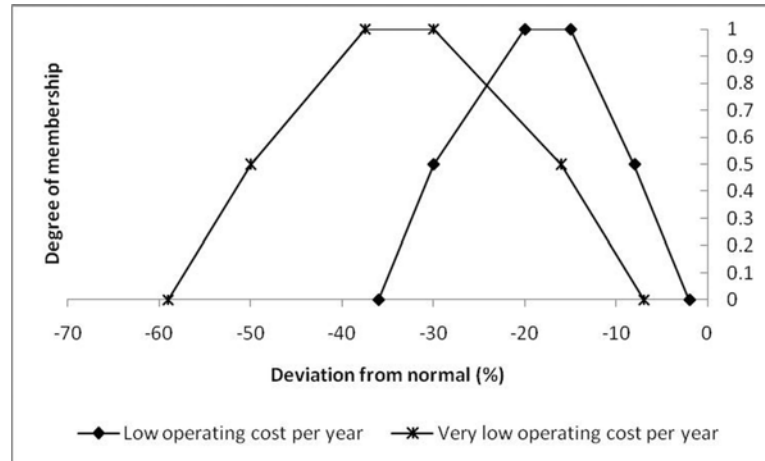


Figure 6. Scatter diagram of the membership functions for low and very low operating cost per year of artificial lighting systems that meet energy efficiency improvements that are equivalent to 6 and 12 Green Mark points respectively



For each of the main rules (i.e. Rules 1 to 4), sub *if-then* rules can be created to further support clients and consultants on their decisions. For example a rule that expands on the Rule 3 relates to artificial lighting system design that meets energy efficiency improvements that are equivalent to 6 Green Mark points. For Rule 3, the membership functions of high capital cost and low operating cost per year have been combined and the plot is shown in Figure 7.

Based on these two membership functions, the corresponding percentages of the cost components are associated with their respective degrees of membership (i.e. '1' is for full membership, '0.5' is for medium membership, '0' is for least membership) which are described in terms of likelihoods of occurrence (i.e. absolutely high, medium and absolutely low).

Rule 3 (with reference to Figures 5 & 6):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 6 Green Mark points”,
- Then set *initial capital cost* to “high” and *add the message* “the initial capital cost is 5% to 15% higher than normal”,

- And set *operating cost per year* to “low” and *add the message* “the operating cost per year is 2% to 24% lower than normal”.

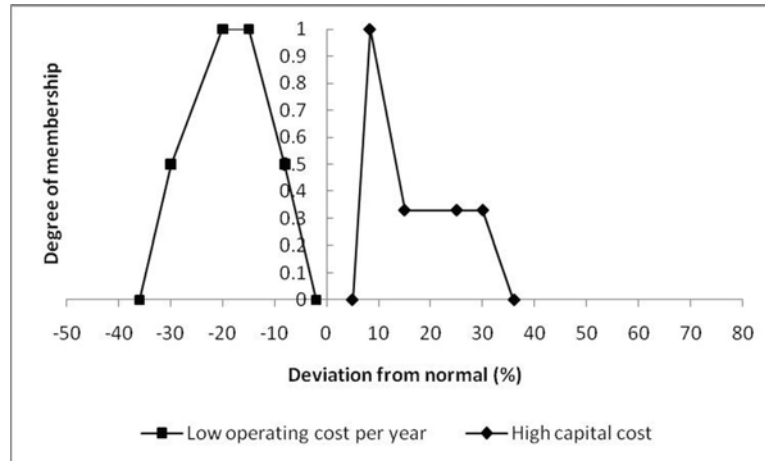
Rule 3a (with reference to Figure 7):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 6 Green Mark points”,
- Then set *high initial capital cost* to “8% higher than normal” and *add the message* “the likelihood of this is absolutely high”,
- And set *low operating cost per year* to “15% to 20% lower than normal” and *add the message* “the likelihood of this is absolutely high”.

Rule 3b (with reference to Figure 7):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 6 Green Mark points”,
- Then set *high initial capital cost* to “7% to 13% higher than normal” and *add the message* “the likelihood of this is medium”,
- And set *low operating cost per year* to “8% to 30% lower than normal” and *add the message* “the likelihood of this is medium”.

Figure 7. Scatter diagram of the membership functions for high capital cost and low operating cost per year of artificial lighting systems that meet energy efficiency improvements that are equivalent to 6 Green Mark points



Rule 3c (with reference to Figure 7):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 6 Green Mark points”,
- Then set *high initial capital cost* to “5% to 36% higher than normal” and *add the message* “the likelihood of this is absolutely low”,
- And set *low operating cost per year* to “2% to 36% lower than normal” and *add the message* “the likelihood of this is absolutely low”.

The same logic applies to Rule 4 and another example is provided to illustrate its expansion. It relates to artificial lighting system design that meets energy efficiency improvements that are equivalent to 12 Green Mark points. For Rule 4, the membership functions of very high capital cost and very low operating cost per year have been combined and the plot is shown in Figure 8.

Rule 4 (with reference to Figures 5 & 6):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 12 Green Mark points”,

- Then set *initial capital cost* to “very high” and *add the message* “the initial capital cost is 15% to 45% higher than normal”,
- And set *operating cost per year* to “very low” and *add the message* “the operating cost per year is 24% to 59% lower than normal”.

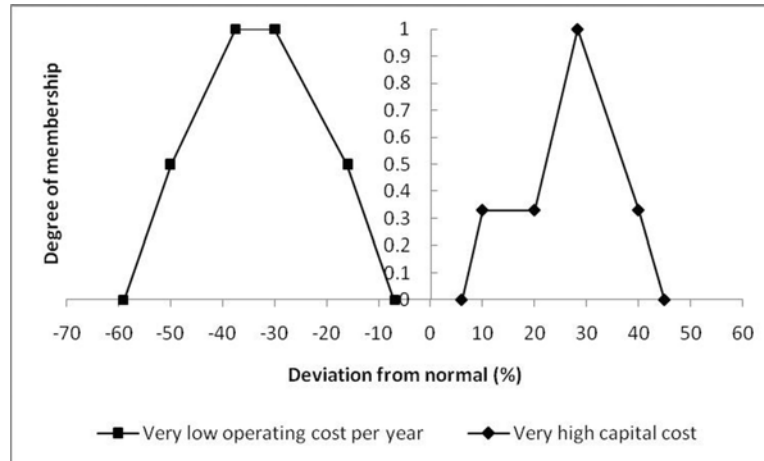
Rule 4a (with reference to Figure 8):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 12 Green Mark points”,
- Then set *very high initial capital cost* to “28% higher than normal” and *add the message* “the likelihood of this is absolutely high”,
- And set *very low operating cost per year* to “30% to 38% lower than normal” and *add the message* “the likelihood of this is absolutely high”.

Rule 4b (with reference to Figure 8):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 12 Green Mark points”,
- Then set *very high initial capital cost* to “22% to 37% higher than normal” and

Figure 8. Scatter diagram of the membership functions for very high capital cost and very low operating cost per year of artificial lighting systems that meet energy efficiency improvements that are equivalent to 12 Green Mark points



add the message “the likelihood of this is medium”,

- And set *very low operating cost per year* to “16% to 50% lower than normal” and add the message “the likelihood of this is medium”.

Rule 4c (with reference to Figure 8):

- If *artificial lighting system design* meets “energy efficiency improvements that are equivalent to 12 Green Mark points”,
- Then set *very high initial capital cost* to “6% to 45% higher than normal” and add the message “the likelihood of this is absolutely low”,
- And set *very low operating cost per year* to “7% to 59% lower than normal” and add the message “the likelihood of this is absolutely low”.

Testing the Rules

The different sets of rules developed for the main elements of a building will be verified against the process or product used in those buildings that have been awarded the Green Mark. Essentially,

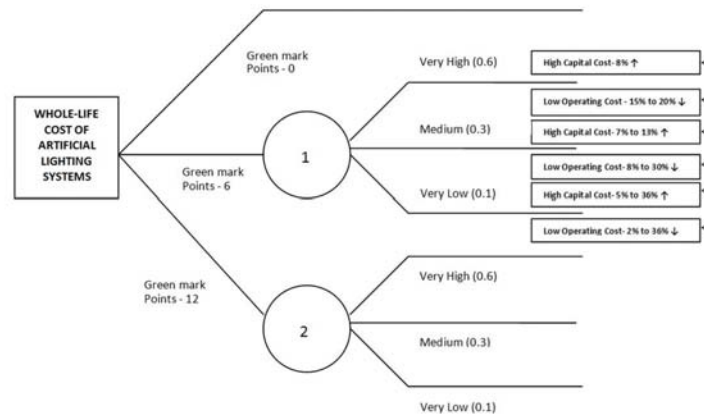
such Green Mark certified buildings would have adopted energy efficient features, water conservation measures, made substantial use of greenery in their projects and ensured a good indoor environmental quality for their users, setting them apart from other buildings. Therefore, the rules will be adjusted or modified according to the best practice adopted in the Green Mark certified buildings.

Application of the Rules

In order to represent the decision logic of the created rules graphically, a conceptual decision tree is drawn to illustrate, possible actions that can be taken, the possible states of nature and their probabilities, and the possible payoffs associated with each action and each state of nature. By incorporating Rules 3a to c and 4a to c into the decision tree (shown in Figure 9), a simulated optimal solution can be obtained for the assessment of the whole-life cost of the designed artificial lighting system based on the actions made available to the client and his consultants:

a1 = {do not participate in Green Mark Scheme
– 0 points}

Figure 9. A conceptual tree to represent decision logic for whole-life cost assessment of artificial lighting systems design



a2 = {to achieve energy efficiency improvements equivalent to 6 points}

a3 = {to achieve energy efficiency improvements equivalent to 12 points}

4 FUTURE TRENDS

In the future, the industry (as a whole) needs to study deeper into, how change can be accelerated in the construction industry (which, is traditional in practice, fragmented and diverse in nature, generally price- and cost-driven, lacks in co-ordination and communication between parties, have informal and unstructured learning process, operates on adversarial contractual relationships and lacks in customer focus). In other words, “Can an industry that is often regarded as inward-looking -in terms of improving its technology and related processes- meet the challenges posed in the future?”

In essence, the construction industry must be able to deliver buildings and structures that provide greater satisfaction, well-being and value to customers and users without compromising on the use of sustainable approaches (DETR, 2000). The industry is increasingly called upon

“to become more market responsive, to reduce the number of accidents on site, to minimise waste, to put an end to its appalling record of pollution incidents, to integrate the supply chain, to engage all stakeholders, to create a far more ethical and enhanced sustainability profile” (Myers, 2005: 781) as means to developing a new vision where social and environmental benefits go -hand in hand- with lower costs and higher profits. Arising from this development, national studies in the UK have suggested that in order for the construction industry to change from its traditional fragmented processes to a more client-orientated business approach, some key emerging trends must be recognised.

One of the emerging trends to be acknowledged here is for clients, i.e. to lead and drive performance improvement and innovation in the construction industry. As the focus of this chapter, it is clear that for now and in future, expectations of clients would be the BIM support in the design of energy efficient buildings, so that information technology can be increasingly used to facilitate complex design processes and analyses that were previously too laborious or expensive to perform by design consultants. With decision support from tools created to guide feedback from the clients,

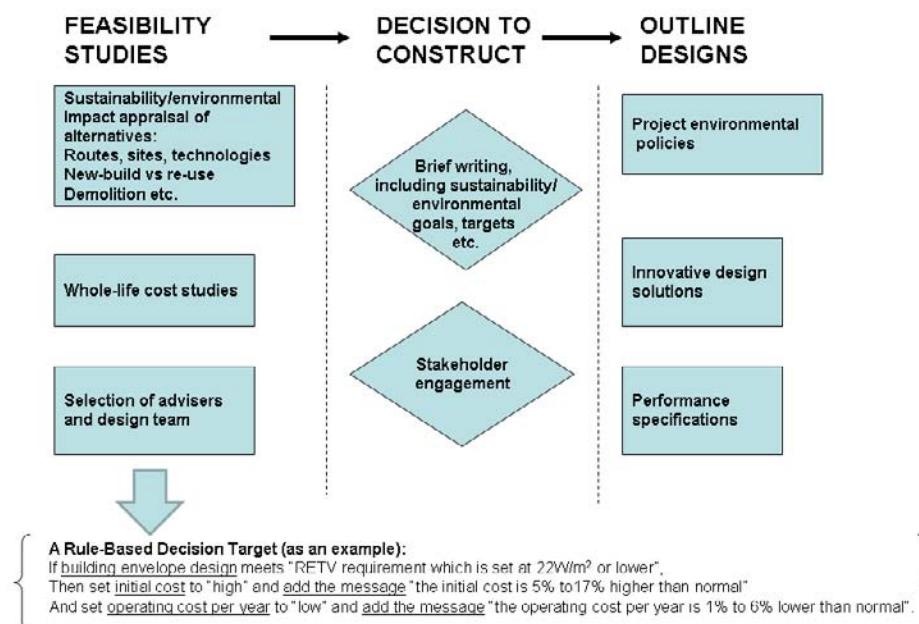
both the architects and engineers can freely engage in concurrent design as they are well aware that the BIM is always reflecting their clients' latest decisions. In turn, it is not surprising to note that among all project users of the BIM, the greatest gains are realised by the client. Benefits to the client include, receiving more reliable budgets, better designs, more efficient construction, better control over processes and proper documentation (during construction) that will facilitate building operation and maintenance.

As explained, for most clients, decisions are guided by cost and most of these decisions are made during the preparation of the budget at the project feasibility stage, as shown in Figure 10. When clients adopt a rule-based decision support approach to arriving at the budget, project consultants would have better confidence knowing that the budget had been set in a systematic and knowledgeable manner. In other words, the possibility of any change to be made in the budget, as

well as the design that follows, will be relatively low. In the context of using the BIM for creating sustainable designs, the proposed tool can form an interface with CAD applications (Design and Green BIM tools) to facilitate designers with the task of designing to a better ascertained budget or cost plan. As an illustration, the process flow, as well as the flow of information, for a typical new building project from feasibility studies to the final design stage is shown in Figure 11. The involvement of the client and/or his project consultants at each stage of the process is also shown.

Applying the process to Singapore, the final design prepared using object-oriented BIM tools will then be uploaded onto the e-Plan Check System for it to analyse and interpret the design according to the requirements of the building regulations for obtaining planning approvals. This part of the process is shown in Figure 12. Also, the whole process, as depicted in Figures 11 and 12 will fit well into Singapore's plan for

Figure 10. A simple illustration of when and how the rule-based decision support tool is applicable to the client and his consultants during the initial briefing stage



the use of BIM, which has been described earlier in the chapter.

5 FURTHER WORK

The chapter has presented the methodological process of ascertaining the type of knowledge and acquiring it for developing a rule-based system that will contain decision-support rules pertaining to the assessment of (whole-life) cost implications for environment-friendly building projects. The examples and illustrations have been based on a case study of Singapore's BCA Green Mark Scheme.

In this chapter, the scope management and requirements analysis phases of a fuzzy rule system have been demonstrated for a few building components by a pilot study. As illustrated in Table 9, further work is necessary to fully develop the decision rules for the entire framework of the Scheme's requirements before systems development can begin.

In the next phase of the research, the system will be developed using the ILOG *JRules* software.

JRules is a business rule management system that will present rules in a readable language and, hence, allows both business and IT users to easily and successfully manage the rules that apply to the business. On systems flexibility, users can manage the rules throughout their life cycle, i.e. from creation through testing, deployment and retirement.

In summary, the chapter has explained the client's role in the Green Building Concept, and the reasons for the increasing need for clients to embrace sustainability through the concept of whole-life costs. The gain from applying whole-life costing would be, to obtain best value of the design and procurement for the development. The client (who is often the building owner and user) can realise this benefit over the development's entire life cycle. However, in order for clients and their consultants to arrive at the best value, proper guidance is needed for making critical capital investment and operation decisions relating to budgeting and design. It is particularly essential during the feasibility stage of project and even at scheme design stage. A fuzzy rule-based decision support tool has been proposed to serve for this

Figure 11. The process and information flow of a proposed building project from feasibility studies to detailed design with the application of the rule-based decision support tool

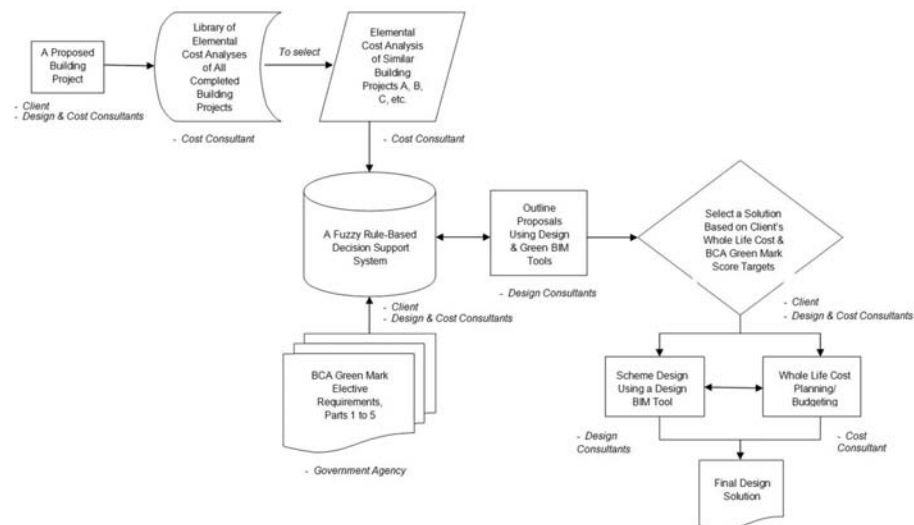
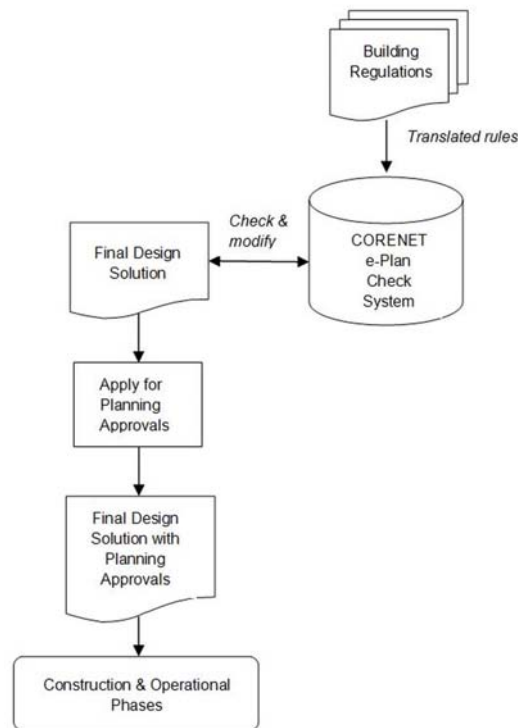


Figure 12. Singapore's solution for implementing BIM through the BCA Green Mark and e-Plan Check Schemes



function. Its relevance to BIM has been discussed (in relation to having the need for the concept to fully work and benefit all stakeholders of the construction industry, i.e. to be encompassing clients as an important group of stakeholders).

Knowledgeable clients will want to lead projects to ensure their success. However, the extent to which knowledge can be managed and best utilised by clients (for making critical project decisions relating to, for instance, cost budgeting, innovative design solutions and their environmental impact) would have a large effect on whether project success is achievable. It is evident that using IT advances the field of knowledge management and application, and intelligent enterprises constantly build up their decision-making capability in this respect. It is understood that decision-support systems provide the business intelligence to organisations to enable them to strategically manage

their activities. Specifically in this chapter, the concepts and stages of development of a fuzzy cost-based application to support the use of BIM for designing energy efficient buildings have been demonstrated and presented.

ACKNOWLEDGMENT

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Table 9. Elemental framework of BCA Green Mark requirements with if-then decision rules

Group Element and Element	BCA Green Mark Scheme Requirement and If-Then Decision Rules
SITE PREPARATION Demolition Site clearance Earthworks Soil investigation	[Decision Rules to be created ...]
SUBSTRUCTURE Piling Foundation Basement Ground Slab	[Decision Rules to be created ...]
SUPERSTRUCTURE Columns and structural walls Upper floors Roof Staircases External walls and cladding Internal walls and partitions Doors	<u>Elective Part 1 – Energy Efficiency:</u> <u>1-1 Building Envelope – RETV:</u> Decision Rule 1: IF <u>building envelope design</u> meets “RETV requirement which is set at 22W/m ² or lower”, THEN set <u>initial capital cost</u> to “high” and <u>add the message</u> “the initial capital cost is 5% to 17% higher than normal”, AND set <u>operating cost per year</u> to “low” and <u>add the message</u> “the operating cost per year is 1% to 6% lower than normal”. Decision Rule 2: IF <u>building envelope design</u> meets “RETV requirement which is set at 20W/m ² or lower”, THEN set <u>initial capital cost</u> to “very high” and <u>add the message</u> “the initial capital cost is 17% to 45% higher than normal”, AND set <u>operating cost per year</u> to “very low” and <u>add the message</u> “the operating cost per year is 6% to 62% lower than normal”.
FINISHES Wall finishes Floor finishes Ceiling finishes	[Decision Rules to be created ...]
FITTINGS, FIXTURES AND FURNISHING Sanitary wares and fittings Fixtures and furniture Artworks and sculptures Soft furnishing	[Decision Rules to be created ...]
SERVICES INSTALLATIONS ACMV Sanitary and plumbing Electrical installations Transportation Communications installations Security systems Fire protection systems Gas installations Maintenance equipment Pool and water feature installations Special installations	<u>Elective Part 1 – Energy Efficiency:</u> <u>1-4 Lighting:</u> Decision Rule 3: IF <u>artificial lighting system design</u> meets “energy efficiency improvements that are equivalent to 6 Green Mark points”, THEN set <u>initial capital cost</u> to “high” and <u>add the message</u> “the initial capital cost is 5% to 15% higher than normal”, AND set <u>operating cost per year</u> to “low” and <u>add the message</u> “the operating cost per year is 2% to 24% lower than normal”. Decision Rule 4: IF <u>artificial lighting system design</u> meets “energy efficiency improvements that are equivalent to 12 Green Mark points”, THEN set <u>initial capital cost</u> to “very high” and <u>add the message</u> “the initial capital cost is 15% to 45% higher than normal”, AND set <u>operating cost per year</u> to “very low” and <u>add the message</u> “the operating cost per year is 24% to 59% lower than normal”.
EXTERNAL WORKS Surface treatments Drainage External services Minor building works	[Decision Rules to be created ...]

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KEY TERMS AND DEFINITIONS

Client: The client is the person or organisation responsible for initiating and financing the building work. This person or organisation is

also called the 'developer', 'building owner' or 'proprietor'.

Whole-Life Costing: Whole-life costing is a form of modelling technique that considers the total cost of the building asset over its operational life.

Fuzzy Logic: Fuzzy logic is a theory that deals with reasoning that is approximate rather than precisely deduced from classical predicate logic. In other words, fuzzy logic deals with well thought out real world expert values in relation to a complex problem.

Sustainable Building: Sustainable building (or construction) refers to a concept that is concerned with the complete life cycle, a building needs to be considered from its design and construction, through the operational stage, to its demolition and site remediation. It is a concept that encompasses the creation and management of a healthy built environment based on resource-efficient and ecological principles.

Decision Support Systems: A decision support system is a type of information system that is used to assist in the evaluation or calculation of the consequences of different alternatives before a decision is made. When human knowledge is incorporated into the system, it is termed as a knowledge-based (or expert) system.

Section 6

Spatial Applications

Chapter 16

Integrating BIM with Urban Spatial Applications: A VEPS Perspective

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ABSTRACT

BIM as a developing concept is adding sophisticated data structures to 3D building models. From recent experience, it can be seen that BIM is enabling the sharing and management of building information. However, BIM is a building scale concept; to fully consider and assess the building information, BIM should be put in the larger geospatial information context, because buildings cannot be isolated from the context of their surrounding neighbourhood and city environment. A review of (3D-) GIS tells us that GIS adds an attribute database to geospatial data, and therefore greatly enables geographical analysis. Geo-spatial related decision-making now-a-days can hardly be done without the help of GIS systems. This chapter reviews recent research into integration of geo-spatial information and building information and in particular, it reviews the VEPS project, its scenarios and approaches, achievements and future development. This review shows the benefit of integrating BIM with the urban scale contextual data. More than that, this chapter also discusses the range of stakeholders such as building contractors, estate agents, city management, and public sector that will benefit from the integration of BIM and (3D-) GIS. Finally, there is a discussion of the way forward in the integration of BIM and urban models.

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1 INTRODUCTION

Before the emergence of GIS and its popularization in the later 1980s, the traditional representation of geographic data (information) was mostly static map products. Even a digital map displayed on a computer could do no more than zooming in and out and pan. The information on the map cannot be changed once it is created. GIS adds an attribute database to the geographic data, and therefore GIS greatly enables geographical analysis (Burrough 1998; Bolstad 2005). Spatial decision-making now relies on GIS systems. An estimated 80% of actions taken by municipal authorities are supported by geo-spatial information (Hnojil et al. 1998; Lemmens 2001). However, in some GIS applications, there is a request to know more detailed information about a particular interest area, for example, an estate agent might want to show particular building information to their clients in detail and meanwhile the client should be able to see the construction in a large scaled context. For public participation scenarios, it should also be very useful to show participants not only the urban area as a basic map, but also detailed information of particular buildings.

BIM as a recent emerging and developing concept has added more sophisticated data structures to 3D CAD models. Because of this, 3D building models becomes a feature-and-object based model from just a graphic representation. Each feature in the geographic representation represents a real world object such as a window or a door in the model and has its own property information. This is also true for the field of 3D city models in a large scale modelling approach for whole cities or boroughs. Instead of setting up a visual representation of the urban space by modelling the geometry and appearance of the objects, standards like CityGML also define additional properties and semantics for buildings and other elements of urban space (Gröger et al. 2008). However, BIM is still a building scaled concept. To fully consider and assess the building information, BIM

should be combined with geospatial information, because buildings cannot be isolated from the affect of their surrounding neighbourhood and city environment. For example, the location of the building in terms of transport connections etc. has a big impact on the way the building can be used. From a sustainability perspective, to achieve sustainable planning it is necessary to gather city information together. This integrated information has to include both urban scaled spatial data as well as detailed information of particular buildings in the city. The integration of the BIM and GIS technologies offers a City-BIM approach which would make it easier for users to holistically consider the planning and regeneration issues.

This chapter reviews the VEPS project scenario using the Stuttgart city model that the authors have cooperated on. The review presents the aim of the project i.e., using 3D city models for the public participation process, and will also outline possible extensions beyond the public participation scenario integrating BIM data. Possible applications based on the technology developed in VEPS could support the information needs of stakeholders such as building contractors, estate agents, city management, and public sector etc. through the integration of BIM and 3D city models.

The integration of BIM and (3D-) GIS has already been investigated in terms of a technical integration of these two domains and the mapping of data models and semantics (Isikdag & Zlatanova 2008; Wang 2007; Song et. al. 2007). This work already shows examples of integrating the two worlds on a data level and in technological terms. This is also discussed in another chapter of this book on “BIM integration with geospatial information within the urban built environment”

This paper will however review the integration from an application perspective. It discusses the VEPS project the authors were involved in, and city scaled modelling. From the urban modelling perspective and lessons learned from the VEPS project, the authors will outline the need and usefulness of integrating BIM data into digital

urban models. Potential applications that need information on both scales of urban space and detailed information about specific buildings, as well as a large-scale overview, will be discussed and outlined.

Section two will review research from both industry and academic field about the integration of Building and Geospatial information. Section three will review specifically the urban scaled VEPS project, its aims, technological concepts and implementations. Based on the work in the VEPS project the paper is going to demonstrate the possibilities of creating city BIM systems, and their potential usefulness. Section four will outline the cooperation with the City of Stuttgart during VEPS and ideas on how to use the system beyond public participation and its potential for further improvement towards an urban BIM system. Then the final section five concludes the paper with a discussion on taking forward integration work and the constraints that are currently faced.

2 REVIEW OF THE INTEGRATION BETWEEN BUILDING INFORMATION AND GEO-SPATIAL INFORMATION

Geospatial technologies are used for visualisation and analysing geo-spatial features such as buildings, roads, subways, bridges etc. Many activities also require precise information about these features - internal and external. Bacharach, the Executive Director of OGC stated (2006), there are two key points in the integration of building information and geo-spatial information: Communication between different software systems to enable CAD/Geospatial integration; the harmonization of Geospatial Data Models and Building Information Model so software can readily manage both. This statement very clearly points out the application level and the data level of integration between these two.

2.1 Integrated nD Modelling Database Approach

Between 2002-2006, researchers in the Research Institute for the Built and Human Environment, BuHu, at the University of Salford developed the nD modeling concept. nD modelling is seen as an extension of the building information model by incorporating all the design information (such as a 3D building model, time, cost, accessibility, sustainability, maintainability, acoustics, crime, thermal etc.) required at each stage of the lifecycle of a building facility (Lee et al., 2003; Aouad et al., 2005). This concept was extended into an nD urban information model, by the efforts of integration of a wide range of datasets. The concept of an nD urban information model is defined as a representation of urban data sets and their relationships to provide a conceptual view of urban information (Wang and Hamilton, 2004, Hamilton et al, 2005). The n-Dimensions include the 3-dimensions of the urban physical structure, time, economy, society, and environmental dimensions. This nD urban model can integrate diverse and scattered data sources together in order to implement the interoperation between various datasets.

This nD urban model approach was essentially an information framework or infrastructure for data integration and interoperability (Song et al., 2007). This framework can be used to gather and store a wide range of information from geo-spatial information to building feature information for urban planning application systems.

This approach was used in the Intelligent Cities (IntelCities) project, an integrated project funded by the European Commission (EC) Information Society Technologies programme under framework 6 (6.8 million Euro, January 2004 to October 2005). The aim of the IntelCities project was the development of open, secure, interoperable and re-configurable e-Government services at the city level. In this project, an nD modelling schema was developed to describe geographic features and IFC objects. A centralized relational

Figure 1. Peking University campus model in Google Earth. (<http://sketchup.google.com/3dwarehouse/placemarksanon?clid=1bc008ad1a828acb6c0588f54279ef9a&rtyp=kml>)



database was designed and setup to host all the relevant information (Wang and Hamilton, 2005; Tanyer et al., 2005). An integrated conceptual system of Built Environment Data Integration System (BDIS) was developed based on the nD urban modelling database. The system reads both geo-spatial data and building feature information from the database and can visualize them as well as generate reports about the data (Hamilton et al., 2005b; Song et al., 2007).

This approach integrates geo-spatial and building information into one centralized database and provides access to client software systems. The required infrastructure is clear but is difficult to implement in real world project. In the real world, there are always multiple data sources and multiple formats co-existing and conversion and sharing in a centralised database is difficult.

2.2 Google Earth Approach

It is possible to use virtual globes like Google Earth to integrate with the users' own data to provide integration of both building information and wide scale urban information. In this case, with the popularity of the Google Earth, information is available to very large user group including lay

persons. Fig. 1 is a Campus model of Peking University in Google Earth. This is one of the results from the 2008 International Model Your Campus Competition which was organized by Google. In this event, all participants created their models using SketchUp. There were 9 winning team in the 2008 competition, and this is one of them.

In this approach, the visualization of data is highly influenced by the data provider, such as Google. There are also problems of limited abilities attaching building features information apart from geometry. As the Google Earth file format of KML is not a BIM file format, it is impossible to give detailed information of individual building features from the model itself. But it is possible to click on the building to get limited building information.

2.3 GIS and IFC Mapping Approach (IFG)

IFC can be used to model much attribute- and meta-information related to the geometry. The Norwegian State Planning Authority (Statens Bygningstekniske Etat) initiated the IFC for GIS project (also known as IFG). The aim of the project was to be able to provide geographic information

created using GIS systems within the framework of the Industry Foundation Classes (IFC) schema defined by the International Alliance for Interoperability. The reason for this was to support a growing set of business requirements emerging within Statens Bygningstekniske Etat. This work is described as follows (Wix, 2006):

“IFC for GIS development focussed on support for making the zoning plan and building plan submission process more efficient. Key to this was the integration of GIS information in a central building and property registry with AEC/FM information about the individual buildings that are registered. For a building that is to be designed and constructed, information is taken from the registry to provide location map data including property data, utility services, zoning and more. The IFG project set out to define a bridge between AEC/FM systems and GIS systems. It did not seek to create complete geographical information inside IFC. Instead, it recognized the existence of other competent models for this purpose, notable the model underlying the Geographic Markup Language (GML) produced by the Open GIS Consortium (OGC). However, by providing the bridge, IFC facilitates the mapping of information between AEC/FM and GIS” (Wix, 2006).

In summary, different approaches and significant progress toward the integration of building and urban information has been reviewed above. In this book we can see a different approach in another chapter on “BIM integration with geospatial information within the urban built environment”. In this chapter, BIM and Geo-spatial information integration framework is defined, which uses web services to push BIM into a wider scope. In particular, CityGML and IFC are adopted in this framework.

In the following sections of this chapter, we will discuss other ways of relating urban and building information developed in the VEPS project in detail. This will be from an application perspec-

tive and includes the design, implementation and future work discussion.

3 VEPS - INTEGRATED SYSTEMS FOR URBAN PLANNING

3.1 Introduction

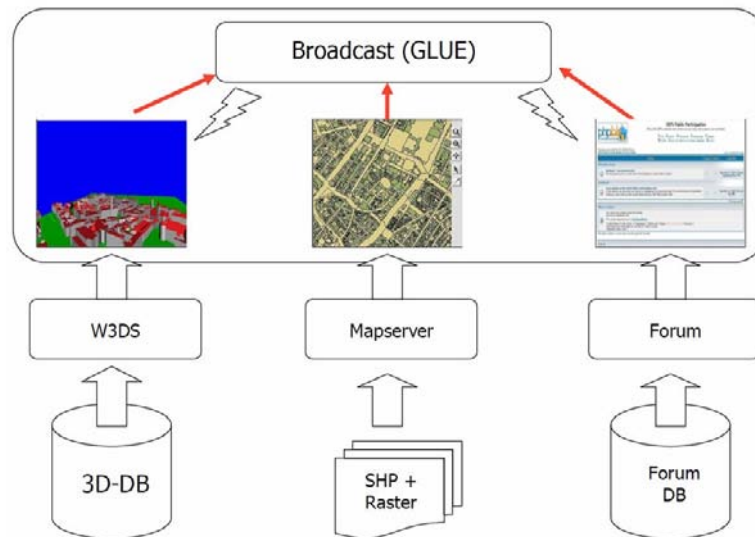
The VEPS (Virtual Environmental Planning Systems) project (2004-2008), was an INTERREG IIIB funded, 4 million Euro European project (E109), led by the Environment Agency for England and Wales (EAEW). A key activity in VEPS was the use of a variety of data sets, within Virtual Reality (VR) visualization software and the subsequent delivery of a 3D model view via the Internet. VEPS intended to provide larger scaled urban area environment information and interaction rather than just a realistic 3D model. VEPS also investigated the potential of integrating detailed building information with large scaled urban area information (Wang 2007; Hamilton 2007). Through the VEPS project, issues of building data capture and building data integration were to be considered at a larger scale through investigating data standardization, modelling, interoperability and integration with other (VR) systems (Counsell et. al. 2008; Song et. al. 2008). This section will introduce what VEPS achieved and how it has been realized.

3.2 VEPS Products

The VEPS project developed and demonstrated the use of interactive, web-based technology to help people understand planning proposals and share their views about them online. This is through an approach allowing people to view, query, modify and leave comments about planning using 3D visualisation software in a web browser, within the context of an existing landscape or cityscape.

The software developed by VEPS allowed users to freely explore and interact with 3D models

Figure 2. VEPS system architecture



and write comments via an online Forum system, which could be accessed from their normal computer over broadband connection at any time. The comments submitted, as well as the VEPS models would be available to others accessing the web applications. An important feature of the participation system is the linkage of the 3D/2D components and the commenting platform through a purpose built client side broadcasting “GLUE” module (Fig. 2). This small piece of system allows separate web applications (2D, 3D and Commenting) to link together in order to build the participation system for planning. Besides the big advantage of being able to exchange specific modules of the system quite easily, it also links the discussion with certain aspects of the planning area, e.g. specific buildings, a 3D position, a 3D perspective and the relevant object.

This gives users the ability to participate and better understand planning proposals: they can navigate in 3D or, if it is difficult to operate in 3D, it is possible to use the 2D map to navigate while the 3D scene automatically rescales itself based on the 2D navigation. Also, if you open up a topic in the commenting panel, both 2D and 3D

would load the position or feature into the centre of the scene which matches to the topic.

The “broadcast/GLUE” mechanism (see Figure 2) is a client side component but is invisible to the users. This module gives the system an advanced feature in terms of the interoperability and the capability of integration with each system component. The VEPS partners developed a series of tools to bring spatial and non-spatial information to internet users. Users can query an urban scaled planning proposal as well as zoom in to a building level to see more details. More than that, users can click on a 3D or 2D scene to add comments about this feature or this particular view point.

The following briefly introduces the main products delivered in the VEPS project. These products all demonstrate one fact in common: the scenario of public participation needs an urban scale approach as, planning proposals for projects need to provide information about the surrounding as well. In the planning stage, citizens as well as planners and other professionals need contextual-building information as they should decide on ‘urban design’ issues and not primarily

on detail elements like windows, doors or facade material.

But as the authors will discuss in later sections of this paper, in other stages of planning projects, detailed discussions among experts about details of building elements might be necessary. These experts will definitely need more detailed models, which are represented by BIM nowadays. However, the discussion might not take place on an isolated building; it should be explored in its urban surrounding. Therefore section 4 will discuss the integration of BIM into the VEPS approach and how expert users could benefit from it. Features of VEPS products are considered below:

3.2.1 3D Participation Tool

The 3D participation tool aims to improve access to information and public participation in the planning process by allowing any participants to:

- view information about a planned development in 2D and 3D;
- (using 3D-views to) help people understand the proposed designs and their environmental impacts;
- make comments on the proposal in either 2D or 3D. 3D coordinates and orientation will be saved for comments to create 3D view point which can be accessed by all system users.

3.2.2 3D Commenting Tool

The 3D commenting tool is to encourage active public involvement in planning. It allows people to:

- Navigate in 2D and 3D;
- Leave comments about specific buildings, and attach photos, video clips and web links relating to comments;
- Click on a comment-marker or a building to see information and comments;

- Click on attachments to see photos, video clips and other files;
- View simple flood models in 3D.

This allows the users to access information about proposed developments, explore the models, and view developments that are important to them. The tool can also help people to view and compare different development options.

3.2.3 3D Master Planning Tool

The 3D master planning tool offers advanced 3D manipulation capabilities to web users. It allows people to:

- view planning proposals that others have uploaded to the web within a realistic 3D scene of an existing city and/or landscape;
- comment on the planning proposals by inputting text comments to selected view. Comments can include hyperlinks to other web resources, such as images, video, or other documents. Comments and views can be explored sequentially.
- create alternative proposals by adopting updated proposal, uploading CAD 3D models into the scene or sketching up a plan footprint onto the landscape and extrude its height and choose the roof-shape.
- compare different proposals by switching between two alternative proposals.
- show 3D scanned LiDAR points on the scene to help checking height accuracy of 3D models.

3.2.4 Two Dimensional (2D) Commenting Tool

There are two systems developed based on 2D digital maps by VEPS partners. Both deliver the map with different open source software and both have slightly different interfaces. However, both of them support users in adding comments

and querying features on the map. Both systems manage the comments as geo-coded points so that the comments can be displayed on the map accurately. Map features and comments can be enhanced by attaching images, panoramic images, videos or other form of information for the users of the system to have a more detailed vision of the planning area.

3.3 VEPS 3D Participation Tools Design and Implementation

Section 3.2 outlined the main products VEPS delivered. This section will concentrate on one of the VEPS prototypes, a 3D participation tool and will discuss its design and implementation. Although it is only one of the VEPS products, it shows the whole idea and the technical structure of VEPS developments.

3.3.1 3D Participation Tool Design

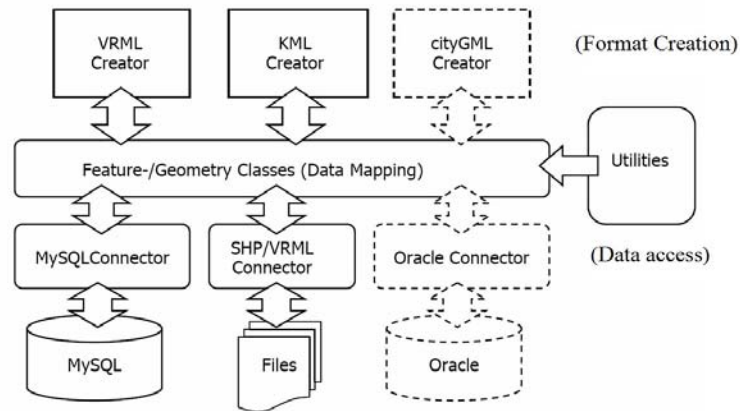
3.3.1.1 Server Interface and 3D Model Management

The server side of the participation tool includes two separate web applications, a 3D city model application and a discussion forum. It is optional on the server side to have a 2D map application, because it is possible to use Google Maps Services to provide the client side 2D map window. The two necessary components on server side were responsible for the management of the discussions/commenting (PHP-based open source forum software) and the management of the 3D city model data (java based framework and W3DS interface (Quadt&Kolbe 2005)). A data management framework, called CityModel Administration Toolkit 3D (CAT3D) was developed at the HFT Stuttgart – University of Applied Sciences, which also participated in the VEPS project. As this data framework would play a major role in the integration of BIM data in future development steps of the system, it will be described here in more detail.

The CAT3D framework (Bogdahn et al. 2007) was developed in order to manage 3D city models and to provide them to various client applications in different project scenarios. This framework was actually used in the VEPS project as well as in other projects, as it can be easily extended and adjusted to other project scenarios. The framework basically consists of 3 layers and a utility module (Fig. 3). The first layer is ‘data access’, which includes components that are capable of reading different data formats and connecting to (spatial-) databases (MySQL spatial etc.). This layer basically decodes the information provided by the data source and translates it to the feature and geometry classes that are used as a general internal data representation used within the framework. In the second (i.e., data mapping) layer all the external data can be merged to one model. Utilities can be utilized in this part in order to harmonize and merge the data appropriately. The modules on the top are in the ‘format creation’ layer (VRML, KML and CityGML). These modules actually encode the information from the ‘data mapping’ layer into the output format that is required by the client application. This also includes handling the limitations of certain formats in regards of semantics or additional attributes.

The data model used within the framework is also based on objects and features and can also include semantics, attributes and properties of the real world objects. Especially the connection to a geospatial database makes it necessary to work with (geospatial) features and objects, as most of the spatial database management systems are based on the OGC Simple Features specification (Herring 2006). This feature based approach is essential for certain functionality that might be necessary for 3D models in interactive applications. One example is the query of features based on the feature properties. A client might support queries like: “Show me all public buildings” or “Show me all residential buildings”. Requests like these can only be supported if the underlying interfaces and the management framework sup-

Figure 3. The CAT3D architecture



port a feature based approach and the integration of geometrical data and attribute data in order to model real world features with all their properties. The extension of this framework in order to support BIM data, respectively IFC/IFG formats, will be discussed in more detail in Section 4 of this paper and issues about mapping of IFC/IFG and other technical details can be found in the chapter on “BIM integration with geospatial information within the urban built environment” in this book, and other relevant literature.

3.3.1.2 Client Components

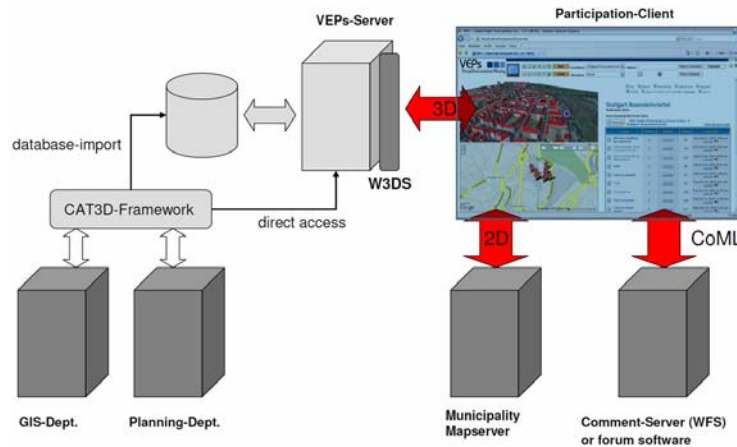
The VEPS common service modules can be categorised as: User function modules (2D, 3D and commenting modules) and system function modules. The user function modules directly provide interaction between user and the system through a user interface, while the systems function modules handle data requests, and communication between different modules. This design gives the system flexibility in terms of the interoperability. Features of the design are detailed below:

- The 3D module provides functions to create and manipulate 3D virtual models. A client side 3D plug-in enables the visualization of 3D scenes received by the W3DS and rendered using VRML and X3D scene

graphs. Manipulation of the scene as well as presenting information of the features in the scene graph is enabled by using client side scripts VBScript or JavaScript.

- The 2D module displays a map on the client side. With reference to the urban scaled context discussed elsewhere in this chapter, the 2D map is useful for an overview of the whole surroundings and helps users to index the area under exploration. In VEPS prototypes, there are two open source techniques used, MapServer plus PHP MapScript or Google Maps plus JavaScript. As mentioned in 2.3.1.1, the Google Maps approach will not necessarily need a server side application to support it as Google Maps provide the map services. However, the coordinate transformation between the 3D scene local coordinate system and 2D map real world coordinate system must be in place.
- The commenting module is developed based on an open source application called ‘PHPBB’ forum application. The software provides functionalities for forum management, user account management, as well as various ways for user communication with other users. In VEPS, this tool was integrated with the above 2D/3D modules

Figure 4. VEPS 3D participation tool architecture



in a way that each post in the forum has a spatial position or a 2D/3D object or a view point related to it. This was done by modifying its original PHP script so that the forum can respond to the 2D/3D operation, and also by modifying its original database so that each post in the forum software can attach additional information about the spatial position or 2D/3D object or view point. This effectively means that each post is a comment.

3.3.2 Approach and Implementation

3.3.2.1 System Architecture and Integration into Existing IT-Environment

One part of the project, which was conducted during the extension phase in close cooperation with the city of Stuttgart (planning and geo-data department), was an integration test into the municipality's IT-infrastructure. As already outlined in section 3.3.1 the system is designed in a flexible way and allows the integration of different web applications and existing data sources, especially in terms of the 3D model component. The architecture depicted in Fig. 4 shows the general integration test architecture. It can be noted that for the city department test the 3D model was cre-

ated from two sources, the geo-data department and the planning department. Another notable point is that the project team tried to exchange the Google Maps window for content provided by the municipality map server. As described in section 3.2 the flexibility of the architecture makes this exchange easily achievable.

In this architecture diagram (Fig. 4) it can also be seen that the integration of the data building the 3D model is done by using the components of the CAT3D framework, outlined in section 3.3.1.1. This framework is the back-end for an OGC W3DS interface in order to provide 3D scenes to the client. This component also has the capabilities to link 2D+Attributes datasets, e.g. classical GIS datasets like SHP+DBF, to the 3D model. This attribute integration links additional information to the 3D objects (which can be accessed and used within the client's 3D component). For further developments towards the integration of BIM data, this framework can be extended and BIM information can be integrated into the 3D component of the tool (discussed in Section 4). If this way is chosen, it still needs to be investigated in terms of how the internal data representation (which is mainly GIS based) would be able to model BIM data. This investigation would clearly link into the aforementioned

work about CityGML/IFC mapping. Another issue would be if the W3DS interface could still be used in order to provide BIM scale data, or if other interfaces need to be used, such as Building Feature Services (BFS) developed by one of the authors (Wang 2007). These and other issues about the possible extensions and their usefulness as a basis for a CityBIM tool will be discussed in section 4 in more detail.

3.3.2.2 3D Scene Additional Information

The 3D model is queried and loaded in the client side through W3DS query. The function which calls the W3DS is in a script inside a VRML scene. However, real world objects normally do not only consist of their visual shape or the geometry, but there is also a lot of information which is connected to the object, like address, owner information, land registry data and much more. The participation tool provides this information to the user in order to make the planning proposal easier to understand for participants. And also, 3D objects can hyperlink to videos, images or additional documents which describe the object in more detail. This additional information is accessible through the 3D scene: the user clicks on the object and receives additional data or hyperlinks to external websites, contact persons or even the e-mail address of the estate agent which is going to sell apartments in a newly built complex. This is the concept of BIM in the urban context. In its current state the tool treats a building as an object with no detailed information, even if the user 'zooms' to a specific building. The modelling of the data is done at a 3D city model level, which at the moment is a LoD 2 model in terms of the CityGML specification. This is sufficient for the public participation context, but one could imagine using the tool for other aspects of the planning process, maybe as an expert collaboration tool. These experts need much more detailed information in certain scenarios that also provides domain specific information on building elements, e.g. windows. Therefore additional information,

the depth of this information, as well as the LoD of the model, should be adjustable according to users' needs. This might be achieved by a seamless transition between city scale information and detailed building information (See section 4 for detailed discussion).

3.3.2.3 Interaction between Client Side Modules

The commenting module, 2D map module and the 3D module are all available on the client side. As introduced in Section 3.3.1.2, the 2D map was provided to give an overview and help users to easily navigate through the scene, while the comments module makes relationships between each comment and the 2D/3D scene.

Actually, all three user components in the client side are integrated through a broadcast mechanism, called GLUE (mentioned in Section 3.1). For example, once a comment (a post in the forum module) is selected, a message would be passed to both 2D and 3D modules, both of these two would automatically reload the scene to situate the referenced objects at the centre of the scene. If a user changes the extent of the 3D scene, a message would be passed to 2D to change its scope of area accordingly. Meanwhile, if an object was clicked on 2D or 3D, and there are comments related to the object, the forum module would automatically open up that comment.

Furthermore, for best interoperability, all VEPS components developed by different partners would be able to be seamlessly integrated into the GLUE environment. That means they should be able to send and receive messages through this broadcast. GLUE is built to integrate developing and ready-to-use prototypes, so GLUE, itself indeed does not do any VEPS system functional operation. In other words, any functional operation should be handled by the functional components (2D/3D/Commenting) themselves. GLUE is situated in the middle of the client side to support communication, i.e., to pass requests and responses between functional components. In order to adopt GLUE

component, there were 4 fundamental steps to follow for each functional component:

- To extend the components by including the GLUE java script in original code to make it support GLUE.
- GLUE should have a mechanism to recognize/manage a list of all the components to be integrated.
- The component to be integrated should extend itself to be able to respond to messages received from other components and to implement accordingly.
- The component to be integrated should have functions to send a message to GLUE when it wants to broadcast an event which requires other components to respond.

This client side functionality would allow the integration of detailed BIM information on the application level: it would be possible to integrate the 'BIM system' as a further component that needs to be synchronized with the 3D model view. In that way the user would have a 3D model context overview and a detail BIM of a specific building in separate windows. This approach will also be discussed in section 4.2.

3.3.3 Summary

This system demonstrates that the VEPS participation system integrated 2D, 3D and commenting modules through a communication mechanism and powerful server side components that are specialized for their specific task. The VEPS prototype described in this section shows that GIS information, especially attribute data, can be linked to 3D models. This principal is also supported by specifications like CityGML and describes the need for semantic 3D models. This approach is also taken in the domain of BIM, which should allow the integration or harmonization of both approaches. The described tool focuses on a public participation scenario, in which the information

on a building level is sufficient and appropriate for the scenario. However, for other specific tasks, more detailed information about buildings and their parts might be required. This data is better covered by BIM and therefore an integration of the two data spaces might be beneficial for certain applications.

3.4 Summary of VEPS Systems

VEPS systems in common use separate server side applications to integrate 2D, 3D and commenting modules through communication mechanisms in the client side. Through this integration, 3D urban information, 2D map, and spatial related commenting information, are integrated and provided to users through web browser based client interfaces. The web based interface enables a good accessibility to the systems.

The VEPS technologies described in this section can be considered as one possible basis for developing the functionality needed in production of full city BIM systems; and this section illustrates ways to realize such a system. This will also be addressed in detail in Section 4.

4 URBAN BIM - THE FUTURE

This section is going to outline aspects of existing VEPS prototypes as described in Section 3, in regards to potential extensions in order to integrate BIM data. This section will discuss issues from a scenario perspective as well as application design concerns and client side challenges.

4.1 BIM Integration from Application Perspective

From an application perspective the VEPS prototypes were more or less focused on public participation. However, the tools can also be used in a slightly different way, as the authors of this paper in the project tested. An integration

test was conducted in Stuttgart to incorporate the VEPS prototype (described in Section 3) into the IT infrastructure and the daily work of the city's planning department. In this case the VEPS prototype was more or less an expert collaboration tool for internal communication about planning issues. This application still focuses on the urban scale mainly treating a building as single object. Nevertheless it can easily be extended to a multi-department system where information in another scale might be relevant. For example, if the fire department would be involved and would have to assess emergency corridors and other issues in the closer surrounding of a building, the focus would be on a specific building or a group of buildings but always in the spatial context. This scenario can be extended to the whole municipality, which would set up a centralized 3D model that is built by data from the specific departments involved. This model is then available again to all staff in the municipality acting as an urban information space. The city of Stuttgart for example has introduced a working group for exactly this scenario, involving representatives of several city administration departments to discuss the needs of data exchange and possible solutions and also issues concerning the integration of this information in a 3-dimensional virtual model. The cooperation of several departments inevitably involves work on different scales of information as specific tasks also focus on differently scaled problems. In terms of urban information this ranges from regional scale to systems working on one specific building or a block of buildings. In order to provide a platform to integrate all these special data sets working in the aforementioned scales a 3D city model seems to be ideal to build the frame for an urban information space. CityGML as one of the most influential data models provides Level of Details (LoDs) from regional to building level, and even for building interiors. This LoD definition overlaps with the scale that BIM defines. The two domains seem to work on the same issue approaching it from opposite directions: providing and modelling

urban information. The overlap in their definitions seems to make it even more sensible to integrate the two, not only technically, but also by linking the world of Geoinformatics and the Building/Architectural world as well as the field of urban planning. Of course, this would not mean that the particular departments would not use their decision support systems anymore, but they would use the urban information space in order to access other information and to analyse their own data in the context of other available information. In order to integrate all the information that is available about urban space, an integration of BIM and (3D-) GIS seems inevitable.

4.2 BIM Integration from a System Design Perspective

Major cities like Stuttgart have started to build 3D city models and to manage them in geospatial databases supported by flexible and efficient management applications for data integration. Most of these cities have specialized departments that produce specialized data sets. In order to integrate these data sets into a 3D city model it is necessary to be able to read this data and to store it in a database together with other data applicable to the 3D model. In the VEPS project the authors only worked with two departments, the planning department and the geo-data department. But already at this level it was not an easy task to integrate the provided data in order to have a 3D model showing the existing buildings and the planning alternatives. Therefore flexible data frameworks as described in 2.3 or in (Haist & Coors 2005) are needed in order to combine information, especially in terms of data that is needed to form appropriate 3D models. In order to integrate BIM formats like IFC/IFG into the VEPS system, it would be necessary to develop a 'Data Connector-Level' component that is capable of mapping IFC data to the internal data structure of the system. As this internal data structure is mainly based on the OGC Simple Features specification (Herring 2006), it

needs to be investigated if the geometrical definition of IFC/IFG is modelled in a similar way to the OGC definition. If that is the case the mapping of the geometric part should be possible. Further investigations might be necessary to find out if and how the additional attributes provided in IFC can be modelled in the data management framework. One approach could be to use a specific subset of IFC that can be used in GIS-based frameworks mentioned above, although this would possibly omit information that needs to be present if the system provides very detailed information, which is characteristic for BIM. This would clearly restrict the transition between the two scales/worlds as information would be lost.

Another aspect of the VEPS systems in terms of BIM information integration is the interface of the 3D system to the client. At the moment an OGC Web 3D Service (Quadt&Kolbe 2005) is used as the interface to the client side 3D component. This service, like all the other OGC interface specifications, focuses on the GIS world and the support of open Spatial Data Infrastructures (SDI). They were implemented and tested and are mainly used for city and regional scale tasks, in terms of 3D urban data. It needs to be investigated if these interfaces are also suitable for a situation where highly detailed BIM data is integrated and needs to be queried from the server. As these models provide more 'data depth' there might be an issue about flexibility of the requests and adjustment of the data depth to user needs. Real world tests might be necessary to evaluate if BIM data can be provided using OGC services in order to integrate this data into (3D) SDIs and therefore into systems like the one developed in the VEPS project. If there are comparable interfaces for the construction or architecture BIM domain it might be useful to map additional functionality to OGC specifications, or to integrate interface signatures (Want, 2007). Another approach might be to abandon OGC services for communication between client and 3D management framework and use a proprietary solution. Nevertheless, the

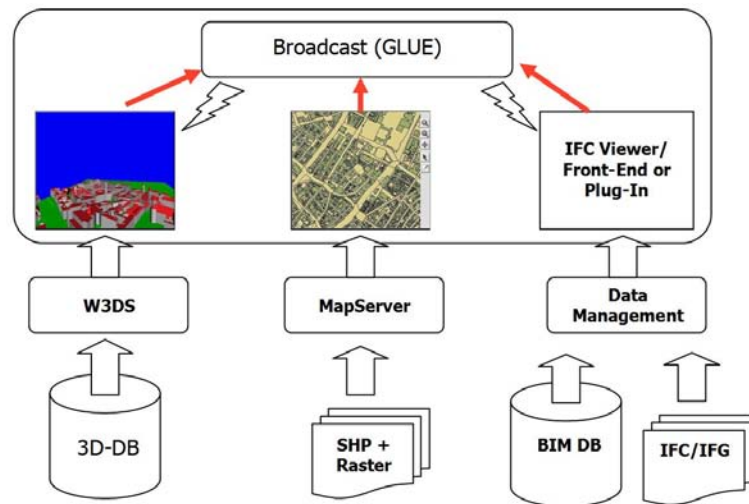
integration of data can still work based on OGC services for GIS data and by a IFC connector for BIM. But all this would remain at the data integration level, where the SDI environment might be a bigger priority. The communication with the 3D visualization component could be done using a specialized format and application interface. Although this would mean in consequence i.e., the framework in this case would be limited to this specific 3D client as the interface and the exchange format would not be standardized.

Another solution for the integration of a BIM view into the current VEPS system would be to add a 'BIM application' (mentioned in Section 3.3.2.3). Due to the integration capabilities of the client side, the system basically consists of separate web applications synchronized on the client side (Figure 5). This would theoretically allow integrating a 'BIM web application', which would manage data and transmission independently but integrate its capabilities into the client. It would be possible, for example, to have a 3D window for the general overview and spatial context, in which the user can select buildings he wants to see in detail i.e., by the GLUE component the 3D window would send a message to the BIM component with a request to load the selected building at BIM information level. All the functionality to analyse and use the BIM data will be provided by the BIM component. However, some sort of data integration is still needed on the server side, as objects in the 3D model database should have a reference to the object in the BIM dataset, as they need to be at least loosely connected. This connection is absolutely necessary for the client components to synchronize, and it would make a 'detailed data mapping' on the server side unnecessary.

4.3 BIM Integration from Client Application Perspective

The visualization of the data managed in frameworks as described in the sections above can be

Figure 5. Integration of BIM application on client side (possible approach)



realized by various clients. As the framework is capable of generating output in different formats, it is possible to use virtual globes like Google Earth or World-Wind as well as VRML-Viewers or custom visualization tools. In the case of virtual globes the visualization of data is highly influenced by the data of the provider. For example, if the terrain model in the globe changes, maybe because there is a more accurate model available, the 3D building objects might not fit to the terrain data anymore. The same problem exists in terms of accurate geo-referencing of ortho-photos. As an application/data provider linking content to a virtual globe there is always a dependence on the data of the globe. However, if the virtual globe API is providing the possibility to control/add most of the data from outside (terrain, ortho-photos, 3D buildings, etc.) this problem is not as severe but the virtual globe is then used more or less as a rendering tool.

In terms of visualization and analysis it would also be possible to generate data framework modules that produce output formats for GIS or CAD systems, e.g. shp or dxf. So there are many possible ways to use these models. In regards to BIM and the integrated visualization of high detail build-

ing models and a low detail large scale overview models of a city, the visualisation tool should be capable of providing both types of information. For both types of data, BIM and 3D city model, it would be essential that the visualization tool is capable of providing access to the attribute data and to visualise semantics in an appropriate way. BIM and 3D city models provide a vast amount of additional information about objects and features that need to be provided to the user. A simple rendering of the visual appearance would not be sufficient. In order to make this additional data available the data in the visualisation tool also needs to keep some kind of object structure and to provide IDs for the specific objects. This issue has already occurred for the current version of the VEPS 3D client component using a VRML viewer. In VRML there is no explicit object structure or semantics in terms of urban modelling. Therefore it raises the question: are there better data formats to use in order to transmit 3D data to the client side 3D component? The issue about CityGML is that it cannot be used instantly for rendering and needs to be parsed first. This might be a lot of work for a thin client on a website, especially when it comes to very detailed BIMs. The issue of client-server

communication for a possible extension of the VEPS tool needs more investigation and cannot be answered completely at the moment.

For a seamless transition between the BIM scale and the city model scale, a powerful and flexible data framework would be necessary in order to provide the appropriate information for the specific scales. This transition between the data scales can be done in different ways. One could think of an automatic way that mainly works like a distance sensitive LoD switch. If the user moves very close to a specific building more and more data for this specific building is loaded into the viewer until the full BIM is loaded and accessible. This would also include some investigations on which content is streamed at which user distance and to evaluate a sensible distance mark for the whole dataset to be loaded. One other possibility would be that the user navigates in the 3D city models scene and actively selects building objects that should be loaded in detail. Both approaches have to be supported by flexible data management on the server side in order to be able to request/stream the appropriate data. They all need to include a mechanism to unload the detailed data when the building loses focus and to return to the 3D city model scale. It would certainly not be possible to provide BIM scale information for a whole city; on the other hand information for one building on city model scale would not be sufficient for certain applications. Therefore a seamless transition including the capability to request the appropriate data fast and efficiently is very important when it comes to integration of BIM data and 3D city models.

5 CONCLUSION

The GIS industry has been adding 3D capabilities to the original 2D representation of spatial data to do 3D representation as well as 3D analysis. This is normally at the city scale but may be at the regional or national scale. However, BIM is

adding the information sharing, analysis capabilities to the 3D CAD industry. If we see the effort from GIS industry as macro-scope of 3D capacity enhancement, BIM is a micro-scope of 3D information analysis improvement, which mainly stores, retrieves and analyses in-depth building feature information such as windows, doors, roof, and floor features etc.

Integrating these two technologies enhances their functionality for most of the user-groups of these two technologies. Building scale model users such as estate agents can easily look for a holistic view of the whole surroundings and make more accurate estimation of house prices. While in urban scaled scenarios, such as an urban regeneration or public participation scenarios, both planners and public participants can overview the whole region under consideration and query information with regards to the whole area, such as population and employment conditions, as well as getting the information about a specific building which might be an important landmark of the area or a special construction project carrying on in the area.

From the discussion in this chapter, it is clear that both system development technologies (such as web/Internet based development technologies) and data model standards such as IFC/CityGML etc. enables a great future for integration of BIM and large scaled GIS technology. The integration of these two technologies must be developed further in some way, as they are working on the same issue just coming from different domains i.e., providing information on urban space. This integration will be important for everyone who is working on more sophisticated solutions for urban space development and enhancement.

However, there are still issues such as accuracy that researchers need to focus on. For example, when loading your own model into Google Earth, you have no control of the accuracy of Google Earth terrain models and the final representation of the data will have to rely on the stability of the data on Google Earth. Other issues are the interface development for the integration of information

and graphical models, visualization and analysis systems. Specifically, in the public participation domain, a user-friendly interface makes it easier to involve a wide range of stakeholders. These are all in the authors' future research agenda.

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KEY TERMS AND DEFINITIONS

Building Information Model (BIM): Building Information Model is a digital representation of physical and functional characteristics of a building often based on CAD models. Construction and management of buildings and building-elements

involves many stakeholders. A BIM provides for one logical place for all actual building project data (objects with attributes & interrelations, 3D representations, visualisations etc.) which relevant stakeholders can share and manage during the entire lifecycle of a building.

Geographic Information System (GIS): An information system, which allows storing, managing, reorganizing, visualizing and analysing geographical data. GIS is a 'smart' digital map system. A major aspect of a GIS is the ability to execute queries on the data that normally includes a spatial or location aspect.

Geography Markup language (GML): A mark-up language based on XML. GML schema definition is developed by the Open Geospatial Consortium (OGC) and becomes an ISO standard. GML can be used to define spatial objects (features) with their geometry, attributes and relations and is intended to be an open format for the exchange of geospatial features between systems.

CityGML: CityGML is an extended GML schema for the representation, storage and exchange of virtual 3D city models. CityGML models geo-referenced 3D vector data and the semantics associated with the data. It is also extensible to further enrich the data. CityGML has been adopted as an official OGC Standard from its version of 1.0.

Industry Foundation Class (IFC): A data model which can be used to model attribute- and meta-information related geometry objects. IFC is defined by the International Alliance for Interoperability (IAI) and is also an ISO standard. This data model focuses more on single buildings in their entire complexity (windows, doors, supply lines, etc.) and to model all the different parts with their specific attributes. IFC is mainly used in order to exchange data between construction software.

IFG: IFG = IFC for GIS which provides geographic information within the framework of the IFC or vice versa for Interoperability. The

key of IFG is the integration of GIS information with individual buildings information. The IFG bridges between system on building level and GIS systems.

VEPS: Virtual Environmental Planning Systems, an EU research project from 2004-2008 funded by INTERREG IIIb. VEPs developed and demonstrated interactive, 3D web applications to help people understand proposed planning developments and share their views about them online. One major aspect was the integration of virtual 3D models into the participation process in order to support decision makers and citizens in making judgments about the planning proposals.

OGC Web Service: includes WMS, WFS, W3DS, WCS - the OGC web services are defined in order to provide open standard interfaces in order to exchange geospatial data between systems. The various services provided fulfill specific tasks: one of the most prominent ones is the Web Map Service that can be used to query map data (images) from a server. Because the definitions are publicly available, they can be used to link systems and are a popular way to generate 'geospatial mash-ups'.

Chapter 17

BIM Integration with Geospatial Information within the Urban Built Environment

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ABSTRACT

In the construction industry, BIM is enabling the information sharing and integration practise culture to emerge. Consideration of the geo-location is essential at the design and planning stage for building construction. It is important to integrate BIM with surrounding geo-spatial information which will not only benefit the construction industry in getting site information, but also help urban management in getting building details in the city. This chapter reports the emerging efforts on BIM integration with geospatial information within the urban built environment. The authors have been working on the design and development of the integration framework of BIM and geospatial information. In this framework, a BIM web service, Building Feature Service (BFS), is defined to retrieve building objects and elements information based on OGC's Web Service. This framework can extend the scope of BIM to the urban built environment to support life cycle information services for both city management and the construction industry.

1 INTRODUCTION

In the construction industry, Building Information Model (BIM) is enabling the information sharing and integration practise culture to emerge (Pressman 2007). Research and development work has been carried on using BIM to improve information flow for construction projects to enable better product

quality and value for money investment. In previous chapters of this book, the concept of BIM has been defined and the BIM's impact on facilitating information exchange and interoperability in digital format during the entire building lifecycle has been discussed from different perspectives. However, considering the context of construction sites (e.g. location, traffic etc.) is essential at the design and planning stage of the building life cycle.

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The AEC and real estate worlds often need to use building information in the context of map layers such as the cadastre, communications, demographics, environmental hazards, land use and zoning, land cover, soil, transportation, utilities, hydrography and elevation (Bacharach 2006). Actually, on the one hand, all construction industry (e.g. BIM) benefits from the geospatial context; on the other hand, the geospatial domain also benefits from the construction industry.

From the urban management perspective, urban built environment includes not only the building information but also the surrounding environmental information in order to meet the needs of sustainable development, maintenance and facility management in urban context. Since buildings are the most important elements in the urban environment, most urban planning tasks are closely related to buildings. To make holistic decisions, there is an increasing need to seamlessly integrate the relevant datasets at both building and urban scales.

BIM can be seen as the effort from construction industry of information sharing and integration for building life cycle. To extend the scope from building life cycle into a wide urban built environment, it is necessary to include relevant urban context information. Research shows 80% of municipal information could be geo-referenced (Stillwell 1999; Lemmens 2001). Indeed, geo-location is often the only factor that different urban datasets have in common. Geospatial Information (GI) provides the structure for collecting, processing, storing and aggregating various datasets.

Therefore, seamless integration of building and geospatial information will be able to benefit both construction industry and the urban management. It helps with design visualization and coordination, owner/tenant communication, construction sequencing, energy simulation, traffic/egress simulation, facility management and other activities. Emergency and disaster management also requires the ability to share data across organizations at all levels (Bacharach 2006).

This chapter will present our research efforts on extending single building BIM to urban BIM which includes buildings and surrounding urban context. The focus will be on the integration of BIM and geospatial information. The contents of this chapter is organised as following: In section 2, the BIM and urban built environment are introduced. In section 3, the relevant work in BIM and Geospatial Information System (GIS) integration is introduced. Section 4 describes the design of BIM and geospatial information integration framework. In Section 5, a BIM web service, Building Feature Service, is defined within this integration framework. Section 6 introduces the prototype implementation based on this integration framework. The research work carried out by the authors is summarised in the final part of this paper.

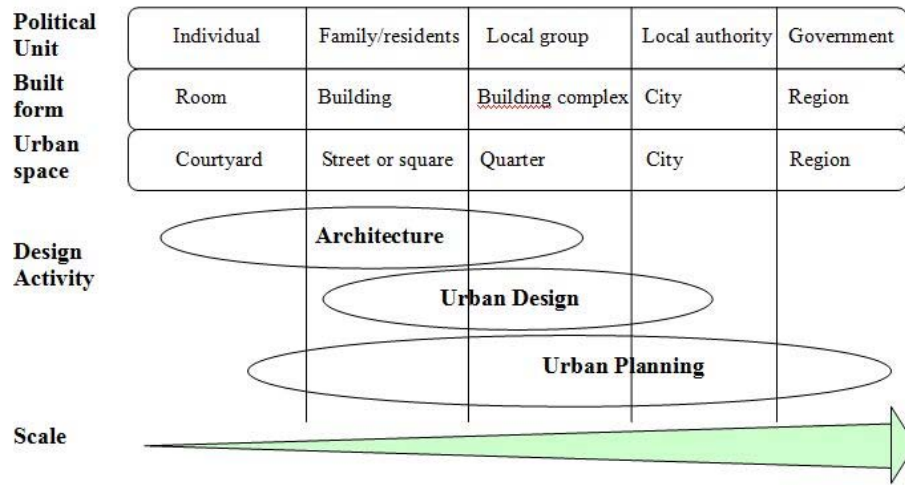
2 BIM AND GEOSPATIAL INFORMATION IN THE URBAN BUILT ENVIRONMENT

Building Information Modelling can be seen as the latest generation of Computer Aided Design (CAD) systems in which all of the intelligent building objects that make up a building design can coexist in a single ‘project database’ or ‘virtual building’. A Building Information Model (BIM) provides a single, logical, consistent source for all information associated with the building (Howell 2003). To extend the scope from building scale into the wide urban built environment, it is essential to consider the relevant geospatial information in the context of the urban built environment.

2.1 Urban Built Environment

The urban built environment consists of the man-made surroundings ranging from the large-scale civic surroundings to the personal places in an urban area. The creation or modification of urban built environments that are socially acceptable,

Figure 1. The scale of urban built environment (adapted from Roberts, 2001)



economically affordable and environmentally sustainable, pose an immense challenge for planners, architects, developers, engineers and other professionals. Figure 1 shows the scope of the urban built environment and design activities.

2.2 CAD and GIS: Two Types of Systems for Urban Built Environment

Two main categories of systems used to describe urban built environment digitally are GIS and CAD. This section will generally introduce and compare these two systems.

2.2.1 CAD and GIS

CAD and GIS software systems have evolved independently but in parallel over the past 30 years. The aim of both of them is to model the real world, but each one does this by its own way. Historically, CAD and GIS have been developed as solutions to different problems in different domains — the former optimized for the modeling of new but well-defined objects; the latter for the reconstruction of existing objects about

which only spare and incomplete information is available (Oosterom 2005).

Computer-Aided Design (CAD) systems originally have focused on automating the drafting process with electronic drawings. The CAD applications represent 2D/3D geometry via graphical elements, such as lines, arcs, symbols, etc. In the last decade, CAD technology has experienced the shift from 2D drafting to 3D modelling. 3D CAD focused on creating geometry in support of visualisation, and subsequent advances concentrated on creating realistic rendering and lighting effects. Today CAD, is not limited to drafting and rendering and ventures into use standard methods for describing data, being semantically richer and based on the object-oriented paradigm. BIM support is becoming the feature for the state of art CAD technologies in construction domain. Currently, most of CAD vendors begin to support file import/export from its own proprietary data formats into a standard format (e.g. IFC). However, the data exchange and sharing is still main document-based and most of CAD models are stored as files in a file system (Oosterom 2005).

Geographic Information Systems (GIS) is a system for capturing, storing, analyzing and

managing data which are referenced spatially with the earth. GIS software systems have more formal data models with rule-based editing and topology as well as an emphasis on spatial analysis and high-end cartography. GIS data is stored and managed in databases. The information can be altered, changed or edited to allow the information to best fit the requirements. The evolution of GIS over the last few decades has seen the trend towards 3D GIS, Mobile GIS and Web GIS. Especially, OGC has been leading the efforts on geospatial information and service standardisation which will be introduced in the following section. With its powerful capacity for spatial data management, spatial analysis and graphic visualisation, nowadays GIS has been widely used to support a wide range of applications.

2.2.2 CAD/GIS Integration

There are increasing needs for an integrated CAD and GIS functionality since both systems are used throughout the life cycle of the same set of objects. It is important to understand the relevant urban context during the planning and design stage of a building construction project in order to help planners and developers to make effective decisions regarding the nature of the development and its location, including impacts on local environments and communities. For example, geospatial information can be used for designing new buildings, i.e. to see how a new building will fit in with its immediate surroundings and what this will look like. Furthermore, the building structure details and any changes to existing buildings should be recorded by cities and combined with geospatial information for purposes like fire escapes and disaster management etc. Typically, facilities management could be positioned somewhere between the CAD/GIS, and future solutions will need to borrow from both, particularly the ability to handle large databases and seamless mapbases from GIS and the design capabilities of CAD (Oosterom 2005).

CAD designers have been frequently confronted with the request to provide the means to link small scale mapping to newly designed construction models. Also GIS users more and more often use tools available in AEC systems to reconstruct and edit large-scale, realistic 3D models (Zlatanova and Prosperi, 2005). In most of current geo-information sources, the description of building features only includes 2D building footprints (with building heights sometimes). Geo-information based visualisation is generally limited to 2.5D which is not particularly impressive for either professionals or the public. Many realistic 3D city models have been developed by integrating CAD, GIS and other data sources together (Jepson 2001; Yao 2003). However, these city modelling methods focused on rendering and visualisation, little attention has been paid on the semantic information presentation and users can not get the feature level information (Zlatanova 2002; Kolbe 2005).

Currently, if users wanted to integrate CAD and GIS to be able to bring data into either environment, the commonly used approach is file transfer which converts data from one data format to another. However, information loss, constraints of data synchronization and integrity may be difficult to manage also costly. The ability (or inability) to integrate CAD and GIS data into a seamless information flow with rich semantics is a longstanding and ongoing problem in spatial information management (Bacharach 2006).

2.3 Geospatial Information and its Sharing & Interoperability

Various GISs have been developed to analyse, process, and manage spatial data using proprietary storage formats. The integration or conversion of geospatial information is resource intensive. There have been continuous efforts to integrate multiple sources and multiple formats geospatial information within geospatial community (Garton 2001; Butenuth 2003; Reed 2005). The Open GIS

Consortium (OGC) is making particular efforts to overcome these problems and to develop implementation specifications for the interoperability of the spatial data. This section will introduce the OGC's GML/CityGML standards and OGC's Web Service (OWS).

2.3.1 Geospatial Information

In a broad sense, Geospatial Information (GI) can be any type of data that has an explicit reference to a location (Berhardsen 2002). In order to efficiently organise GI, GIS usually classifies geospatial data into layers (Heywood 1998; Berhardsen 2002). One layer usually stores only one kind of object, such as parcel, river, or buildings etc. A geospatial data model is defined to manage geographic information either as a collection of files in a file system or as a collection of tables in a relational database management system.

In the geospatial world the focus is on depicting things in the real world as points, lines, or polygons and their attributes (information about those objects). Traditionally geographical data models have been divided into raster and vector data models (Longley 2001). The vector data model uses points and their x-, y-coordinates to construct spatial features of points, lines, and areas. The raster data model uses a grid and grid cells to represent the spatial variation of a feature. The non-spatial attribute data provides descriptive information like the name of a street, the owner of a building.

2.3.2 OGC and GML

The Open Geospatial Consortium (OGC) (<http://www.opengeospatial.org>) is an international organization promoting the interoperability and sharing of geospatial resources and services in the distributed environment through the development of consensus-based standards and implementation specifications. OGC standards and specifications are widely used by geospatial communities for

sharing data and resources and some of the specifications are becoming ISO standards.

In order to support the sharing and interoperability of GI, OGC has defined a framework 'OGC Reference Model' and a series of specifications to implement interoperable solutions and applications for geospatial services, data, and applications. OGC Web Services (OWS) (the standardized interfaces of spatial web services) and OGC's CityGML (a 3D city model standard) will be introduced in the following sections.

Geography Mark-up Language (GML) was defined by OGC and is commonly recognised as a geo-spatial data exchange standard to enhance the data sharing and interoperability between applications. GML is based on OGC's Abstract Specification which has been developed and agreed to by the vast majority of all GIS vendors in the world. It describes the world in terms of geographic entities using the concept of 'features'. Essentially a feature is nothing more than a list of properties and geometries. Properties have the usual name, type, value description. Geometries are composed of basic geometry building blocks such as points, lines, curves, surfaces and polygons. A feature can be composed of other features. The geometry of a geographic feature can also be composed of many geometry elements. A geometrically complex feature can thus consist of a mix of geometry types including points, line strings and polygons.

GML is a powerful new way to look at spatial information using XML encoding. It promises, however, much more than a mere encoding standard. The inherent transformability and accessibility of GML will open a whole new domain in geo-spatial information management.

2.3.3 OGC's Web Service

Web services are self-contained, self-describing, modular applications that can be published, located, and dynamically invoked across the web (ISO 2001). Web services provide access to sets

of operations accessible through one or more standardized interfaces.

OGC's implementing specifications for standardizing the interfaces of spatial web services are called OGC Web Services (OWS). OWS is an evolutionary, standards-based framework that will enable seamless integration of a variety of online geo-processing and location services. OWS will allow future applications to be assembled from multiple, network-enabled geo-processing and location services (Schilcher, 2005). Some basic Web services were specified by OGC, as services applied to registry, composition, visualization and codification. The main and relevant OWSs are described below (Davis 2005).

- **Web Feature Service (WFS):** provides an interface for the insertion, selection, updating and removal of geographic features (objects). GML is the default encoding for transporting the geographic features, but other formats can also be supported.
- **Web Coverage Service (WCS):** supports electronic interchange of geospatial data as "coverage". It provides available data together with their detailed descriptions; allows complex queries against these data; and returns data with its original semantics (instead of pictures) which can be interpreted, extrapolated, etc. -- and not just portrayed.
- **Web Map Service (WMS):** a service for the production of static maps over the Web. Maps, in this service, are mostly rendered in a pictorial format which do not include the actual geographic data or occasionally as vector-based graphical elements in Scalable Vector Graphics (SVG)
- **Web 3D Service (W3DS):** a service for the production of 3D scene graphs over the Web. 3D models will be rendered and explored in real time by any Web client. W3DS merges different data layers in

one scene graph using VRML or optional X3D.

2.3.4 CityGML

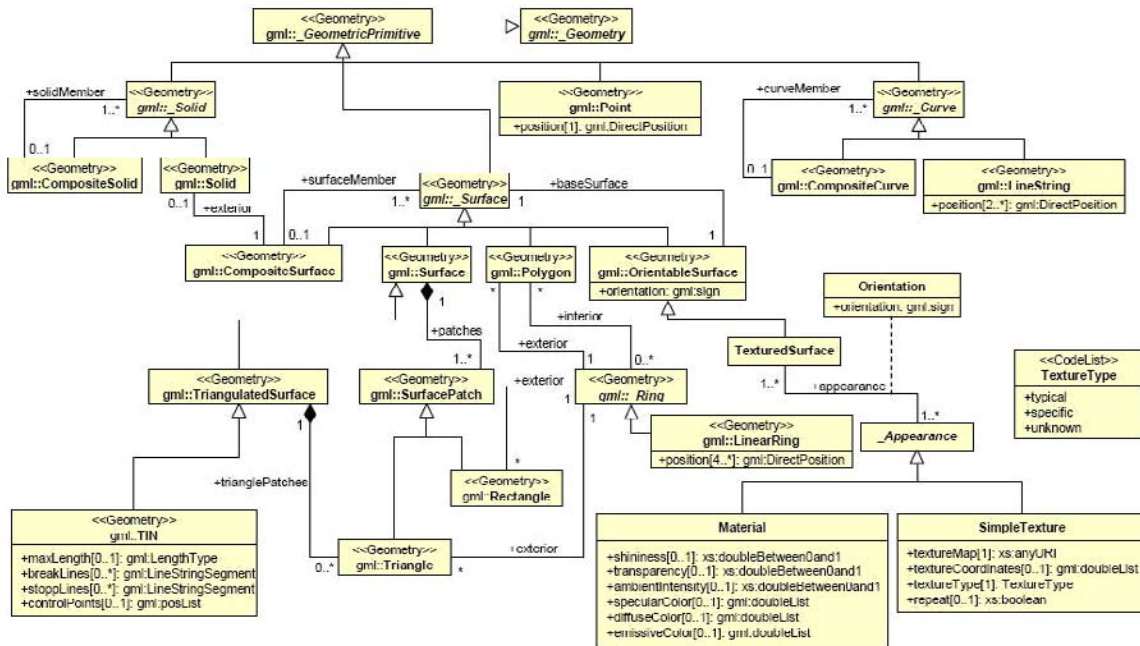
CityGML is a 3D city data model developed by OGC's Special Interest Group 3D (SIG3D) from North-Rhine Westphalia (NRW), Germany (<http://www.citygml.org/>). CityGML is an application scheme based on OGC's GML 3.1. In August 2008, CityGML has been approved as a 3D city model standard by OGC.

CityGML not only represents the graphical appearance of city models but especially takes care of the representation of the semantic representation, thematic properties, taxonomies and aggregations of digital terrain models, sites (including buildings, bridges, tunnels), vegetation, water bodies, transportation facilities and city furniture (Kolbe, 2005).

The ability of maintaining different levels of detail makes it suitable for small and large area utilizations. The underlying model differentiates five consecutive levels of detail (LoD), where objects become more detailed with increasing LoD, both in geometry and thematic differentiation (Kolbe 2006);

- LoD0: a two and a half dimensional Digital Terrain Model (DTM), over which an aerial image or a map may be draped.
- LoD1: block models, without any roof structures or textures.
- LoD2: buildings have differentiated roof structures and textures. Vegetation objects may also be represented.
- LoD3: detailed architectural models with wall and roof structures, balconies, bays and projections. High-resolution textures can be mapped onto these structures. In addition, detailed vegetation and transportation objects are components of a LoD3 model.

Figure 2. CityGML UML geometry model, <http://www.opengeospatial.org/standards/citygml> (OGC 2008). Copyright © 2008 Open Geospatial Consortium, Inc. All Rights Reserved. <http://www.opengeospatial.org/ogc/document>



- LoD4: “walkable” architecture model with LoD3 modelling features plus interior structures like rooms, interior doors, stairs, and furniture.

The following summarises the CityGML geometry model and theme model.

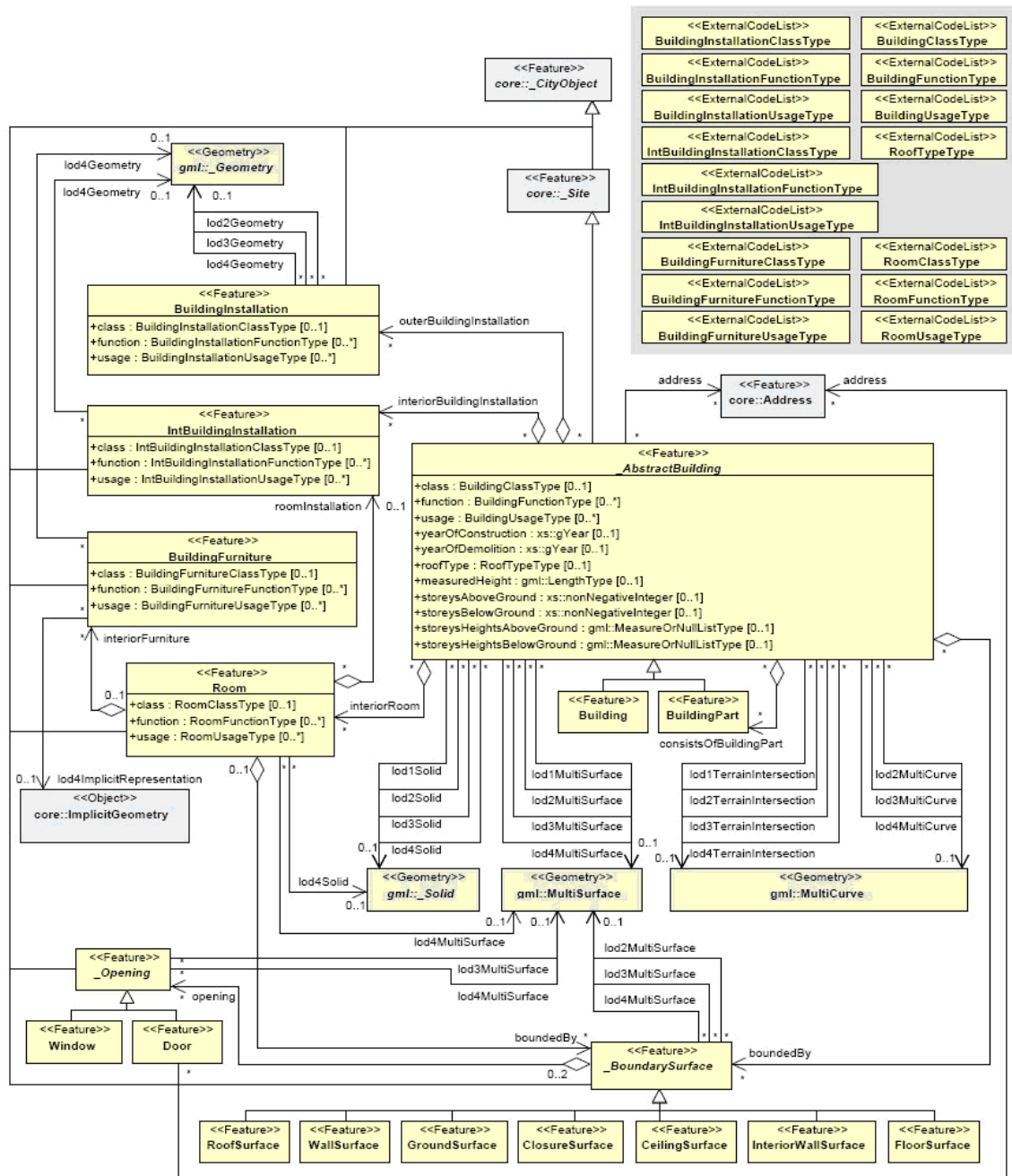
The CityGML geometry model is derived from OGC GML specification 3.1.1. It uses the GML elements `gml:Polygon`, `gml:CompositeSurface`, `gml:CompositeSolid`, `gml:Solid` and `gml:Surface` to describe three dimensional objects. At present, the geometry model does not make use of GML’s topology model (`gml:topology`) which would allow for accelerating computational geometry. CityGML extends the GML3 geometry model by adding concepts for representing textures and other material properties of surfaces as shown in Figure 2.

The building model is the most detailed thematic concept of CityGML (OGC 2008). As

described in last section, CityGML maintains five consecutive levels of detail (LoD) while the representation of thematic and spatial aspects of buildings, building parts and installations are mainly in four levels of detail: block models (LoD-1), geometry models (LoD-2), architectural models (LoD-3), and interior models (LoD-4). Detailed building information can be accommodated into a CityGML-based virtual 3D city model. The UML diagrams (Figure 2 & 3) provides an overview of the building model in CityGML.

As discussed in this section, OGC has pushed forward a series of standards to advance the concept of open standards and interoperability. Actually, GIS domain is quite a few years ahead of CAD world in terms of open standards and interoperability (Oosterom 2005). These OGC efforts in geospatial technologies could be brought into the larger information technology world. Incorporating BIM into geospatial web services architecture could be beneficial to the manage-

Figure 3. Building model in CityGML, <http://www.opengeospatial.org/standards/citygml> (OGC 2008). Copyright © 2008 Open Geospatial Consortium, Inc. All Rights Reserved. <http://www.opengeospatial.org/ogc/document>



ment of urban built environment and help the advance of open standard and interoperability in CAD world.

3 EMERGING EFFORTS IN BIM/GIS INTEGRATION

As discussed in other chapters in this book, IFC are capable of modelling much attribute and meta-information related to the geometry and supports the vision of BIM. With the rapid growing use of BIM in construction domain, the integration of CAD/BIM and GIS is pursued by different stakeholders in order to benefit from the information sharing and interoperability across from the construction and urban domains.

3.1 BIMStorm Build LONDON Live

In the “BIMStorm Build LONDON Live” event (<http://www.buuildlondonlive.com/>), the teams across the world worked collaboratively for a completely mixed urban re-development of Greenwich Peninsula, London. Some design criteria has been set up regarding the mixed development in this area like office space, dwellings, retail and entertainment facilities etc. The principal author has been involved in this event as an observer.

The participants are given access to the Onuma Planning System (OPS) and the Asite Collaboration system (Asite cBIM).

OPS, developed by ONUMA, was employed as a BIM -Model Server. The Model Server uses the open standards of the web to make the entire BIM accessible to users, eliminating the need of downloading the entire BIM and then opening it in client applications, i.e. an unwieldy process at best. OPS provides strong support for many open standards like IFC, KML, CityGML. It can store data about projects from early planning through design and then into lifecycle and portfolio management. Data such as municipal GIS and parcel data and analysis data can be also

translated and imported into the Model Server to be used by BIMStorm participants. OPS can create IFC, Google Earth and other files on the fly. Once exported from OPS, the standalone files can be edited in desktop applications (Microstation, Revit etc.) and imported back to OPS or exported to other applications.

Asite cBIM can act as the central repository for all design data, the workflow tool to manage all team interactions, and handle real-time updates to the desktops and email inboxes of participants and observers throughout the collaborative process.

The combination of these two systems and their ability to work with open standards as well as document management through the web allows for real time collaboration among teams.

3.2 OGC/Building SMART Collaboration Projects

Open Geospatial Consortium (OGC) has worked with IAI/BuildingSMART in two test-bed projects, aiming to tackle GIS and CAD cross-domain information integration and interoperability issues.

The OGC’s OWS-4 project and testbed definitely proved the feasibility of merging CAD, GIS and BIM data. In 2006, OGC started an initiative for gathering requirements and defining OGC Web Services (OWS) that integrate information resources and workflows from the world of Architecture Engineering and Construction (AEC) with the geospatial world. While the geospatial world has typically concerned itself with information about the outdoors, and largely two or two-and-a-half dimensional information as would be found in maps, images and terrain models, there are many assets and activities that occur in the three dimensional context of buildings. Integration of the information resources of the AEC world with geospatial world will provide very important information resources for decision makers in urban environments, in situations like disaster management. A testbed experiment described where a CAD/GIS/BIM client editor will

combine the information obtained from multiple OGC web services for responding to a disaster scenario (Lapierre and Cote 2007).

Another on-going OGC's test-bed project, Architecture, Engineering, Construction, Owner and Operator (AECOO), represents the beginning of a cooperative environment where AEC and geospatial standards organizations can jointly promote rapid standards development, testing and validation. In 2007, OGC, BuildingSMART and National Institute of Building Sciences of USA etc. began to work together in addressing issues of geospatial and AEC information convergence (<http://www.opengeospatial.org/projects/initiatives/aecoo>). A testbed is designed to support business transformation as defined in the US National Building Information Modelling Standard (NBIMS) by applying technology for interoperability involving intelligent building models with 3D geometric capabilities. The AECOO testbed is a global, hands-on and collaborative rapid prototyping project designed to develop and deliver proven candidate standards. The first phase, AECOO-1, was kickoff of in July 2, 2008 and is focusing on documented ways to interoperable integrate early-stage (http://www.geoconnexion.com/geo_news_article/OGC-AECOO-Testbed-off-to-good-start/3715).

3.3 ByggSøk Project in Norway

The ByggSøk project (<http://www.xn--byggsk-fya.no>) in Norway has deployed a building zoning and permitting service that allows interoperability between the BuildingSMART and OGC standards based applications and information distributed across government agencies throughout the country (Rooth, 2005). The vision is to deliver better and more efficient public services and improve the industrial competitiveness by nationally standardizing zoning proposals and building applications.

ByggSøk consists of three modules: an information system, a system for submission of building

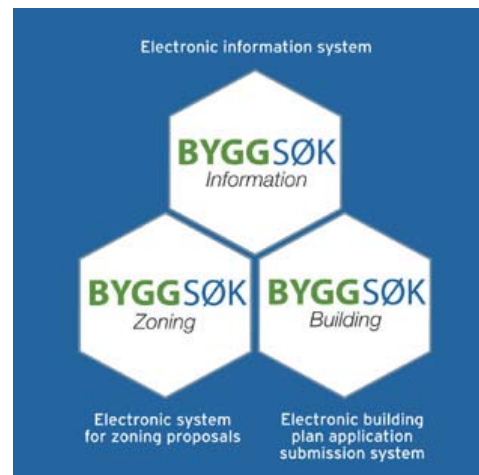
applications and a system for zoning proposals as shown in Figure 4. These systems are designed to encourage more efficient processes, for both the private and public sectors. Use of ByggSøk is free of charge to the public and local governments. Local authorities all over Norway then started to receive applications submitted electronically. The electronic e-submission system is shown in the Figure 5.

ByggSøk Information is a system for information required when preparing a plan or application. All 431 municipalities in Norway are offered the opportunity to publish information on a joint website related to zoning and building. ByggSøk Information provides general and municipality-specific information related to zoning plans and building applications.

ByggSøk Zoning serves as a basis for communication between developers and local governments. This module provides a forum for developers to enter into dialogue with local authorities early in the zoning process. The system for submission of zoning initiatives has been available since January 2005.

Building applications are registered via the Internet. The applicant is guided through an application process customized to the matter concerned, and receives assistance during the process. Once

Figure 4. ByggSøk systems



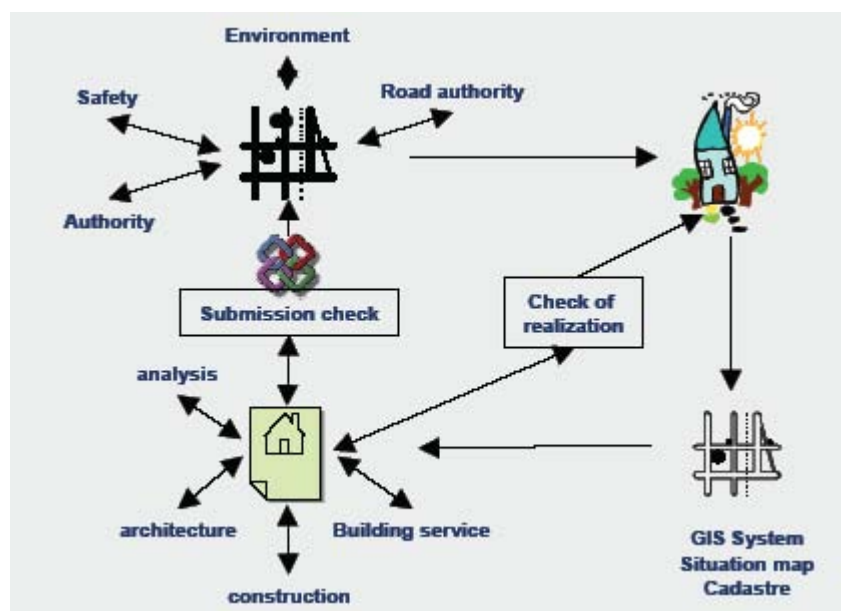
all the information has been entered, the content is checked. If the application is complete it can be printed or submitted electronically to the local authority. Applications will be more correct, saving local authorities and the applicant time and money.

Norway has been playing a leading role in promoting the BIM application and GIS/CAD/BIM integration. Norway has been worked closely with BuildingSMART (IAI) to map the IFC building data scheme to zoning and planning data in Norway's geographic information systems. Their collaboration project, IFC for GIS (IFG), worked on the development of capabilities to capture GIS information via the Industry Foundation Classes (IFC) information model. The outcome of IFG project became the part of IFC standard and fed into ByggSøk's regulatory information and permitting e-submissions system. The IFC-GIS tool can be used to automate checks of zoning submissions of IFC-compliant models. The ByggSøk brings together geographical data and factual information

about the physical environment, as well as zoning regulations from local governments.

The above sections have reviewed recent developments in BIM/GIS integration. BIMStorm addresses the collaborative planning and design issues mainly from the construction point of view. The OGC/BuildingSMART collaboration projects aims to develop and deliver proven candidate standards by exploring the cross-domain information integration and interoperability issues. Norway's ByggSøk project has tried to deliver better and more effective public services and to improve industrial competitiveness through central government; although the technology is not yet fully developed (Rooth 2008). However, this research and development has not focused on integration from the perspective of urban built environment management. More research is needed on how to incorporate BIM into geospatial web services architecture in order to be beneficial to the management of the urban built environment. In this research, the focus should be on extending

Figure 5. ByggSøk e-submission system (Rooth 2005). (<http://www.xn--byggsk-fya.no/english/english.php>)



the scope of BIM from a single building into the urban built environment, Urban BIM, in order to facilitate data sharing and integration across urban and construction domains using emerging web service technologies.

4 BIM AND GEOSPATIAL INFORMATION INTEGRATION FRAMEWORK

As described in the previous section, web service is quite popularly used in geospatial world. It could be beneficial to the management of urban built environment if BIM can be incorporated into geospatial web services architecture. This section will present a framework which can facilitate the BIM and geospatial information integration using web service.

4.1 Design the BIM and Geospatial Information Integration Framework

4.1.1 Design Considerations

This framework aims to support sharing and integration of BIM and geospatial information from different organisations and give users an integrated view of the diverse datasets. For the design of this framework, the following aspects need to be taken into consideration.

Data standardisation: BIM and geospatial datasets are from different sources and in different formats. There are many significant advances in data standardisation to address the data exchange and interoperability (Murray 2002; Wang 2005). The OGC standards have been growingly used for geo-spatial data sharing and integration (Craglia, 2003). IFC was defined as a building information standard in construction domain as discussed in previous chapters. The design of this integration framework should align with these widely accepted standards as much as possible. The relevant OGC standards have been discussed in

previous sections (e.g. the OGC's GML, OWS, and CityGML etc).

Data discovery mechanism: Datasets are owned by different organisations. Sometimes the other stakeholders even don't know what data sources are available. It is necessary for data users to access the data sources without knowledge of the details regarding its location, formats and data access methods. The data catalogue and metadata are very important component for data discovery. This framework should have mechanisms to access the metadata descriptions and services catalogue for data discovery.

Distributed service: BIM datasets are distributed in different organisations while the geospatial information is stored within local authorities. This drives demand for data service in a distributed environment. Implementing the data service in a distributed environment relies on the technical architecture adopted. Web services are flexible enough to allow one discipline to build its own specialized tools, but defined enough so that the basic enabling software works across organisations and domains. The OGC's Web service provides the definition of delivering up-to-date spatial and thematic data in a standard format from the source over the Internet using HTTP protocol. Therefore in this framework, the OWS will be extended to the construction domain to implement the web service for BIM.

On-the-fly Integration methods: Data users need the information not only to be accurate but also up to date. Tight integration physically combines all required information together for one specific application. This one-off method always incurs the high cost of acquiring and integrating the various datasets. Furthermore these kinds of combination will lose value once the specific application has finished. A generic solution should employ loosely-coupled integration system to let users logically refer to the required data in a distributed environment and allow the dynamic "on-the-fly" integration.

4.1.2 The Integration Framework

Based on these considerations, the open and flexible architecture for the integration framework was designed as shown in Figure 6. Two main technologies: mediating integration systems and web services were employed in the integration framework.

This framework is specifically designed for BIM and geospatial information integration which could present the urban environment with smaller scale and richer details. The significant advantage of this framework is that it can support integration by the mediating service. A common data model is used as a communication protocol between distributed data sources and the mediating service, and between the mediating service and clients. This framework uses Web service and

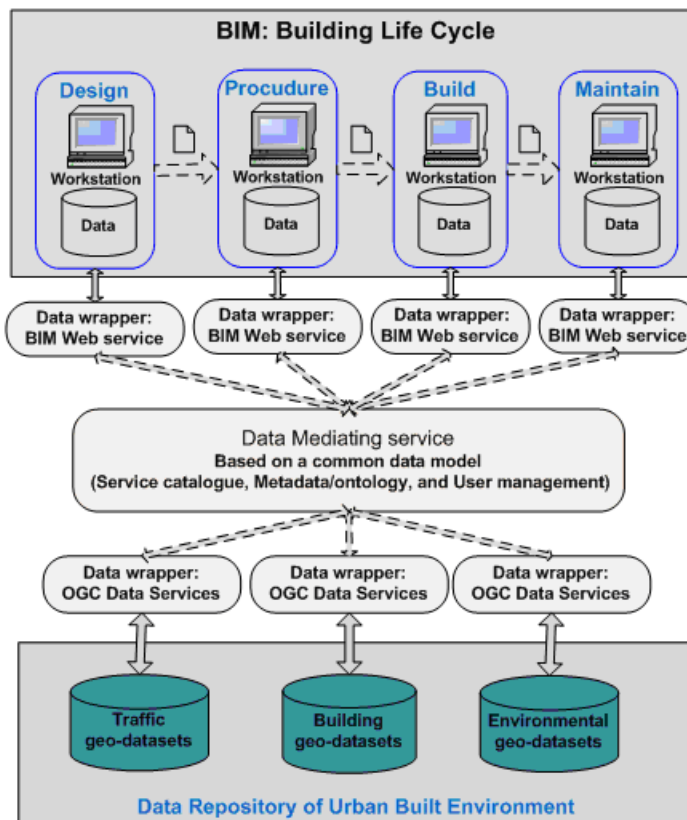
standardised data formats to model and transport information.

The geospatial information of the urban built environment could form a basic data repository for urban built environment. The BIM data at every stage of building life cycle can be internally created by relevant stakeholders in their own building model repositories. The traditional paper-based or file-based information exchange from one source to another source can be replaced by real time data sharing and integration using various web data services.

4.2 Data Wrappers

A data wrapper is a piece of software which supports data transaction service. A wrapper can update a data store, extract data from a data

Figure 6. BIM and geospatial information integration framework



store and provide the required information to the mediating service in a common data model. The wrappers encapsulate details of each data source, allowing data access using a common data model. One wrapper has to be developed for every different data source. Wrappers should be managed by data owners considering the close link with the data sources. Data owners can decide what kinds of data can be managed and accessed by different users. In this framework, the wrappers are developed as web service.

For geospatial data, the OGC's data service can be employed as a wrapper. The burden of developing wrappers is greatly reduced since the OWS is strongly supported by many commercial and open source GIS software packages. Web Feature Service (WFS) allows a client to retrieve and update geospatial data encoded in GML from multiple WFSs. A server that implements the OGC WFS specification can distribute geographic features to a client application. WFS can be invoked by submitting requests in the form of URLs (GET/POST requests) (OGC 2005a).

For CAD/BIM information, currently there is no standard implementation specification for web data service. The author defined a BIM Web service called Building Feature Service (BFS) which can act as a wrapper for building model. This is based on the idea of OWS's data service. The BFS can retrieve building features from CAD building models encoded in the common data model — CityGML or IFC. The detailed description of the BFS will be given in the following Section 5.

4.3 Common Data Model

Within this framework, data source heterogeneity is managed by wrappers which export a common view for each data source. This common view is supported by a common data model

A common data model can be seen as a virtual view of a number of data sources with their own internal models. This common data model is es-

sential to enable transformations of the inputs and outputs of different models so that models can be combined. In order to have a realistic level of data integration and data sharing, the common data model must be used as a basis for describing the information to be shared within construction and urban domains.

There is always an argument about which standard to follow or which new technology to use. In order to support the real time web service, XML is used as an exchange media which allows data integration and exchange in a more flexible and extensible way. The possible choices for the common data model are two XML-based data standards: CityGML and IFCXML. As discussed previously, CityGML is a standard 3D city model with rich semantic building information while the new version IFC2X4 has added geospatial information description in its building model.

4.4 Mediating Service

The mediating service is composed by web service mediators. A mediator is a software module that exploits encoded knowledge about some datasets to create information for a higher layer of applications (Wiederhold 1994). The mediating service can integrate the standard format from a collection of wrappers of various data sources and offer an integrated view of the data. This integrated view is supported by the common data model.

The mediating service also includes the description of data sources in the metadata/ontology repository and the description of data service in the catalogue of data wrappers. It also manages the information on user authentication. The descriptive and management information can reflect the needs of its potential users, but it does not maintain a database of objects.

Metadata (defined as data about data) describes existing data holdings, making it possible for people outside an agency or organization to access, search, and use data from these sources (Committee on Geographic Foundation Agenda

21, 2002). Metadata helps people know that what data exists and where data resides. For example, when making important land-use decisions, it is helpful to know where to find the needed geographic data.

The service catalogue describes the information of available data services. The service catalogue is required to support the discovery and binding to registered data resources within a cross-organisation environment. The OGC's Catalogue Service Specification defines common interfaces to discover, browse, and query metadata, services, and other potential resources (OGC, 2005b).

The mediating service dispatches user queries to the distributed heterogeneous data sources and assembles query results. First, the mediating service can receive a request from a client. Based on metadata and service catalogue, the request is decomposed into sub-requests to the wrappers of distributed heterogeneous data sources. The wrappers retrieve the requested information from data sources and send the query results back to the mediating service in a standard format. Then the mediating service assembles the query results and replies to the client with the combined result.

Since the common data model is XML-based, the assembly work is relatively easy which mainly includes the merging of XML documents. However, the despatch of a query is always a challenge for the development of mediators.

5 BUILDING FEATURE SERVICE – A BIM WEB SERVICE

In the above design of the Integration Framework, there is a need for a wrapper which can provide a web-based data service for CAD/BIM. Building Feature Service (BFS) is defined as a BIM web service by the authors based on the OWS principle.

5.1 From WFS to BFS

The OGC's Web Feature Services (WFS) interface specification is to provide a reputable structure and mechanism for the query and retrieval of geographic features (Reed, 2005). Users can obtain requested objects at feature level based on their specific working contexts. A WFS may optionally also support transaction which allows insertion/update/deletion of feature data. Using WFS, the data presentation and rendering are not controlled at server level. This provides some flexibility for users to decide the display contents.

However, WFS is designed for geo-spatial information. The digital building models have different geometric and semantic definitions from the building features in the GIS domain. The OGC WFS's operations for retrieving and manipulating geographic features can not be fully matched for building model handling. Therefore, the BFS has been created by the principal author. Current BFS development focus on retrieving building objects and transaction service is not supported yet. The BFS can then provide building objects information to users according to the common rules of WFS. Current BFS is in this research

The BFS can directly access building information sources which can be IFC/IFCXML files, OO building model database etc. It allows a client to retrieve building features on the Web. The exchange documents between client and the Web-based BFS server are XML documents which have detailed building and element descriptions. As discussed in Section 4.3, the two possible XML-based standards are CityGML and IFCXML (which have detailed building feature descriptions).

5.2 BFS Implementation Specification

The author defined the implementation specification as a standard interface of IFC building information model by referring to the OWS. At

present, the OWS only supports Internet hosting of the implementation of the Hypertext Transfer Protocol (HTTP) as a distributed computing platform (DCP). An HTTP Uniform Resource Locator (URL) is used to locate the online resource of each operation supported by a service instance. To implement BFS, the first task is to encode user requests in the form of URLs (HTTP GET/POST requests). This process is the same as OGC's WFS Keyword-value pairs (KVP) encoding. KVP means that parameters consist of name-value pairs in the form of "name=value" and the pairs are separated by the "&" character. The details can refer to the OGC's specification (OGC 2005a).

Several basic BFS operations are defined as:

- **GetFeature:** to serve a request, and to retrieve feature instances like whole building or building elements such as windows, doors.
- **GetCapabilities:** to describe its capabilities i.e. service metadata including which building features it can serve and what operations are supported on each building features.
- **DescribeFeatureType:** to request the schema description which describes the structure of any building features it can serve.

For BFS, the common parameters for all operations are URL prefix of web service name (BFS) and request version. Some parameter definitions have been changed to suit for the building model. The filter definition is modified to set constraints of user requests for the building model.

These three BFS operation are similar to OGC WFS. The following section will only introduce the GetFeature implementation specification as an example.

5.3 BFS GetFeature() Implementation Specification

The GetFeature operation facilitates servicing a request and retrieving feature instances like a whole building or building component parts such as windows, doors, from a BFS. A GetFeature request is processed by a BFS and an XML document, containing the result set, is returned to the client.

This operation is similar to the WFS's GetFeature specification (OGC 2005a). Because of the different natures of CAD model and GIS model, two changes have been made in BFS comparing to WFS. The bounding box parameters (BBox) of WFS are not suitable for building models. Instead, the parameter BLOD (Building Level Of Detail) is used. RESULTFORMAT parameter was added to specify the output document format currently having two choices: 0 (CityGML) and 1 (IFCXML). Based on the WFS definition and the characters of building model, the GetFeature is defined as in Table 1.

5.4 BFS Discussion

As discussed above, the BFS can work as a building information service from which users can retrieve building objects and elements information. There are two issues that need to be addressed here. One is the data source of the BFS. Another issue is the BFS's valuation both in urban and construction domains.

Since the information retrieved by BFS is not only geometrical information but also semantic information about buildings, the data sources have to be rich-information building model. The research efforts in the construction domain have led to the building model development from 2D drawing to 3D model into a 4D/nD building model. The BIM (in theory) provides a single, logical, consistent source for all information associated with the building. The IFC, as a standard data model, makes the building information sharing between

Table 1. GetFeature specification (Based on OGC's WFS specification)

URL Component	Optional / Mandatory	Description
REQUEST =GetFeature	M	The name of the BFS request.
PROPERTYNAME	O	A list of properties may be specified for each feature type that is being queried. Comma is used to separate the properties. A "*" character or the absence of a value indicates that all properties should be retrieved.
MAXFEATURES=N	O	A positive integer indicating the maximum number of features that the BFS should return in response to a query. If no value is specified then all result instances should be presented.
RESULTTYPE =[results/hits]	O	The resulttype parameter is used to indicate whether a BFS should generate a complete response document or an empty response document indicating only the number of features that the query would return. A value of results indicates that a full response should be generated. A value of hits indicates that only a count of the number of features should be returned.
TYPENAME	M	A comma separated list of feature types to query. If no value is specified that is to be interpreted as all feature types.
FILTER (Prerequisite: TYPENAME)	O	A filter specification describes a set of features to operate upon. The filter is defined as specified in the Filter Encoding Specification. If the FILTER parameter is used, one filter must be specified for each feature type listed in the TYPENAME parameter. Individual filters encoded in the FILTER parameter are enclosed in parentheses "(" and ")".
BLOD	M	BLOD is a positive integer which describes the Level of details (LOD) for building features. The LOD specification can refer to the CityGML which is used in our prototype. BFS mainly serves the LoD3 and LoD4 building information requests from CAD building model, since LoD1 and LoD2 building information requests can be served from WFS by assessing geospatial data.
RESULTFORMAT		The RESULTFORMAT parameter is a positive integer which indicates what format the result document should be generated from BFS. Currently, the two choices are: 0 - CityGML 1 - IFCXML

various processes and professionals possible and is most popularly used by BIM. At present, the possible formats of BFS data sources could be IFC/IFCXML files, OO building databases, any CAD models with semantic definitions etc. The BFS can be seen as a light-weight implementation for vision of the BIM in certain way.

BFS is defined as a web-based building information service which could be beneficial for both urban and construction management. On one hand, the BFS can convert building models from the construction domain into the large scale urban environment. It can act as a bridge between the construction and urban domains. Urban professionals can get more detailed and meaningful information about buildings. On the other hand,

the BFS can also provide building and construction information access and sharing among the different actors in the construction domain.

Actually, the geospatial world has seen a transition from file-based approach to database management system (DBMS) approaches and, more recently, service oriented architectures (SOA) in particular OGC Web Services. In contrast, "to date, CAD systems are still dominated by a file-based use, despite the fact that all modern CAD systems have connections to a DBMS" (Oosterom 2005). The BFS can be seen as an attempt to move the construction domain in this direction. The BFS can make the building information gathered in one stage of the building life cycle useful for the next stage.

6 PROTOTYPE IMPLEMENTATION FOR BIM AND GEOSPATIAL INFORMATION INTEGRATION

In order to demonstrate the concept of the integration framework, a prototype is developed. In this prototype, there are one common data model (i.e. CityGML), two types of data sources (i.e. surrounding geospatial data and a detailed building model) and three Web Service components (two wrappers and a mediating service). This section will introduce the implementation of BFS as a BIM wrapper first and then the implementation of the integration framework prototype.

6.1 BFS Implementation

A BFS implementation acts as the wrapper of the IFC building model. The BFS was developed as ASP.Net web service by using C# programming language based on the Microsoft .Net framework. In the implementation of the BFS prototype, the author worked on mainly generating a CityGML document with LoD3 building description from IFC building model. The three main tasks are manipulating IFC documents; coordinating transformation and geometry conversion; generating service output in CityGML/GML. The implementation diagram is shown in Figure 7.

For manipulating IFC documents, there are some toolkits like IFCsvr, EDM and EuroStep etc. In this prototype, the IFC document manipulation is implemented by using a freeware IFCsvr ActiveX component (IMS,2002). The main reason of choosing it is because it is a freeware and easy to be embedded in the development environment as an ActiveX components. The shortcoming is that ActiveX components can only be used in Microsoft's Window platforms.

The second task is to transform the building elements information from IFC to CityGML. The first transformation is from Local Coordinate System into the World Coordinate System of IFC buildings model. The transformation matrix can be calculated

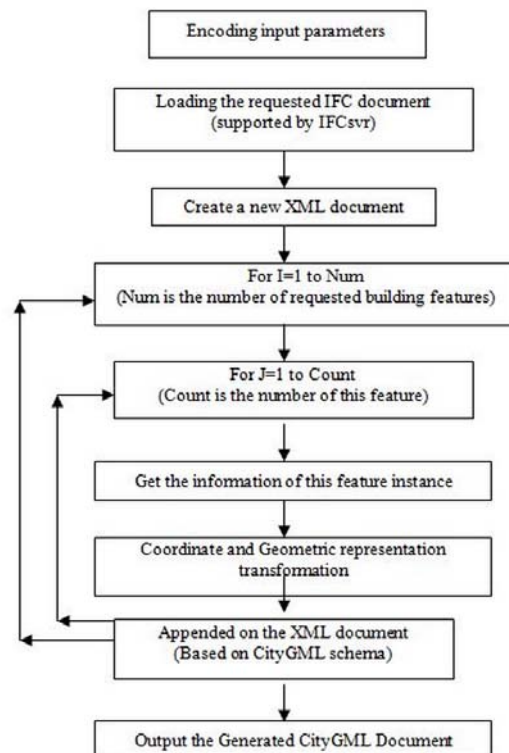
based on the relationship between these building elements, specifically in IfcLocalPlacement's PlacementRelTo and RelativePlacement attributes in the IFC document. The second transformation is from the geometric representation type in IFC into the geometric representation in CityGML.

An XML document is then generated based on the CityGML schema definition. The System.Xml namespace in Microsoft .Net framework provides standards-based support for processing XML files. It is fairly easy to call the relevant functions for generation of a XML documents based on CityGML schema.

6.2 Prototype Implementation

The CityGML is chosen as the common data model since it is a GML application schema with a detailed building model.

Figure 7. The BFS Getfeature() implementation process



The tested building model is an IFC document. The tested geo-spatial data is shape file which describes the urban objects like building footprints, roads etc. These data sources could be distributed in different computers or locations. The test geospatial data used is Ordnance Survey (OS) Land-Line data that covers a small area in east Manchester area. This Land-Line provides a detailed representation of the real world in its plan position (OS, 2003). The test building is Jactin House in the Ancoats of east Manchester. The Jactin House data was first captured by using a 3D laser scanner and was processed into an IFC building model (Arayici, 2005).

The three Web service components are one mediating service and two wrappers (one BFS and one WFS). The BFS is developed and acts as the wrapper of an IFC document as discussed in last section; Geo-server's WFS implementation acts as the wrapper of geo-information. The mediating service is developed to merge the query results (two XML documents) from the two wrappers. The mediating service receives a request from

clients or applications and returns the integrated information as a CityGML document.

Figure 8 shows the current implementation structure of the prototypes.

The following Figure 9 shows the integration results of the converted 3D building model (from IFC) and surrounding building footprints (from GIS) in a CityGML viewer.

7 SUMMARY

This chapter mainly presents the development of the web-based BIM and geospatial information integration framework in support to achieve the vision of Urban BIM. This integration framework employs the mediating loose integration method and OWS architecture. It can support the sharing and integration of geospatial information and building information across the building and urban scale. The BFS was defined to implement the retrieval of building information model on Web according to the OWS data service principle. The

Figure 8. The prototype architecture

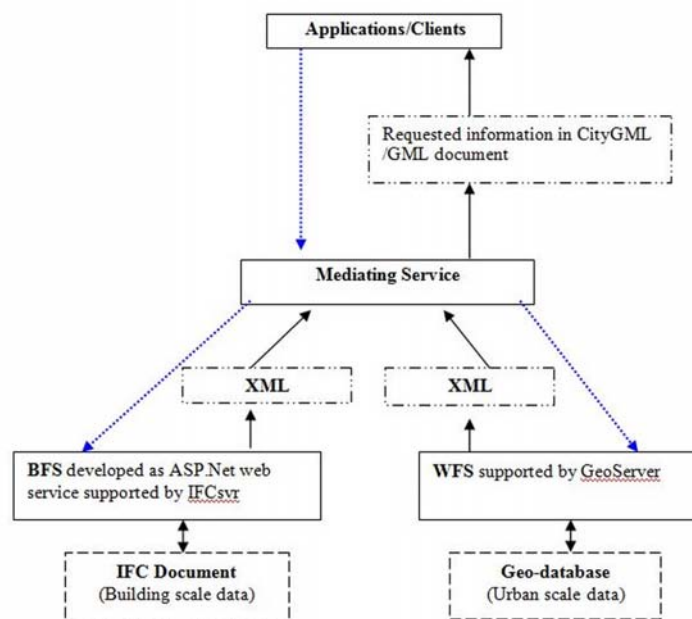
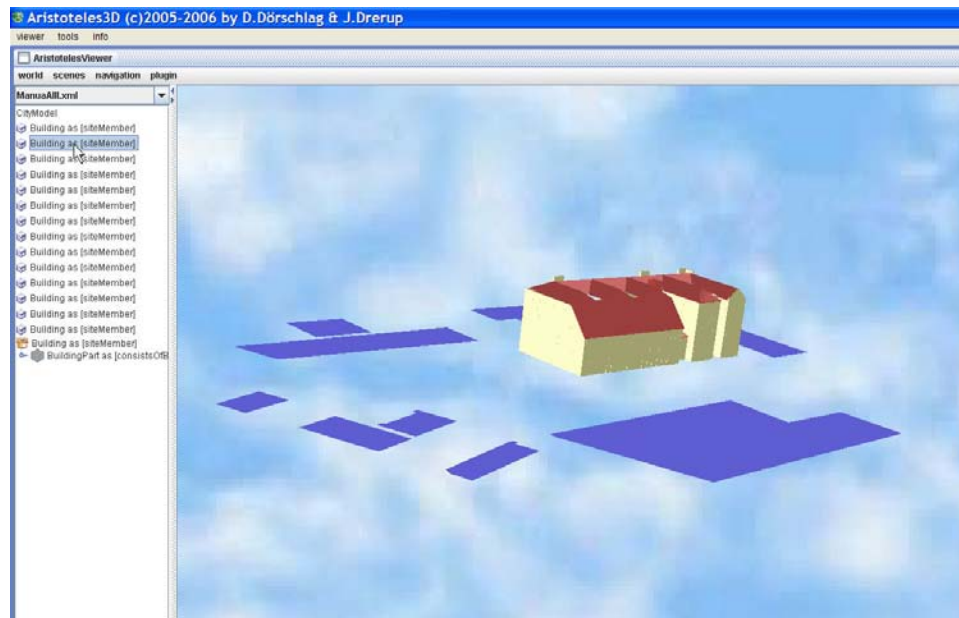


Figure 9. The integrated CityGML file displayed in Aristoteles3D viewer



BFS can bring the rich-building information into the urban model. Furthermore, it can also act as a web-based information sharing and exchange service within the construction domain.

A prototype is developed to demonstrate the use of this integration framework. The common model is based on GML/CityGML. A WFS server was implemented to act as a wrapper of geospatial information, while a BFS server was implemented to act as the wrapper of building model. The mediating service was designed to respond to the client request, retrieve the building features from a BFS and geospatial features from WFS and send back the combined results. Although this initial prototype has limited functions, it demonstrated the use of the integration framework.

This BIM and geospatial integration framework could facilitate the efficient data sharing and exchange across urban and construction domains. By using this integration framework, the datasets from on-line sources can be customised according to the specific requirements for construction

or urban planning development. Thus a BIM and geospatial information integration framework could serve as the urban information space for the whole municipality. Geospatial datasets collected for urban management can be used for the construction industry, while detailed building models from the construction industry can be used in the management of the urban built environment. Relevant stakeholders could get the needed datasets in a standard format in real time. For example, the fire department would be able to assess the information of a building interior structure and the spatial context of the surrounding built environment in real time in emergency situations. For new building design, it is possible to get the geospatial information to see how a new building will fit in with its immediate surroundings.

In summary, this research work extends the scope of BIM and has potential to benefit the construction industry as well as management of the urban built environment.

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KEY TERMS AND DEFINITIONS

CAD: Computer Aided Design

Building Information Model (BIM): is digital data model of graphical, physical and functional characteristics of buildings. Construction and management of buildings and building-elements involves many stakeholders. The complexity of BIM data model is believed to add necessary simplicity for the sharing and management of information over the entire lifecycle of a building.

Geospatial Information System (GIS): An information system, which allows storing, managing, reorganizing, visualizing and analysing geographical data. GIS is a ‘smart’ digital map system. A major aspect of a GIS is the ability to execute queries on the data that normally includes a spatial or location aspect.

Geography Markup language (GML): A mark-up language based on XML. GML schema definition is developed by the Open Geospatial Consortium (OGC) and becomes an ISO standard. GML can be used to define spatial objects (features) with their geometry, attributes and relations and is intended to be an open format for the exchange of geospatial features between systems.

CityGML: extended GML schema is also an XML-based format for the representation, storage and exchange of virtual 3D city models. CityGML models geo-referenced 3D vector data and the semantics associated with the data. It is also extensible to further enrich the data. CityGML has been adopted as an official OGC Standard from its version of 1.0.

Web Service: Taking the World Wide Web Consortium (W3C)’s definition, a Web service is a software system designed to support

interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL). Other systems interact with the Web service in a manner prescribed by its description using SOAP-messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards.

OWS: OGC Web Service includes WMS, WFS, W3DS, WCS - the OGC web services are defined in order to provide open standard interfaces in order to exchange geospatial data between systems. The various services provided fulfil specific tasks: one of the most prominent ones is the Web Map Service that can be used to query map data (images) from a server. The Web Feature Service, for example provides ‘raw’ geospatial features that can be analysed, converted and used for other purposes than map display. Because the definitions are publicly available, they can be used to link systems and are a popular way to generate ‘geospatial mash-ups’.

Building Feature Service (BFS): ABIM based Web feature service. Information of a building object and its elements is retrieved and provided to users through OGC Web Service. The BFS uses XML as exchange format between client and the BFS server, which have detailed building and element descriptions. BFS is seen as an approach to bridge BIM and the urban built environment to support life cycle information services for both city management and the construction industry.

Mediating Integration System: A specific client/server architecture system, in such a system, a mediating service module is designed to bridge the data source layer and client application layer. The idea is to make better system architecture in terms of its modularity. Mediating integration systems are more flexible and extensible than a normal client/server system. In this chapter, the mediating service module responds to the client request, retrieves building features from the BFS and sends combined results to the client.

Chapter 18

Query Support for BIMs using Semantic and Spatial Conditions

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ABSTRACT

A query language for Building Information Models allows users and third-party application programmers to not only analyze the digital building under specific criteria but also to extract partial models from a full building model. This functionality is of crucial importance, since the full BIM is meant to comprise the information of all domains involved in the planning process, but an individual user or programmer is normally interested in only a small subset of it. To specify this subset, a formal language is required which makes it possible to formulate conditions the resulting data set has to fulfill. This concept is also known as providing a certain view of the data available. This chapter gives an overview of the currently available query technologies for BIMs and compares the different options in terms to expressive power and ease of use. The emphasis of the chapter, however, lies in the introduction of spatial query technology for BIMs that has been developed by the authors. Spatial operators extend the analysis and submodel specification capabilities of a query language substantially by providing an intermediate level of abstraction that is close to the human understanding of the geometric-topological properties of building components and the relationships between them.

1 INTRODUCTION

The computer-based modelling of buildings has been an important topic of the construction informatics research community for more than 15 years now. An object-oriented Building Information Model

(BIM) that not only captures the 3D geometry of the building elements but also their semantics and the relationships between them promises to enable a seamless integration of design software and downstream applications, and hence to serve as a solid basis for the highly collaborative work in AEC projects.

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Sophisticated digital building models can facilitate the collaboration between the various participants involved in the design and engineering process, including architects, structural engineers, HVAC engineers and interior designers, to only name a few. Though in modern AEC processes these participants work in parallel on the same building, they only use specific subsets of the entire building information model tailored to the needs of their particular domain and/or their specific task. To store these sub-models in separate files for further processing, they need to be extracted from the full building model.

As the resulting partial models represent a certain view of the shared BIM, they are of considerable value also for the aforementioned downstream applications, such as the various visualization, analysis and simulation tools that form an integral part of modern construction engineering. In most cases, these tools require only a subset of the full building model data to perform their specific task.

A well-established technology for retrieving parts of digital models is the use of a declarative query language, which is most familiar from the context of database management systems. In general, a declarative query language enables the user to define conditions that need to be satisfied by the required model subset, while simultaneously hiding the complex task of an efficient query processing.

Besides creating partial model, however, a query language for BIMs also enables the *analysis* of building models with respect to its components, their properties and the relationships between them. A sophisticated query language can accordingly be used to define rules or conditions that need to be fulfilled by the building model. In contrast to employing a programming language for this purpose, these rules are defined independently of the processing algorithms and thus provide an excellent basis for the future encoding of national and international building regulations.

This chapter gives an introduction to the query techniques currently available for Building Information Models and compares them with respect to their expressive power and ease of use. It meanwhile focuses on two different types of conditions: *Semantic conditions* that rely on the values of the attributes and relationships predefined in the building information model, and *spatial conditions* that concern the topological and geometrical properties of the building model and its entities.

Since spatial operators are not yet available in current commercial implementations of BIM query languages, this chapter gives a detailed account of the development of a spatial query language for BIMs including the formal definitions of the spatial operators and their technical implementation.

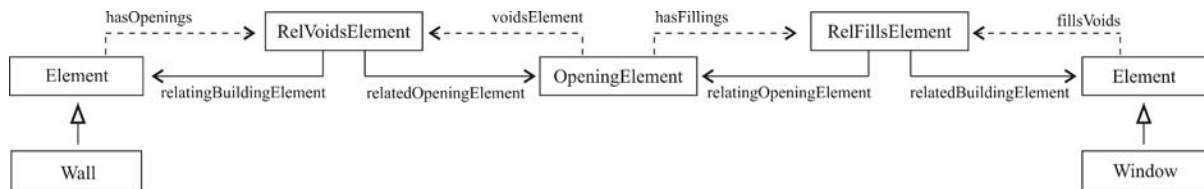
2 BUILDING INFORMATION MODELS AND PRODUCT MODEL SERVERS

2.1 Building Information Models and STEP

A Building Information Model (BIM) is a digital representation of a building that is either at the planning stage or has already been built. It describes the structure of this building by means of an object-oriented model, capturing the 3D geometry of the building elements, their semantics and the relationships between them.

In order to achieve interoperability between different software applications used in the design and construction process, it is necessary to use a standardized data model (schema) representing a blueprint for the digital models of actual buildings. The most mature data model standards in the AEC domain are the Industry Foundation Classes (IFC) (International Organization for Standardization, 2005) and the CIS/2-Standard (Eastman, Wang, You, & Yang, 2005).

Figure 1. Fraction of the IFC model that represents the relationship between a wall and the windows contained in it. Note that the inheritance graph has been radically reduced to show the essential parts only.



For historical reasons, both data models have been developed using STEP, the ISO standard for the exchange of product model data (International Organization for Standardization, 1995; Fowler, 1995). On this account, Building Information Models are also referred to as Building *Product Models*. Part 11 of the STEP framework defines the object-oriented data modelling language EXPRESS which has also been employed to describe the IFC and CIS/2 data models.

EXPRESS provides a rich set of object-oriented modelling features including the definition of *entity types* (the equivalent of a *class*) which encapsulate *attributes* representing the common properties of the objects belonging to the same entity type. Attributes are either of basic type, or are used to model associations with other entity types. In addition, EXPRESS provides pre-defined *collection types* (array, bag, set, list) that are able to hold a number of associated objects, and *select types* that basically model enumeration types. A particularity of EXPRESS is the existence of *inverse attributes* which provide means to identify an association also from the entity being referenced (an incoming association). EXPRESS can be used to define algorithms that are part of integrity constraints, but it does not support the definition of methods, i.e. the behaviour of objects cannot be described.

Of particular interest in the context of query functionality is the mapping language EXPRESS-X defined in Part 14 of the STEP standard and the mapping to the data modeling language XML-Schema defined in Part 28.

2.2 Product Model Data Structure: The IFC as a Case Study

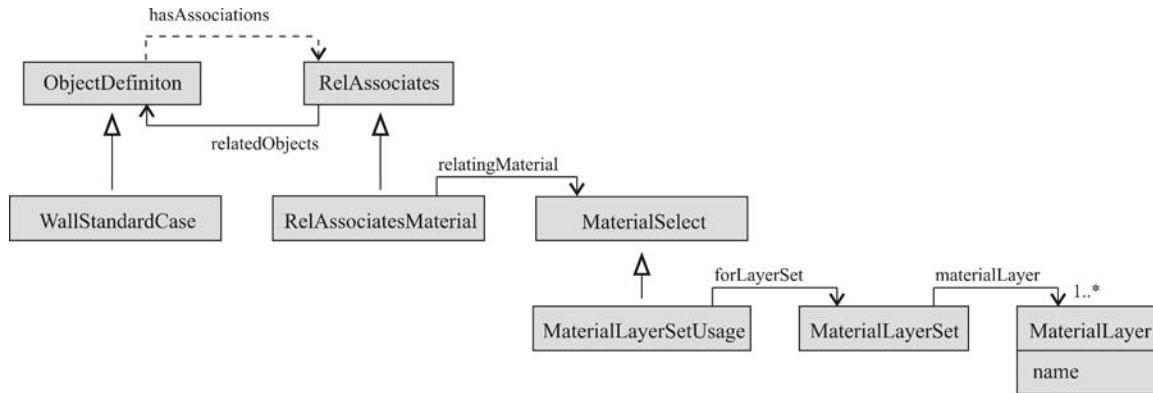
In their capacity as the foremost AEC product model available today, the Industry Foundation Classes (IFC) make extensive use of object-oriented modelling techniques such as encapsulation, inheritance and relationships, leading to a fine-grained and particularly complex data model (Amor, Jiang, & Chen, 2007).

This is illustrated by Figure 1 which depicts the relationship between a wall and a window contained in this wall. Note that the IFC make use of *objectified relationships*¹, and employ the EXPRESS concept of *inverse attributes* that can be used to navigate an association in the opposite direction.

The complex structure of the IFC data model makes the retrieval of relevant attributes very difficult. As shown in Figure 2, identifying the material of a wall involves 4 intermediate steps for navigating along the intermediary entities. This particularly affects the formulation of queries that use the values of such “faraway” attributes as selection predicate.

Throughout this chapter, queries that use attribute values are denoted as *semantic* queries in order to distinguish them from *spatial* queries that rely on purely geometric properties and relationships. As a specimen of semantic queries we will use the query “Find all walls that are made of concrete” and express it by means of the query languages that are introduced in the next Section.

Figure 2. Fraction of the IFC model that represents the relationship between a wall and the material it is composed of. Note that the inheritance graph has been radically reduced to show the essential parts only.



2.3 Product Model Servers and their Query Functionalities

For the future, product model servers that manage the product model centrally and maintain its consistency are seen as the most promising solution to today's data management problems in the AEC industry (Kiviniemi, Fischer, & Bazjanac, 2005). Product model servers that are specialized in handling IFC data and are already on the market include the Jotne EDMServer and the EuroStep ModelServer (EMS). Another IFC model server was developed within the IMsvr research project realized by VTT and Secom Ltd. (Adachi, 2002). All available product model servers provide query languages that allow the users to extract parts of the full building model.

The individual realization of the query language concept depends largely on the technological basis of the product model server itself: On the one hand, there are model servers, that are natively based on EXPRESS and accordingly offer direct support for all EXPRESS constructs including access to aggregates, inverse attributes, SELECT data types and so on. EDMServer by Jotne is one example of a native EXPRESS server. For the purpose of model query functionality it provides proprietary languages that are based on, but not

part of the official EXPRESS standard, including EDMexpressX™ and EDMQuerySchema™.

Model servers that are implemented on the basis of XML, such as the IFC model server, the EuroStep ModelServer and the SABLE server, on the other hand, provide special XML schemata for describing the contents of partial models. In the case of EMS the query schema is called *Product Model Query Language* and in case of the IMsvr it is called *Partial Model Query Language*. We will have a closer look on these schemata in Section 3.2.2.

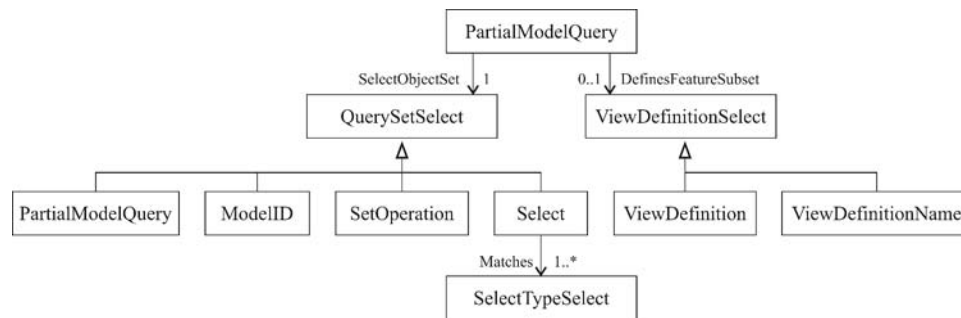
3 REALIZING SEMANTIC QUERIES

3.1 Native STEP Query Functionality

The STEP standard does not provide “real” query functionality. Although there is a QUERY operator available in EXPRESS, it cannot be applied individually, but only within the WHERE part of an entity definition for the specification of integrity rules.

However, native EXPRESS query functionality can be realized by means of EXPRESS-X. The language was originally designed for defining mappings from entities in one EXPRESS

Figure 3. The specimen query defined in EXPRESS-X



schema to entities in another schema (Bailey, Hardwick, Laud, & Spooner, 1996). This mapping functionality of EXPRESS-X was applied in the CIS2IFC project², for example. However, since the result of a query can be interpreted as a view on the underlying model, EXPRESS-X can also be employed for the formulation of queries.

The latest version of EXPRESS-X has a clearly declarative character and is reminiscent of the well-known query language SQL (Denno & Sanderson, 2000). An EXPRESS-X query consists of a FROM, a WHERE, and a RETURN part. The FROM part defines the entity types (extents) over which the query shall iterate and binds local variables to these types. The WHERE part specifies the constraints that have to be fulfilled by the selected entities, and the RETURN part defines how the result is returned.

The formulation of our specimen query “Find all walls that are made of concrete” is depicted in Figure 3. As it illustrates, the main strengths of EXPRESS-X lie in its expressive power with respect to the definition of constraints. This includes the

- navigation along an association chain by repeatedly applying the dot-operator,
- access to inverse attributes (navigating along inverse associations),
- native support for EXPRESS aggregations, e.g. built-in functions for determining the size of a collection

This results in a comparatively short and simple definition of the query without any syntactical overhead.

Unfortunately, at the time writing there are not many EXPRESS-X engines available on the market. Two commercial versions are provided within the STEP toolkits *ST-Developer* by Step-Tools³ and *ECCO toolkit* by PD Tec⁴, respectively. The only engine available under public license is the *Express Engine*⁵ that was originally called *Expresso*, but is not under development any more since 2002.

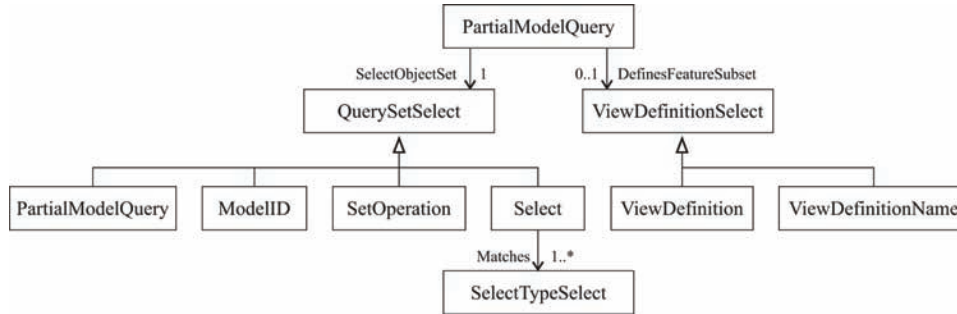
3.2 Schema-Based Approaches

A frequently employed approach for realizing query functionality on product models is the definition of a schema whose instances can be used to describe the content of a sub-model, or a view of the original model, respectively. In contrast to declarative query languages such as EXPRESS-X, XQuery or SQL, the subset is not defined by using a constraint statement, but by an instance of an object-oriented schema. Two variants of query schemata can be distinguished: Those that are defined using EXPRESS and those that are based on XML technology.

3.2.1 Express-Based Schema Approach

An example for an EXPRESS-based approach is the Generalized Model Subset Definition Schema

Figure 4. The GMSD schema consists of two parts: The left part selects individual object instances, the right part is used to define which attributes shall be included in the resulting view. Simplified UML representation.



(GMSD) which has been introduced in (Weise, Katranuschkov, & Scherer, 2003). GMSD is an EXPRESS-based schema that defines entities which can be used to specify the contents of a partial model by identifying objects and attributes that need to be included.

The schema accordingly consists of two parts. The first part is applied to select individual object instances using set theory as baseline. The second part is intended for post-processing of the selected data in accordance with a specific partial model view. Such views can be completely predefined to a large extent to support standard domain perspectives.

To give a better insight on the GMSD schema we have a closer look on the entity *SelectInstances*. It contains the attributes *AttributeName*, *Value* and *Tolerance*. In a concrete instance of GMSD

(a “query”), the user assigns values to these attributes, thereby specifying which instances of the full model should be included in the resulting partial model. Figures 4, 5 and 6 show the individual parts of the GMSD schema.

Note that GMSD allows only the definition of a view as a reduction of the original schema with respect to the number of attributes, it does not support mapping operations where the target schema is structurally different. Accordingly it is only of limited use for query scenarios that aim at analyzing the building model.

3.2.2 XML-Based Schema Approach

For the EuroSTEP Model Server (EMS), the IFC Model Server by VTT/Secom (IMsvr) and the SABLE server, XML schemata have been

Figure 5. Part of GMSD schema used to include individual instances in the resulting subset. Possible criteria for inclusion are: the name of the corresponding schema, the value of specific attributes of the instance, or the existence of a relationship to another entity. Simplified UML representation.

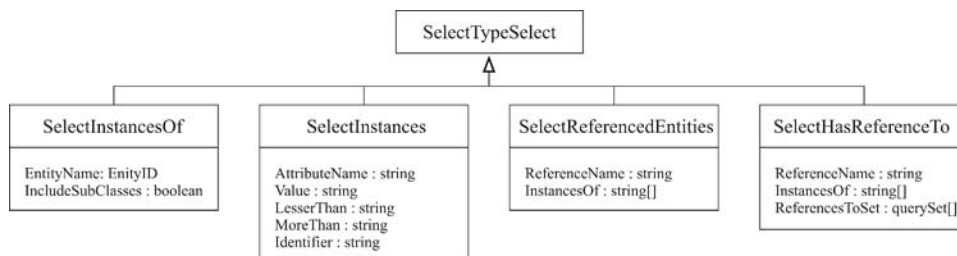
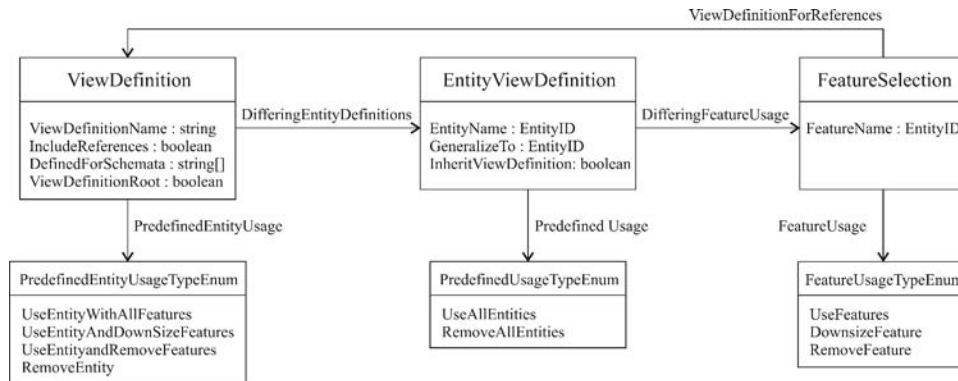


Figure 6. Part of GMSD schema used to define the attributes that are included in the resulting view. Note that in GMSD, attributes are referred to as features. Simplified UML representation.



defined for specifying the contents of extracted submodels. The schemata are denoted as query languages although they are not languages in the narrower sense of the word.

Product Model Query Language. The schema of the Product Model Query Language (ProMQL) of the EuroSTEP Model Server⁶ provides the XML elements SELECT and WHERE which are used in a manner similar to the corresponding parts in an SQL query: SELECT elements define the entities to be included in the results, and WHERE elements define constraints. The constraints are expressed by an XML tree consisting of attribute names, comparison operators and values. Values are either atomic, or sub-trees where the corresponding attribute represents an association to another entity.

The specimen query represented by a Product Model Query Language XML document is presented in Figure 7.

Partial Model Query Language. The partial model query language (PartMQL) has been developed for the IFC Model Server of Secom Ltd. and VTT (Adachi, 2002). It follows the same basic concept as the Product Model Query Language, as its users define the resulting set by means of hierarchical constraints (Figure 8). The two components of a appropriate query language, the selection part and the recombination part, that

are clearly separated in EXPRESS-X (WHERE part and RETURN part) and in the GMSD schema (selection part and view creation part), are mixed up in PartMQL: The *cascade* element that allows to navigate along associations serves both purposes, on the one hand using the values of “faraway” attributes as selection criteria, and on the other hand in- or excluding the respective attributes in the resulting view.

SABLE Model Query Language. The SABLE model query language⁷ results from the merging of ProMQL and PartMQL and a further advancement. It introduces additional schema elements such as *include* and *except* for an advanced specification of the resulting object set by introducing the above mentioned separation between object selection and view definition. Since the language does not operate on the IFC product model, but on a simplified version of the model, we refrain from further examination.

3.2.3 Assessment of Schema-Based Approaches

Schema-based approaches avoid the error-prone usage of a query language and the parsing of the query statement by the processing engine, and allow employing user-friendly input-masks for weaving an object-network that specifies the

Figure 7. The specimen query as XML instance of the Product Model Query Language schema.

```

<webstep_ql>
  <select>
    <entity name="IfcWallStandardCase">
      <where>
        <attribute name="hasAssociations">
          <eq>
            <entity name="IfcRelAssociatesMaterial">
              <where>
                <attribute name="relatingMaterial">
                  <eq>
                    <entity name="IfcMaterialLayerSetUsage">
                      <where>
                        <attribute name="forLayerSet">
                          <eq>
                            <entity name="IfcMaterialLayerSet">
                              <where>
                                <attribute name="materialLayers">
                                  <eq>
                                    <entity name="IfcMaterialLayer">
                                      <where>
                                        <attribute name="material">
                                          <eq>
                                            <entity name="IfcMaterial">
                                              <where>
                                                <attribute name="name">
                                                  <eq>
                                                    <string value="Concrete"/>
                                                  </eq>
                                                </attribute>
                                              </where>
                                            </entity>
                                          </eq>
                                        </attribute>
                                      </where>
                                    </entity>
                                  </eq>
                                </attribute>
                              </where>
                            </entity>
                          </eq>
                        </attribute>
                      </where>
                    </entity>
                  </eq>
                </attribute>
              </where>
            </entity>
          </eq>
        </attribute>
      </where>
    </entity>
  </select>
</webstep_ql>

```

desired result. They can thus be seen as a suitable solution for the specification of sub-models by members of a planning team.

However, the scope of the schema-based approaches is limited to “pure” sub-model creation, since none of the presented schemata allows for a recombination of attributes from different entities, i.e. a schema mapping is not possible. Accordingly, the schema-based approaches have to be classified as less appropriate for analysis purposes.

At the same time, schema-based approaches are less suitable for power users, such as pro-

grammers, because the instantiation of the query objects and the assignment of values are much more tedious and time-consuming than the use of a query language. This biggest problem, however, is the proprietary character of the presented solutions: In each of the presented cases, an engine for processing instances of the particular schema has been implemented only by the creators of the schema.

Figure 8. The specimen query expressed as an instance of the Partial Model Query Language schema.

```

<pmql>
  <select type="entity" match="IfcWall" action="get">
    <cascades>
      <select type="inverse" match="HasAssociations" action="nop">
        <cascades>
          <select type="attribute" match="RelatingMaterial" action="nop"/>
            <cascades>
              <select type="attribute" match="ForLayerSet" action="nop"/>
                <cascades>
                  <select type="attribute" match="MaterialLayers" action="nop"/>
                    <cascades>
                      <select type="attribute" match="Material" action="nop"/>
                        <where>
                          <expr value="name='Concrete'"/>
                        </where>
                      </select>
                    </cascades>
                  </select>
                </cascades>
              </select>
            </cascades>
          </select>
        </cascades>
      </select>
    </cascades>
  </select>
</pmql>

```

3.4 SQL-Based Approach

An obvious technical approach for realizing queries on product models is the utilization of relational database management systems. They provide the well-known query language SQL that is based on the sound foundation of relational theory (Codd, 1970). Besides its primary function as query language, SQL serves also as data definition language (DDL) and data manipulation language (DML).

Two problems hamper the utilization of relational databases for storing and querying product models: The first problem is that there is no standard that defines a mapping from EXPRESS to SQL-DDL. The second problem is that the SQL standard itself is only loosely implemented by the database providers, with the result that there is now a wide variety of SQL dialects, for each of which a different mapping would have to be provided. However, some researchers and tool implementers, have proposed mappings from EXPRESS to specific SQL dialects.

Before having a closer look on them, we indicate that there are two distinct versions of the SQL standard in use today: The purely relational version known as SQL-92, and the object-relational version known as SQL:1999 (International Organization for Standardization, 1999; Eisenberg & Melton, 1999). The latter enables an extension of the database type system in an object-oriented way, especially by providing abstract data types (ADTs) which even may possess member functions (methods) (Melton, 2003; Türker, 2003; Türker & Saake, 2006).

3.4.1 Relational SQL

Purely relational databases as defined by SQL-92 do not offer object-oriented features and have therefore a much more limited expressive power than EXPRESS⁸. Hence, the main challenge is to emulate EXPRESS features such as inheritance, associations, aggregations and SELECT types by means of simple relations.

The technical possibilities for these emulations, including the advantages and drawbacks of the individual solutions, are discussed in detail in (You, Yang, & Eastman, 2004). The mapping of the CIS/2 data model on a relational database is presented by way of an example. However, the fundamental concept of an EXPRESS-to-SQL compiler had been discussed some years before in (Bicarregui & Matthews, 1998). Another initiative that employs a “hand-made mapping” from EXPRESS to SQL-DDL is the German OKSTRA⁹ effort that aims at developing a comprehensive product model for roadways and provides separate SQL-DDL files for all schemata that are developed.

A more general approach is being pursued by the STEPset group at the Institute for System Programming of the Russian Academy of Sciences¹⁰. The group has developed the generic tool *exp2ddl* that translates an EXPRESS schema into various SQL-DDL dialects. A second tool, *p21tosql*, is used to convert STEP-P21 instance documents into SQL-DML statements. Again one of the supported SQL dialects has to be chosen.

For each non-abstract entity of the passed schema *exp2ddl* creates a corresponding table that contains a separate column for each attribute of the entity (including the inherited ones). Inverse attributes are not mapped to SQL. An additional column contains the IDs of individual entities taken from the entity number of the STEP-P21 file (e.g. #24). Attribute columns that represent associations to other entities contain the entity number of the referenced instances.

In case the association is an aggregation of multiple instances and thus modelled using a container (an array, list, set, or bag), the references are stored as entity numbers separated by commas. This results in high syntactical overhead when a SQL query is formulated that involves the aggregation along such a multi-value association, since the reference string must be manually decomposed. To avoid this, we recommend the introduction of a helper function (AGGR_CONTAINS) that

checks whether a certain ID is contained within the list representing an aggregation.

In Figure 9 the specimen query defined in SQL operating on a database created by employing a EXPRESS-to-SQL mapping is depicted. The navigation along the various involved entities to reach the decisive attribute representing the material’s name is realized by means of subsequent joins of the respective relations. This results in a longer but still manageable query statement.

3.4.2 Object-Relational SQL

The SQL:1999 standard describes the access to databases providing *object-relational features* (International Organization for Standardization, 1999; Eisenberg & Melton, 1999). The main feature of object-relational databases is the possibility to extend the database type system in an object-oriented way enabling the user to define abstract data types (ADTs) which may possess attributes and relationships to other such ADTs (Melton, 2003; Türker, 2003; Türker & Saake, 2006). Using object-relational databases, most of the object-oriented features of EXPRESS can be directly mapped to the corresponding SQL:1999 elements (Urban, Tjahjadi, & Shah, 2000). Accordingly, the impedance mismatch is considerably reduced, which facilitates also the formulation of queries.

The formulation of the specimen query in SQL:1999 is depicted in Figure 10. The query is very similar to that formulated in EXPRESS-X (Figure 3), since SQL:1999 also allows the navigation along (multiple) references by applying the dot operator, which avoids applying additional joins as necessary when using SQL-92. Unfortunately, at the time of writing there is no official mapping from EXPRESS to SQL:1999 available. Also, there are no publicly available tools known to the authors that provide an automated conversion of EXPRESS schemata into object-relational performing this mapping.

Figure 9. The specimen query expressed in SQL-92 using the helper function AGGR_CONTAINS.

```
SELECT w
FROM IfcWallStandardCase wall, IfcRelAssociatesMaterial assoc,
     IfcMaterialLayerSetUsage usage, IfcMaterialLayerSet set,
     IfcMaterialLayer layer, IfcMaterial mat
WHERE AGGR_CONTAINS(assoc.relatedObjects, wall.id)
      AND assoc.relaterMaterial = usage.id
      AND usage.forLayerSet = set.id
      AND AGGR_CONTAINS(set.materialLayers, layer.id)
      AND layer.material = mat.id
      AND mat.name = 'Concrete'
```

3.5 XML-Based Approaches

The Extensible Markup Language (XML) was initially defined in 1998 and is consequently a young data modelling standard compared to STEP. It was originally designed to facilitate the exchange of semantic content in the World Wide Web, by clearly separating the content of websites from their visual representation (Abiteboul, Buneman, & Suciu, 1999). In the meantime, however, the general approach of XML, its clear design, the extensive documentation, and the availability of a large set of tools for creating, validating and processing XML documents has resulted in XML being a well-established data modelling language and data exchange format in almost all IT domains.

In response to the growing demand for interoperability between XML and STEP, the STEP standardization workgroup defined a mapping from EXPRESS to XML-DTD in 2003, and a mapping from EXPRESS to XML-Schema in 2007, published as Part28, Editions 1 and 2, respectively (International Organization for Standardization, 2007).

The IFC model support group applied the mapping to the IFC data model resulting in the corresponding ifcXML model (Nisbet & Liebich, 2005). Based on this mapping, the Helmholtz research center Karlsruhe has developed a tool for converting STEP-P21 instance files into ifcXML instance files. The existence of the ifcXML standard schema and the conversion tool creates extensive opportunities especially for the construction informatics research community, since it allows the application of a wide range of software tools available for XML processing which, in contrast to EXPRESS tools, are largely distributed as open source software.

However, since XML-Schema does not provide the full range of data modelling features of EXPRESS, the conversion results in a certain loss of model semantics. This particularly applies to *inverse attributes* that enable EXPRESS users to navigate along associations in the opposite direction (see Section 2.1), but are not mapped to XML.

There were several candidate languages for querying XML, of which XQuery has prevailed (Boag et al., 2007). The basic syntax of XQuery is

Figure 10. SQL:1999 version of the specimen query

```
SELECT *
FROM IfcWallStandardCase wall;
WHERE wall.hasAssociations[1].relaterMaterial.forLayerSet.
      materialLayers[1].material.name = 'Concrete';
```


Figure 11. General structure of an XQuery statement

```

FOR $forvar1 at $posvar1 in <Expr>, $forvar2 at $posvar2
    in <Expr> ...
LET $letvar1 := <Expr>, $letvar2 := <Expr> ...
WHERE <BoolExpr>
ORDER by <Expr> ascending/descending
RETURN <Expr>

```

depicted in Figure 11; it consists of a combination of XML, XSLT and SQL language elements.

The general structure of XQuery is denoted as FLOWR, which is derived from the first letters of its FOR, LET, WHERE, ORDER BY and RETURN parts. The FOR part is the equivalent of the FROM part in SQL, here the element types are specified on which the search algorithm iterates, and to which variables are bound. In the LET part, additional variables can be bound, but their values are fixed, i.e. they do not provoke iteration loops. The WHERE part contains the conditional statement, the ORDER BY part provides means of ordering the resulting set, and the RETURN part describes its data structure. Figure 12 shows the specimen query expressed in XQuery.

Although STEP P28 allows the mapping of inverse attributes to XML, the current configuration of the official mapping from IFC to ifcXML does not include them. In addition, the current standards of XQuery and XPath do not support the dereferencing of references. Due to these facts, the “navigation” to the decisive attributes must be realized using joins on the involved entities, rendering the query much more complicated than the EXPRESS-X statement shown in Figure 3.

However, XQuery provides the full range of query functionalities, including filtering and recombination of attributes for the resulting set. Thanks to the broad application area, there is a large number of XQuery engines available, among which many are provided as public domain software. Hence XQuery can be seen as a very suitable option for providing query support for building

information models, even if its syntax is not as concise as that of EXPRESS-X.

What currently poses a serious problem with respect to the creation of partial models and their subsequent processing is the absence of any standardized back-mapping that converts a valid ifcXML file into a STEP-P21 representation. The respective software application that further processes the retrieved sub-model must therefore be able to read-in the ifcXML format.

3.6 Conclusion on Semantic Query Functionalities

For querying EXPRESS-based Building Information Models using semantic criteria, the application of EXPRESS-X is in general the best choice, since it fully supports all of the EXPRESS language constructs leading to concise query statements. Since however, the number of available EXPRESS-X engines is very limited, alternative approaches have to be seriously considered.

Among them, SQL:1999 and XQuery form the most suitable option. The query language SQL:1999 that is used in object-relational databases provides a rich set of object-oriented language constructs, thus a mapping from EXPRESS to it can be realized with a limited “impedance mismatch”, resulting again in a concise query statement. Though there is a large variety of commercial and non-commercial object-relational databases available on the market, so far there is no standardized mapping from EXPRESS to SQL:1999.

Figure 12. The specimen query expressed in XQuery

```

let $uos := $this/ex:iso_10303_28/ifc:uos
for $wall in $uos/ifc:IfcWallStandardCase,
    $assoc in $uos/ifc:IfcRelAssociatesMaterial,
    $usage in $uos/ifc:IfcMaterialLayerSetUsage,
    $set in $uos/ifc:IfcMaterialLayerSet,
    $layer in $uos/ifc:IfcMaterialLayer,
    $material in $uos/ifc:IfcMaterial
where $wall[@id=$assoc/ifc:RelatedObjects/ifc:IfcWallStandardCase/@ref]
and $assoc/ifc:RelatingMaterial/ifc:IfcMaterialLayerSetUsage[@ref=$usage/@id]
and $usage/ifc:ForLayerSet/ifc:IfcMaterialLayerSet[@ref=$set/@id]
and $set/ifc:MaterialLayers/ifc:IfcMaterialLayer[@ref=$layer/@id]
and $layer/ifc:Material/ifc:IfcMaterial[@ref=$material/@id]
return <QueryResult>{$wall}</QueryResult>

```

By contrast, there exists an official mapping from EXPRESS to XML, and, even more specifically, an official ifcXML representation of IFC building models, which makes the application of XQuery an interesting option. XQuery provides most of the required functionality of a query language, but so far it does not support the navigation along references. Hence, querying faraway attributes requires the application of joins, which results in a much more complicated formulation of these queries. XQuery processing engines are available in a large extent under both commercial and public licenses, however execution performance is a serious issue.

4 REALIZATION OF SPATIAL QUERIES

4.1 Motivation

Humans view buildings primarily as an aggregation of physical objects with well-defined geometry and specific spatial relations. In most cases, the architectural and/or structural function of a particular building component is closely related to its shape and its position in relation to other building components. For architects and engineers involved in designing buildings, geometric properties and spatial relations between

building components accordingly play a major role in finding solutions for most of the design and engineering tasks.

Some of the spatial relationships which are possibly of interest for the user are directly represented in the building product model. In the case of the IFC, some examples of these predefined relationships are *IfcRelFillsElement*, *IfcRelVoidsElement* and *IfcRelContainedInSpatialStructure*. Unfortunately, many product modelling tools do not fill the entire set of spatial relations with appropriate data when exporting a building model into the IFC format. In a recently conducted test, we used the commercial BIM design tool Autodesk Revit 2008 to model a high-rise building completely equipped with interior fittings. The analysis of the exported IFC file showed that, while the *IfcRelFillsElement* and *IfcRelVoidsElement* relationships between walls and windows were set correctly, no *IfcRelContainedInSpatialStructure* relationships had been set. Accordingly it was not possible to query the product model for the furniture contained in a certain room or office, for example.

Other spatial relationships, such as directional relations (e.g. one object above another) are completely ignored by the IFC product model. From the point of view of product modelling this makes absolute sense, because storing all possible spatial relations would (1) result in huge models with many object relations not needed by the major-

ity of applications and (2) introduce even more redundancy, since directional relationships are already implicitly defined by the shape and position of the respective objects. For this reason, we follow an analytic approach here, where spatial relations are not required to be set by the modelling tool in use, but are derived from the objects' shapes and positions, i.e. the explicit geometry of the building's components, instead.

Since product model servers do not know the geometric implications of semantic attributes, they are not able to interpret and process spatial information. This has to be seen as a major deficiency, since spatial relations between building components play a significant role in most of the design and engineering tasks of the AEC domain. To fill this technological gap we have developed concepts and techniques for a 3D Spatial Query Language for Building Information Models. It makes it possible to select specific building components fulfilling spatial constraints defined by the user.

4.2 Related Work

The overall concept of providing a Spatial Query Language for analyzing Building Information Models is closely related to concepts and technologies developed in the area of Geographic Information Systems (GIS). Such systems maintain geographical data, such as the position and shape of cities, streets, rivers etc. and provide functionalities for the spatial analysis of this data. Due to the nature of this domain most GI systems only support spatial objects in two-dimensional space.

The first implementations of spatial query languages on the basis of SQL were realized in the GIS context. In the late 80's, a multitude of different dialects was developed, including PSQL (Roussopoulos, Faloutsos, & Sellis, 1988), Spatial SQL (Egenhofer, 1987), GEOQL (Ooi, Sacks-Davis, & McDonell, 1989), KGIS (Ingram & Phillips, 1987) and TIGRIS (Herring,

Larsen, & Shivakumar, 1988). A good overview of the different dialects and the basic advantages of a SQL-based implementation is provided in (Egenhofer, 1992).

The GIS research community also coined the phrase *Spatial Database* to describe database management systems (DBMS) that provide spatial data types and spatial indexing techniques and thus allow for an easy and efficient access to spatial data (Rigaux, Scholl, & Voisard, 2002; Shekhar & Chawla, 2003). There is now a wide range of commercial 2D spatial database systems, the most widespread ones being *PostGIS*, *Oracle Spatial* and *Informix Geodetic Datablade*. The majority of spatial databases that are available comply with the standard set up by the OpenGIS consortium that defines a common interface for accessing 2D spatial data and accordingly enables the exchangeability of the database component in an overall GI system (OpenGIS Consortium, 1999).

The potential benefits of using the functionality of GI systems for the analysis of dynamical processes in buildings are discussed in (Ozel, 2000). The author states that, even if component-oriented CAD systems provide sophisticated functionality for geometric modeling, they normally lack comprehensive spatial analysis capabilities. For this reason, Ozel stores floor plans of buildings in a GIS database in order to use its 2D spatial analysis facilities. Ozel underlines the fact that 3D spatial analysis would be a much more powerful tool for analyzing processes in buildings.

Up to now, spatial database systems that support 3D spatial analysis are only to be found in a research context. The investigations set out in (Gröger, Reuter, & Plümer, 2004), for example, clearly show that the spatial analysis capabilities of the commercial database system *Oracle Spatial* are limited to 2D space, even though it is possible to store simple 3D geometry.

In the 3D-GIS research community, the main interest lies in the modelling of the ground surface, buildings and infrastructure as well as the subsoil layers. The most important works in this area in-

clude (Breunig, Bode, & Cremers, 1994; Breunig, Cremers, Müller, & Siebeck, 2001; Balovnev et al., 2004) which report on the development of *GeoToolkit*, an object-oriented framework for efficiently storing and accessing 3D geographic and geologic data. The main disadvantage of using the framework for analyzing building models is the need to model all spatial entities according to the mathematical concept of *simplicial complexes*. The obligatory conversion of a boundary representation, as used in CAD tools, to a *simplicial complex* representation is expensive and, in some special cases, absolutely unfeasible. A more flexible, yet theoretic approach for applying algebraic topology on building models is presented in (Paul & Bradley, 2003; Paul, 2010).

In (Zlatanova, Rahman, & Shi, 2004; Zlatanova, 2006; Coors, 2003; Arens, Stoter, & Oosterom, 2005) concepts and data structures for storing 3D city models in spatial databases are presented and the suitability of different geometry models for querying topological relationships is discussed. In general, GIS research follows the approach of choosing geometry data structures that implicitly contain topological relationships. Accordingly many of the proposed data structures rely on a simplicial decomposition of the space (Egenhofer, Frank, & Jackson, 1989; Egenhofer & Herring, 1992; Shi, Yang, & Li, 2003).

In (Kriegel, Pfeifle, Pötke, Renz, & Seidl, 2003) a database system is introduced that allows for the spatial analysis of 3D CAD models. It provides simple volume, collision and distance queries, but supports neither topological nor directional predicates. The implementation of the system relies on a voxel approximation of the CAD parts stored in the database and a special index structure optimized for this representation. We follow a similar approach here but employ hierarchical space partitioning data structures which are created dynamically while processing a spatial query.

4.3 Spatial Algebra

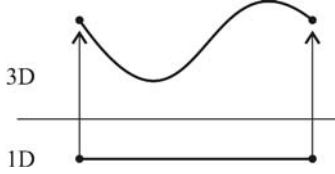
4.3.1 Spatial Types

The proposed 3D Spatial Query Language relies on a spatial algebra that is formally defined by means of point-set theory and point-set topology (Borrmann, van Treeck, & Rank, 2006; Borrmann, 2006, 2007). Besides the fully three-dimensional objects of type *Body*, the algebra also provides abstractions for spatial objects with reduced dimensionality, namely by the types *Point*, *Line* and *Surface*.

This is necessary because building models often comprise dimensionally reduced entities, such as load points, power lines, plates, slabs etc. All types of spatial objects are subsumed by the super-type *SpatialObject*.

For the specification of topological predicates it was necessary to define the *interior*, the *boundary* and the *exterior* for each of the 4 spatial types defined within the Spatial Query Language. These definitions have been published in (Borrmann, 2006; Borrmann, Schraufstetter, van Treeck, & Rank, 2007) and are not repeated here. In summary, the purpose of these definitions is to transfer the specification of *interior* and *exterior* for each of the spatial types from the world of algebraic topology to the world of point-set topology. For example, we intend to define the endpoints of a *Line* element in 3D as its *boundary*, and all other points as belonging to its *interior*. Applying the neighbourhood concept from point-set topology in 3D space would result in all points of a *Line* belonging to its boundary. We accordingly define *Line* objects as mappings from 1D to 3D space, specify the boundary and the interior points in 1D, and assign “boundary” to the mappings of boundary points and “interior” to the mapping of interior points (Figure 13). As result we are able to distinguish interior from boundary points also for “flat” objects in 3D space.

Figure 13. If 3D Line objects are defined as mappings from 1D intervals, the notion of boundary can be preserved for the endpoints.



4.3.2 Spatial Operators

The spatial operators available for the spatial types are the most important part of the algebra. They comprise

- metric (*distance*, *closerThan*, *fartherThan* etc.),
- directional (*above*, *below*, *northOf* etc.) and
- topological (*touch*, *within*, *contains* etc.) operators.

Colloquial language is often vague and ambiguous when used to describe spatial relationships. Because an unequivocal definition is essential for using spatial relationships as conditions in a spatial query language, it is necessary to formally specify their semantics. These formal specifications are presented in the following Sections 4.3.3, 4.3.4 and 4.3.5.

4.3.3 Metric Operators

All metric operators of the spatial query language rely on the Euclidean metric defined in 3D space. Let $p(x_p, y_p, z_p)$ and $q(x_q, y_q, z_q)$, then the Euclidean distance between p and q is defined as:

$$d(p, q) := \sqrt{(x_p - x_q)^2 + (y_p - y_q)^2 + (z_p - z_q)^2}$$

The operator *distance* returns the minimal distance between two spatial objects as a real

number. Let A and B be objects of type *Spatial* and $a \in A$, $b \in B$. Then *distance* is formally defined as follows:

$$distance(A, B) := \min_{a,b} (d(a, b))$$

The operator *distance* returns 0, if the operands touch or penetrate each other.

The operator *maxdist* can be used to determine the maximum distance between two spatial objects. It also returns a real value and is defined as follows:

$$maxdist(A, B) := \max_{a,b} (d(a, b))$$

The operators *isCloser* and *isFarther* are based on the minimal distance. Operands of both operators are two spatial objects A and B as well as a positive real value c . The operators return a Boolean value and are formally defined as follows:

$$isCloser(A, B, c) \Leftrightarrow \min_{a,b} (d(a, b)) < c$$

$$isFarther(A, B, c) \Leftrightarrow \min_{a,b} (d(a, b)) > c$$

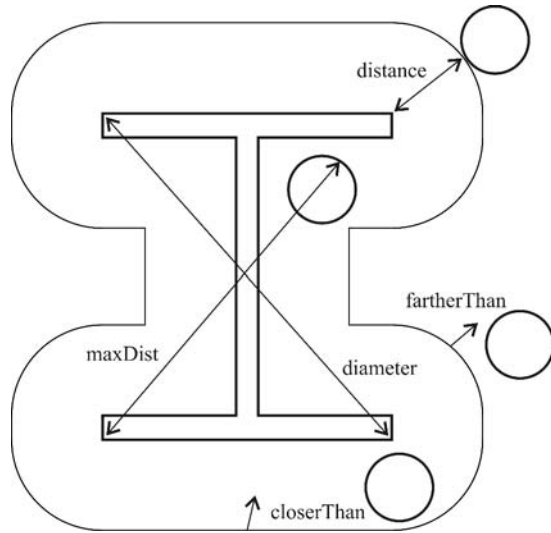
These operators can be used to select objects that are inside or outside a buffer zone around the reference object.

The operator *diameter* returns the maximum distance between two points of one individual object. The operand is a spatial object A , the return value a real number. Let $a, b \in A$. Then the diameter is defined as:

$$diameter(A) = \max_{a,b} (d(a, b))$$

Figure 14 illustrates the semantics of the definitions by means of an example.

Figure 14. The semantics of the metric operators provided within the spatial query language



4.3.4 Directional Operators

Direction is a binary relation of an ordered pair of objects A and B , where A is the reference object and B is the target object. The third part of a directional relation is formed by the reference frame, which assigns names or symbols to space partitions.

According to (Retz-Schmidt, 1988), three types of reference frames can be distinguished: an *intrinsic* reference frame relies on the inner orientation of the spatial objects, such as that defined by the front of a building, for example. A *deictic* reference frame is aligned to the position and orientation of the observer. By contrast, an *extrinsic* reference frame is defined by external reference points. In geographical applications, for example, these external reference points are the earth's north and south pole.

In a geographical context, we usually distinguish between four (*north*, *east*, *south*, *west*) or eight space partitions (*north*, *north-east*, *east*, *southeast*, *south*, *south-west*, *west*, *north-west*). In 3D context, normally the additional directional predicates *above* and *below* are used (Fuhr, Socher,

Scheering, & Sagerer, 1998), which may also be employed in conjunction with the aforementioned 2D sub-direction, resulting in *north-east-above*, *east-above*, etc.

To meet the requirements of different application scenarios, we developed two new models for representing directional relationships between 3D objects: the *projection-based model* and the *halfspace-based model*. Both models use an intrinsic reference frame that is determined by the orientation of the coordinate system chosen by the user.

The proposed directional models are appropriate for arbitrary combinations of spatial types and are based on a separate examination of directional relationships with respect to the three coordinate axes. For each axis, there are precisely two possible relations: *eastOf* and *westOf* in the case of the x -axis, *northOf* and *southOf* for the y -axis and *above* and *below* for the z -axis. We have chosen the names of geographical cardinal directions instead of *left*, *right*, *in front of*, *behind* to clearly label our models as observer-independent.

As opposed to the directional models used in (Guesgen, 1989; Papadias, Sellis, Theodoridis, & Egenhofer, 1995) and (Goyal, 2000), the directional relationships of the relevant axis are not superimposed. Accordingly, the relationship between two spatial objects is not *north-east*, for example, but *northOf* and *eastOf*.

Both models differentiate between two “flavours” of directional operators. Whereas the *strict* directional operators only return *true* if the entire target object falls into the respective directional partition, the *relaxed* operators also return *true* if only parts of it do so.

The projection-based directional model. In the projection-based model, the reference object is extruded along the coordinate axis corresponding to the directional operator. The target object is tested for intersection with this extrusion. Let reference object A and target object B be spatial objects of type *SpatialObject* and $a \in A$, $b \in$

B. Then the formal definitions of the relaxed projection-based operators read:

$$\begin{aligned}
 \text{eastOf\_proj\_relaxed}(A, B) &\Leftrightarrow \exists a, b : a_y = b_y \wedge a_z = b_z \wedge a_x < b_x \\
 \text{westOf\_proj\_relaxed}(A, B) &\Leftrightarrow \exists a, b : a_y = b_y \wedge a_z = b_z \wedge a_x > b_x \\
 \text{northOf\_proj\_relaxed}(A, B) &\Leftrightarrow \exists a, b : a_x = b_x \wedge a_z = b_z \wedge a_y < b_y \\
 \text{southOf\_proj\_relaxed}(A, B) &\Leftrightarrow \exists a, b : a_x = b_x \wedge a_z = b_z \wedge a_y > b_y \\
 \text{above\_proj\_relaxed}(A, B) &\Leftrightarrow \exists a, b : a_x = b_x \wedge a_y = b_y \wedge a_z < b_z \\
 \text{below\_proj\_relaxed}(A, B) &\Leftrightarrow \exists a, b : a_x = b_x \wedge a_y = b_y \wedge a_z > b_z
 \end{aligned}$$

The relaxed operators return *true* if there is an intersection between the extrusion body and the target object, otherwise *false*. By contrast, the *strict* projection-based operators only return *true* if the target object is completely within the extrusion body. Accordingly, the formal definitions of the strict operators are:

$$\begin{aligned}
 \text{eastOf\_proj\_strict}(A, B) &\Leftrightarrow \forall a : (\exists b : a_y = b_y \wedge a_z = b_z \wedge a_x < b_x) \wedge \\
 &\quad (\nexists b : a_y = b_y \wedge a_z = b_z \wedge a_x \geq b_x), \\
 \text{westOf\_proj\_strict}(A, B) &\Leftrightarrow \forall a : (\exists b : a_y = b_y \wedge a_z = b_z \wedge a_x > b_x) \wedge \\
 &\quad (\nexists b : a_y = b_y \wedge a_z = b_z \wedge a_x \leq b_x), \\
 \text{northOf\_proj\_strict}(A, B) &\Leftrightarrow \forall a : (\exists b : a_x = b_x \wedge a_z = b_z \wedge a_y < b_y) \wedge \\
 &\quad (\nexists b : a_x = b_x \wedge a_z = b_z \wedge a_y \geq b_y), \\
 \text{southOf\_proj\_strict}(A, B) &\Leftrightarrow \forall a : (\exists b : a_x = b_x \wedge a_z = b_z \wedge a_y > b_y) \wedge \\
 &\quad (\nexists b : a_x = b_x \wedge a_z = b_z \wedge a_y \leq b_y), \\
 \text{above\_proj\_strict}(A, B) &\Leftrightarrow \forall a : (\exists b : a_x = b_x \wedge a_y = b_y \wedge a_z < b_z) \wedge \\
 &\quad (\nexists b : a_x = b_x \wedge a_y = b_y \wedge a_z \geq b_z), \\
 \text{below\_proj\_strict}(A, B) &\Leftrightarrow \forall a : (\exists b : a_x = b_x \wedge a_y = b_y \wedge a_z > b_z) \wedge \\
 &\quad (\nexists b : a_x = b_x \wedge a_y = b_y \wedge a_z \leq b_z).
 \end{aligned}$$

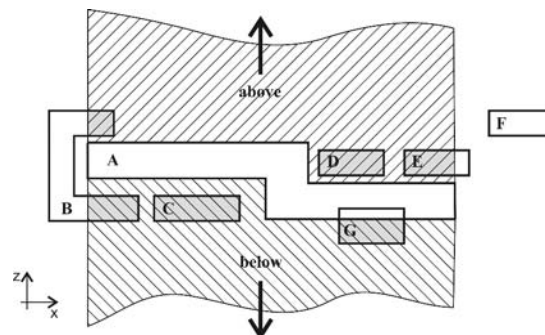
Figure 15 illustrates the consequences of these definitions. In colloquial language, the semantics of the operator *above_proj_strict*, for example, could be described as “directly above” or “exceptionally above”. In Figure 16 the diverging semantics of the different directional operators are illustrated by a practical example.

The halfspace-based model. The second model is based on halfspaces that are described by the reference object’s axis-aligned bounding box (AABB). In this model, the target object is tested for intersection with the halfspace corresponding to the directional predicate. In analogy to the projection-based model, we distinguish strict and relaxed operators. The formal definitions of the relaxed operators are:

$$\begin{aligned}
 \text{eastOf\_hs\_relaxed}(A, B) &\Leftrightarrow \forall a : \exists b : a_x < b_x, \\
 \text{westOf\_hs\_relaxed}(A, B) &\Leftrightarrow \forall a : \exists b : a_x > b_x, \\
 \text{northOf\_hs\_relaxed}(A, B) &\Leftrightarrow \forall a : \exists b : a_y < b_y, \\
 \text{southOf\_hs\_relaxed}(A, B) &\Leftrightarrow \forall a : \exists b : a_y > b_y, \\
 \text{above\_hs\_relaxed}(A, B) &\Leftrightarrow \forall a : \exists b : a_z < b_z, \\
 \text{below\_hs\_relaxed}(A, B) &\Leftrightarrow \forall a : \exists b : a_z > b_z.
 \end{aligned}$$

For the relaxed operators to return *true* it is sufficient if parts of the target object are within the relevant halfspace. By contrast, the *strict* operators

Figure 15. The projection-based directional model relies on the extrusion of the reference object (A) along the respective coordinate axis. In the illustrated example, the relaxed operator *above_proj_relaxed* returns true for the target objects B, D, E and G, but false for any other target object. By contrast, the strict operator *above_proj_strict* also returns false for B, G and E.



only return *true* if the target object is completely within that halfspace. The formal definitions of the strict operators accordingly read:

$$\begin{aligned} \text{eastOf\_hs\_strict}(A, B) &\Leftrightarrow \forall a, b : a_x < b_x, \\ \text{westOf\_hs\_strict}(A, B) &\Leftrightarrow \forall a, b : a_x > b_x, \\ \text{northOf\_hs\_strict}(A, B) &\Leftrightarrow \forall a, b : a_y < b_y, \\ \text{southOf\_hs\_strict}(A, B) &\Leftrightarrow \forall a, b : a_y > b_y, \\ \text{above\_hs\_strict}(A, B) &\Leftrightarrow \forall a, b : a_z < b_z, \\ \text{below\_hs\_strict}(A, B) &\Leftrightarrow \forall a, b : a_z > b_z. \end{aligned}$$

The examples in Figure 17 illustrate the consequences of these definitions.

4.3.5 Topological Operators

Topological operators are used to query the topological relationship between two spatial entities. We distinguish *topological predicates* that represent a certain topological relationship and return a Boolean value indicating whether the operands show this relationship or not, and *selective topological operators* that return the predicate which is fulfilled by the operands.

Topological relationships can be formally described as follows (Clementini & Di Felice, 1995): Let X and Y be topological spaces. A mapping $f: X \rightarrow Y$ is continuous if for each open subset V of Y the set $f^{-1}(V)$ is an open subset of X . If the mapping

Figure 16. Example illustrating the diverging semantics of the different directional operators. In each case, the reference object is depicted in blue, whereas the resulting set identified by the particular operator is depicted in red. Left: *above_proj_strict*. Middle: *above_proj_relaxed*. Right: *above_hs_relaxed*. Please note that, in this example, the result of *above_hs_strict* is equal to that of *above_hs_relaxed*.

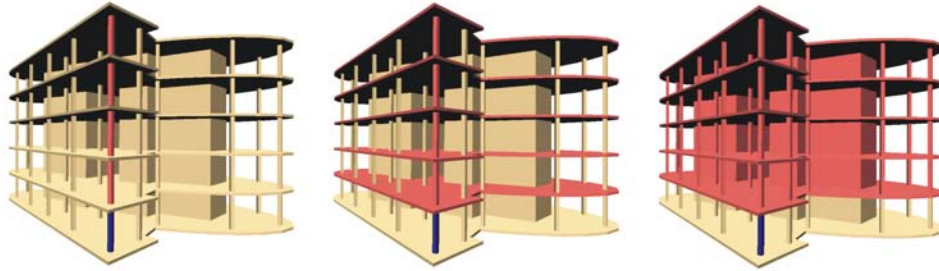
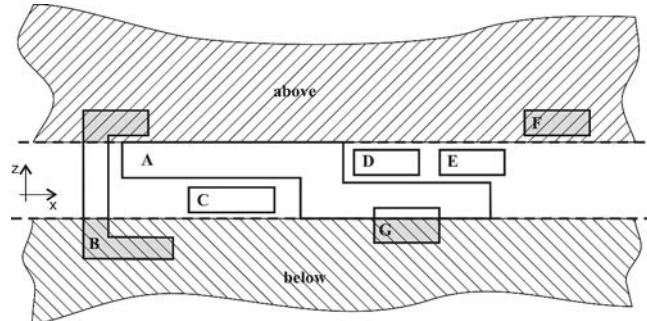


Figure 17. In the halfspace-based directional model the direction tiles are formed by halfspaces defined by the reference object's axis-aligned bounding box. In the given example, A is the reference object. The relaxed operator *above_hs_relaxed* returns true for the target objects B and F , the strict operator *above_hs_strict* only returns true for F .



f is a bijection and both f and f^{-1} are continuous, then f is called a *topological isomorphism*. Topological isomorphisms conserve neighbourhood relationships between points during the mapping. Typical isomorphisms include translation, rotation and scaling ($scaleFactor \neq 0$) as well as any combination of these transformations. Topological relationships are those relationships that are invariant under a topological isomorphism.

Topological relations are among the most intensively investigated spatial relationships in the context of spatial query languages. It soon became obvious that the impreciseness and ambiguity of colloquial language demands a formal definition of topological relationships. However, the main challenge is to find a set of qualitatively distinct relationships that is large enough to allow for a suitable classification and at the same time small enough to keep it manageable for the user.

The first substantial step towards a formalization of topological relationships was the development of the *4-intersection model* by Egenhofer et al. (Egenhofer & Herring, 1990; Egenhofer & Franzosa, 1991). To formally specify the semantics of topological predicates the model determines the intersections between the interior and the boundary of the first object and the interior and the boundary of the second object as an empty or a non-empty set. In theory there are 16 possible configurations but, depending on the dimensionality of the geometric object in question, only a subset can be found in reality.

The intersection concept was first applied to intervals in one-dimensional space (Pullar, 1988) and later extended to cover also relations between simple regions in ² (Egenhofer & Franzosa, 1991). In both cases, 8 different relations to which the natural language denominations *disjoint*, *touch*, *equals*, *inside*, *contains*, *covers*, *coveredBy* and *overlap* could be assigned, were distinguished.

To resolve topological relations between line elements in ² more precisely, the 4-intersection model has been upgraded to the 9-intersection model (9-IM) by incorporating the exteriors of

both operands (Egenhofer & Franzosa, 1991). The resulting nine intersections are recorded in a 3×3 matrix:

$$I_9(A, B) = \begin{bmatrix} A^\circ \cap B^\circ & A^\circ \cap \partial B & A^\circ \cap B^- \\ \partial A \cap B^\circ & \partial A \cap \partial B & \partial A \cap B^- \\ A^- \cap B^\circ & A^- \cap \partial B & A^- \cap B^- \end{bmatrix}.$$

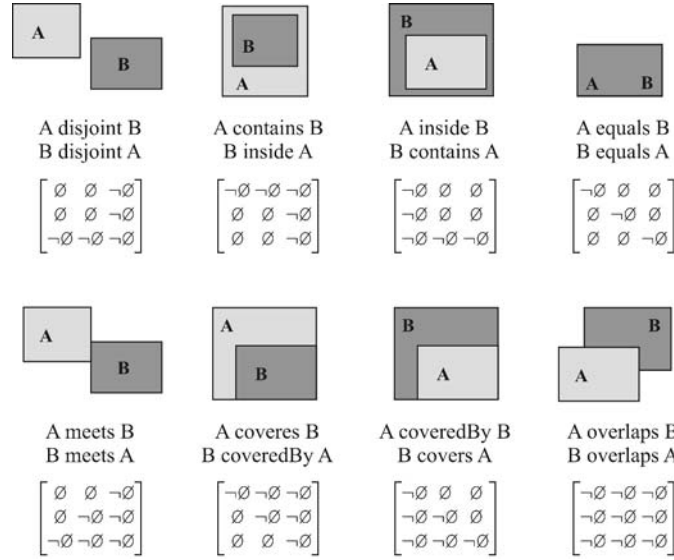
A° denotes the *interior*, ∂A the *boundary* and A^- the *exterior* of the spatial object A (see Section 4.3.5). The 9-IM can also be applied for combinations of spatial objects with a different dimensionality (Egenhofer & Herring, 1992). Figure 18 shows the 9-IM matrices of the eight topological predicates defined by Egenhofer and depicts examples for 2D regions.

One drawback of the 9-IM is that some topological configurations that are intuitively different result in the same 9-IM matrix while others that are intuitively identical are treated as being different. The first problem is partially solved by the *Dimensionally Extended 9-Intersection Model* (DE-9IM) which additionally records the dimensionality of the intersection set (Clementini & Di Felice, 1995).

The DE-9IM forms the basis for the formal definitions of topological relationships in the OGC standard (OpenGIS Consortium, 1999). Here, F (false) is used in the matrices to denote an empty set, T (true) to denote a non-empty set, numbers may be used to define the dimensionality of the intersection set and, in addition, the wildcard (*) may be used at certain places in the matrix that are not relevant for the particular predicate, thereby solving the second of the aforementioned problems. Using this extended set of symbols, the OGC defines the predicates *contains*, *within*, *cross*, *disjoint*, *equals*, *intersect*, *touch* and *overlaps* for arbitrary combinations of (simple) *point*, *line* and *polygon* objects in 2D space.

An important pre-requisite for applying the 9-IM or its derivatives is the formal specification of

Figure 18. The 9-IM matrices originally defined by Egenhofer et al. for 2D space.



the *interior/boundary/exterior* of spatial objects. We can generally distinguish two different approaches to realize this: The first approach relies on algebraic topology using *cellular complexes* (Egenhofer & Herring, 1992) or *simplicial complexes* (Egenhofer et al., 1989; Breunig et al., 1994) to model spatial entities. This implies a complete partitioning of the entire space in a rigorously formal way and thus requires appropriate modelling tools, since conventional B-Rep modellers do not provide these capabilities.

The second approach relies on point-set topology (Egenhofer & Franzosa, 1991; Schneider & Weinrich, 2004; Borrmann et al., 2006): Here, *interior*, *boundary* and *exterior* are understood as point sets. The boundary point set is formed by points whose neighbourhood (a well-defined concept of point-set topology) contains both exterior and interior points. This concept can be easily applied to conventional B-Rep models (Borrmann et al., 2007). Special care has to be taken with dimensionally reduced entities in order to avoid all points becoming boundary points (see Section 4.3.1).

From the 3D GIS domain, there are a number of publications defining topological relationships

by either applying the 9-IM (Oosterom, Vertegaal, Hekken, & Vijlbrief, 1994; Zlatanova, 2000) or the DE-9IM (Wei, Ping, & Jun, 1998). Unfortunately, these definitions are unsuitable for the application in the building model query language context, because they either rely on a cellular decomposition of space, or result in a very large number of topological predicates. For example, in (Zlatanova, 2000) 38 surface-surface relations are identified. This differentiation between topological constellations is much too fine-grained, since it is impossible to find equivalents in human language for each of the constellations, which is required to provide meaningful operators for the query language. For this reason, the authors have decided to set up own definitions.

For our definitions, we use the pure *9-Intersection Model* instead of the dimensionally extended version, because the *dimension* operator cannot be realized by means of the octree implementation technique presented in Section 4.4.1. In order to avoid an unmanageably large number of different topological predicates, we apply the clustering method, as proposed by (Schneider & Behr, 2006), which makes it possible to place wildcards (*) at those places in the 9-IM matrix

that are not decisive for assigning a predicate to a certain constellation.

Besides showing the topological predicates provided within our Spatial Query Language, Figures 19 and 20 also present the corresponding 9-IM matrices and illustrate their semantics for different combinations of types in the form of pictograms. The given system of topological predicates fulfils the demands of *completeness* and *mutual exclusiveness*, i.e. we assign to any topological constellation exactly one of the predicates. This enables the introduction of an additional operator which returns the topological predicate

for any given pair of spatial objects. This operator is called *whichTopoPredicate*.

There are several minor differences compared with the definitions given in (Schneider & Behr, 2006) with respect to the clustering of predicates: The predicates *coveredBy* and *cover* have not been adopted, because in the application domain considered here, it is normally irrelevant whether only the interiors of the operands overlap or whether their boundaries also overlap. Accordingly, these two constellations are subsumed under *within* and *contains*, respectively. In addition, the designation *touch* has been used instead of *meet*

Figure 19. The topological predicates provided by the Spatial Query Language (part 1).

	Point	Line	Surface	Body	Op. B
disjoint $\begin{bmatrix} \emptyset & \emptyset & * \\ \emptyset & \emptyset & * \\ * & * & * \end{bmatrix}$					Op. A Point
					Line
					Surface
					Body
equal $\begin{bmatrix} * & \emptyset & \emptyset \\ \emptyset & * & \emptyset \\ \emptyset & \emptyset & * \end{bmatrix}$					Point
					Line
					Surface
					Body
contain $\begin{bmatrix} \neg\emptyset & * & * \\ * & * & * \\ \emptyset & \emptyset & * \end{bmatrix}$					Point
					Line
					Surface
					Body
within $\begin{bmatrix} \neg\emptyset & * & \emptyset \\ * & * & \emptyset \\ * & * & * \end{bmatrix}$					Point
					Line
					Surface
					Body

in order to gain a maximum compliance to the OGC standard.

4.4 Implementation of Spatial Operators

For implementing the spatial operators the authors developed two different approaches. The first approach is based on a representation of

the operands' geometry as an octree or an octree derivate. The second approach, on the other hand, uses the original boundary representation of the operands, applying more traditional algorithms from computational geometry.

Both approaches have advantages and disadvantages: Whereas the B-Rep-based implementation generally performs faster and returns a more precise result, the octree-based approach allows

Figure 20. The topological predicates provided by the Spatial Query Language (part 2).

	Point	Line	Surface	Body	Op. B
					Op. A
touch $\begin{bmatrix} \emptyset & \neg\emptyset & * \\ * & * & * \\ * & * & * \end{bmatrix}$ $\begin{bmatrix} \emptyset & * & * \\ \neg\emptyset & * & * \\ * & * & * \end{bmatrix}$ $\begin{bmatrix} \emptyset & * & * \\ * & \neg\emptyset & * \\ * & * & * \end{bmatrix}$					Point
					Line
					Surface
					Body
overlap $\begin{bmatrix} \neg\emptyset & * & \neg\emptyset \\ * & * & * \\ \neg\emptyset & * & * \end{bmatrix}$					Point
					Line
					Surface
					Body

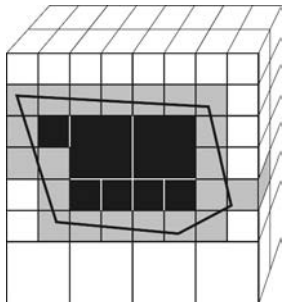
for a fuzzy handling of metric, directional and topological relationships. In some application areas such a fuzzy consideration is closer to users' requirements than an exact one.

4.4.1 Octree Approach

The octree-based implementation of the spatial operators is discussed in detail in (Borrmann, Schraufstetter, & Rank, 2009), (Borrmann & Rank, 2009), and (Borrmann & Rank, 2009a). Here we will only give an overview.

The octree is a space-dividing, hierarchical tree data structure for the discretized representation of 3D volumetric geometry (Hunter, 1978; Jackins & Tanimoto, 1980; Meagher, 1982; Samet, 1985). Each node in the tree represents a cubic cell (an octant) and is either *black*, *white* or *gray*, symbolizing whether the octant lies completely *inside*, *outside* or on the *boundary* of the discretized object (Figure 21). Whereas black and white octants are branch nodes, and accordingly have no children, gray octants are interior nodes that always have eight children. The union of all child cells is equal to the volume of the parent cell, and the ratio of the child cell's edge length to that of its father is always 1:2. The equivalent of the octree in 2D is called quadtree.

Figure 21. Cross-section through an octree. White cells represent the exterior, black cells the interior and gray cells the boundary of the discretized object. Whereas black and white cells are branch nodes, gray cells always have eight children.



In the implementation concept followed here, each spatial object is represented by an individual octree. There are several different approaches for generating an octree out of the object's boundary representation, most of which are based on a recursive algorithm that starts at the root octant and refines those cells that lie on the boundary of the original geometry, i.e. those which are coloured *gray*.

For our implementation we use the creation method developed by Mundani (Mundani, Bungartz, Rank, Romberg, & Niggel, 2003; Mundani, 2005) that is based on the halfspaces formed by the object's bounding faces. In Mundani's approach, the colour classification is based on a simple evaluation of the plane equation of each halfspace for the respective octant and a subsequent combination using Boolean expressions. Accordingly, the algorithm automatically marks inner cells as *black* without the need to perform a computationally expensive filling algorithm. As described in the next sections, the existence of *black* cells is an important prerequisite for the applicability of numerous rules in the algorithms implementing topological and directional relationships.

To cover dimensionally reduced entities with our algorithms, as well, we had to introduce the fourth colour *black/white*. Black/white cells represent areas where the exterior and the interior of the described object exist, but not its boundary (Figure 22).

Slot-tree. The algorithms implementing the projection-based directional operators do not use the octree itself, but a newly developed data structure derived from it. This data structure, called a *slot-tree*, organizes the cells of an octree (the octants) with respect to their position orthogonal to the coordinate axis under consideration.

The basic element of a slot-tree is the *slot*. A slot of level k is formed by the extrusion of a level k cell along the examined axis (x , y or z according to the definitions in Section 4.3.4). It contains all cells which intersect with this extrusion. If we take a look at the z -direction, for example, a slot

contains all the cells that lie above one another (Figure 23). It accordingly possesses a list of octants in the order of their appearance. The octants may stem from different levels of the octree, and consequently may have different sizes (Figure 24). This also means that one octant might appear in the list of different slots. Introducing the slot data structure allows for the application of simple tests based on the colour and absolute position of the cells contained therein in order to decide whether the directional predicate under examination is fulfilled, or not.

In analogy to the octree, the slot-tree organizes the slots in a hierarchical manner. Each node in a 3D slot-tree has either 4 or no children, depending on whether the corresponding slot contains *gray* octants. A slot-tree may be directly derived from an existing octree representation, or generated

on-the-fly while processing the algorithm of the directional operator. The procedure is illustrated in Figure 25. Traversing the octree from the top downwards in a breadth-first manner, we proceed to build up the slot-tree, generating child slots and inserting them into the slot-tree, as required. Such a refinement is necessary if at least one cell in the current slot is *gray*. By coupling the generation of octree and slot-tree with the processing of the directional operator, it is possible to avoid unnecessary refinements at places of no relevance for the operator's results.

In the presented implementation approach, the octree / slot-tree generation is not performed in advance but is coupled with the recursive algorithm presented in the next sections. Thus the octree / slot-tree is built up one level at a time and only at those places that are relevant for verifying or

Figure 22. Dimensionally reduced objects like the disc shown here are discretized using the fourth colour black/white that represents cells which contain interior and exterior points, but no boundary points.

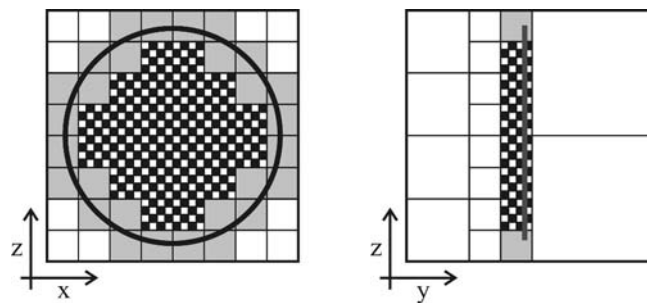


Figure 23. Slots in 3- and 2-dimensional space, respectively. A slot in z-direction contains all the cells that lie above one another.

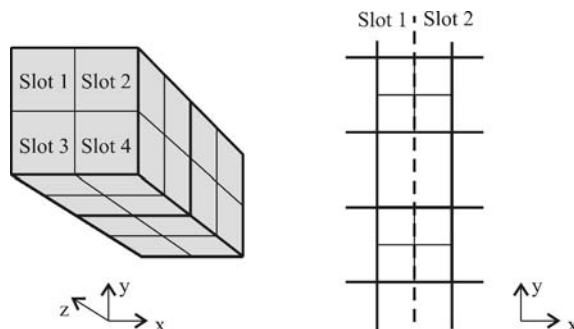
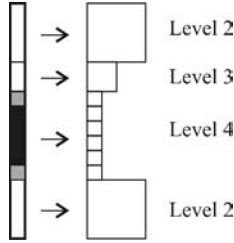


Figure 24. A slot in 2D that owns cells from different levels of the underlying quadtree (Slot 1212 in Figure 25).



disproving the predicate under examination. This significantly speeds up the query processing.

4.4.2 General Principle

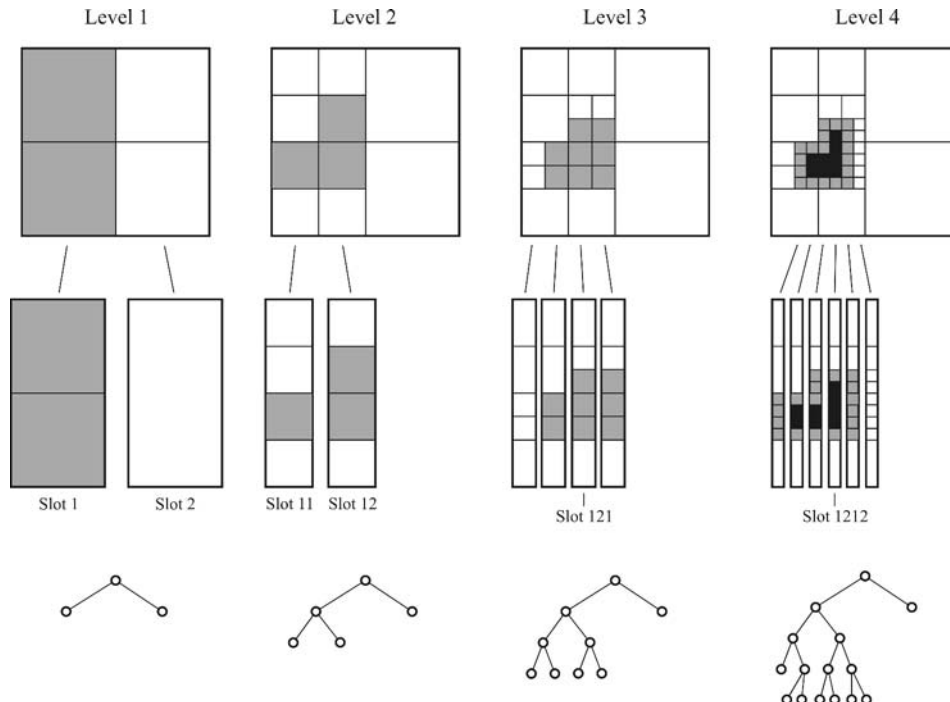
All octree-based algorithms work according the same general principle. As mentioned above, the operands of the spatial operator being processed

are encoded in separate octrees. In a first step, the root octants of both octrees are passed as input to the algorithm.

The algorithm consists in a simultaneous breadth-first traversal of both octrees. During the traversal it creates pairs of octants with one member from each octree. In the case of the algorithm implementing topological operators, both octants cover the same partition of the 3D space, whereas in the case of the metric operators the octant pair is among the candidates for the closest proximity.

The algorithm then applies certain operator-specific rules to the pairs of octants. Depending on the result of this test, the algorithm can either stop the recursion and return *true* or *false*, or it has to continue the recursive traversal by creating pairs of child cells, calling itself recursively and thus entering the next level. The user defines a maximum recursion level – if it is reached, the

Figure 25. Generation of a 2D slot-tree up to level 4. A slot will only be refined if it possesses at least one gray quadrant. A 2D slot tree can be derived directly from the quadtree presentation of the geometry of the objects, a 3D slot tree from an octree representation, respectively.



algorithm returns *true*, *false*, or a number representing the knowledge it has gained so far through the breadth-first traversal.

Though the algorithm implementing the directional operators works on slot-trees instead of octrees, it follows the same general principle. Here, the algorithm performs a breadth first-traversal of the slot-trees. During this traversal, pairs of slots are also created that represent the same partition of the 3D space, and rules are subsequently applied to these slot-pairs.

4.4.3 Metric Operators

In the case of the metric operators, the core of the algorithm consists of calculating the upper and the lower bound of the distance of each cell pair (Borrmann et al., 2009). Since the exact position of the boundary of the objects is unknown when using an octree encoding (Figure 26), an upper and a lower bound of the distance value accordingly has to be calculated for each cell pair. These values represent the interval in which the real distance lies.

When processing the *distance* operator, the rule applied reflects the fact that all cell pairs whose distance is definitely higher than that of any other cell pair can be excluded from further refinement.

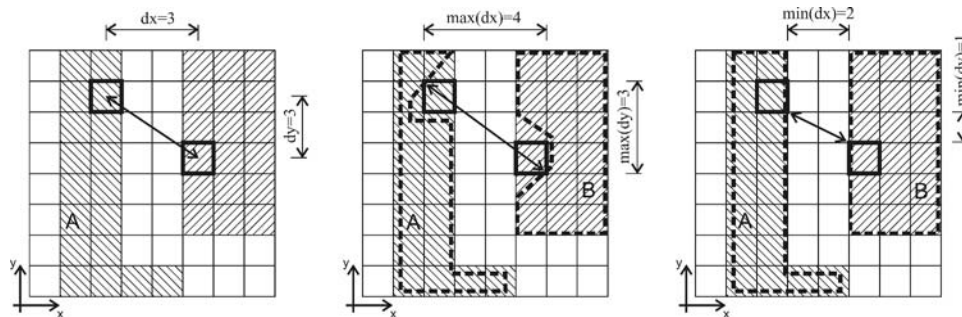
By computing the upper and lower bounds for all cell pairs, it is possible to identify the candidates for the closest cell pair. To this end, the lowest upper bound of all pairs of the current level is determined and all cell pairs whose lower bound is higher than this value are excluded.

All other pairs are candidates. For them, the algorithm is recursively repeated. They are refined, i.e. pairs of the relevant child cells are put together, and the filtering algorithm is applied to the resulting pairs of children, i.e. distance values are calculated, candidates are chosen, and so on. The recursion is aborted when the maximum refinement level is reached.

By descending both octrees in this way, the precision of the calculated distance is successively increased: the calculated distance can be expressed on each level by means of an interval, whose endpoints are calculated from the square root of the upper and lower distance values determined for the cell pairs on the level in question.

The interval in which the real distance lies is calculated after the recursion has finished. The final lower bound results from the square root of the lowest lower bound on the final octree level multiplied by the edge length of an octant on this level. The final upper bound is derived from the square root of the lowest upper bound on the final level, again multiplied by an octant's

Figure 26. Since the exact position of the boundary of the objects is unknown when using octree encodings (left), an upper (middle) and lower bound (right) of the distance have to be determined for each cell pair based on the distance between the midpoints of the cells (left).



edge length. The return value of the algorithm is either a tuple of two real numbers representing the upper and lower bounds of the distance, or a single real number calculated as the arithmetic mean of upper and lower bound. The latter version can be integrated more easily into a spatial query language.

4.4.4 Directional Operators

The halfspace-based directional operators can be implemented by examining the bounding boxes of both the reference and the target object. The algorithms are not explained in detail here, instead the reader is referred to (Borrmann & Rank, 2009).

The core of the algorithm implementing the projection-based directional operators consists of the slot-wise application of rules that are based on the colours of the slots and the octants they contain. First, general tests based on the slots' colours are performed. The colour of a slot is determined by the colours of the octants belonging to it. If at least one of the octants is *gray*, the colour of the slot is also *gray*. The same applies if the slot has both *white* and *black* octants. The slot only obtains the corresponding pure colour if there are just *white* or just *black* octants, respectively.

The occurrence of certain slot colour combinations can lead to a direct validation or disproval of the predicate under examination. In this case,

the recursion can be immediately aborted and the algorithm directly returns *true* or *false*.

For example, if *above_proj_strict(A,B)* is evaluated and a black *B* slot occurs, the algorithm returns *false*, because in this case *B* fills the whole height of the domain, and there is accordingly at least one *B* point that is not above an *A* point.

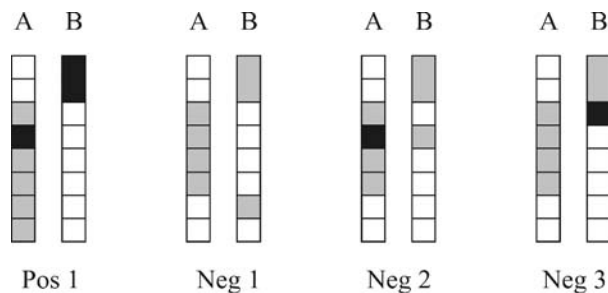
Detailed examinations of the position and the colour of individual cells are only necessary if both slots are *gray*. In this case, the subroutine makes use of the auxiliary functions *lowestNonWhite()*, *highestNonWhite()*, *highestBlack()* and *lowestBlack()* that return the position of the respective cell as integer value, as well as *hasBlack()* that returns a Boolean value. The implementation of these methods relies on a traversal of the list of cells belonging to the slot concerned.

The rules for this exact examination depend on the direction and the version (strict/relaxed) of the operator that is being processed. They are not explained in detail here, but are shown in Figure 27 for the *strict* version of *above_proj* and in Figure 28 for the *relaxed* version of *above_proj*.

If none of the tests yields a positive or a negative result, no definitive statement can be made with regard to the current slot pair and a further refinement is required. Accordingly, pairs of child slots are created.

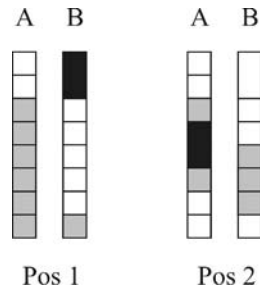
The creation of pairs of child slots is realized as follows: If both slots are *gray*, i.e. not leaf nodes of the corresponding slot tree, each of the four

Figure 27. Examples of constellations where the rules *Pos*, *Neg1*, *Neg2* or *Neg3* are applied during the processing of the algorithm *above_proj_strict(A,B)*. The slots shown side-by-side actually occupy the same position in space.



children of slot A is combined with a child of slot B at the same position, resulting in four pairs of child slots. If one of the slots is either *black* or *white*,

Figure 28. Examples of constellations where the rule *Pos1* and *Pos2* are applied when processing the algorithm above *proj_relaxed(A,B)*. The slots shown side-by-side actually occupy the same position in space.



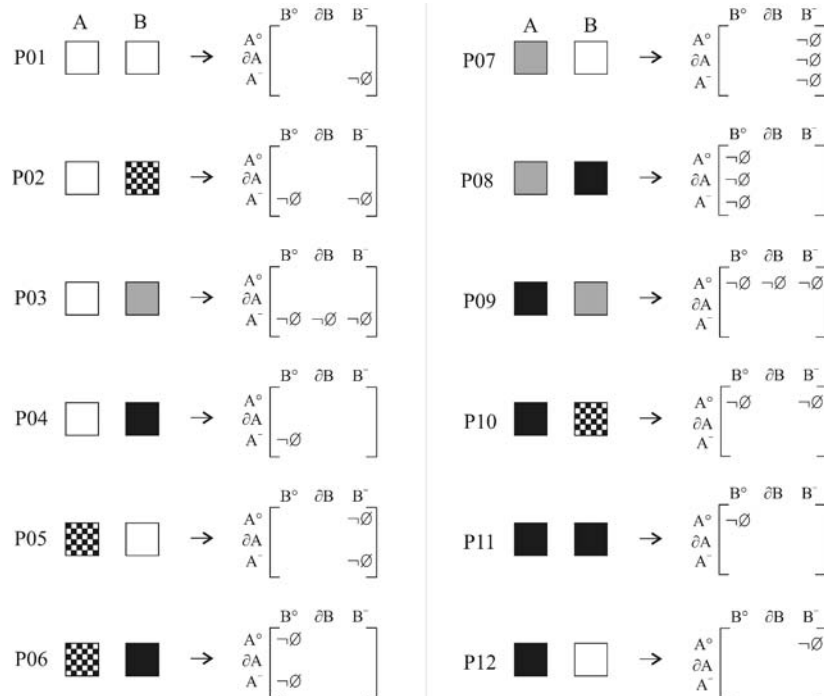
i.e. a leaf node without children, it is combined with each child of the other slot, also resulting in four pairs of child slots. Consequently, there may be pairs of slots from different levels.

The algorithm calls itself recursively until the maximum refinement level is reached. If a decision is still not possible, rules are applied that take the most probable situation into account. This leads to fuzzy handling of directional relationships which is discussed in more detail in Section 4.4.6.

4.4.5 Topological Operators

For implementing the topological operators, pairs of octants are created on each recursion level with one octant originating from object A and one octant from object B , both representing the same sector of the 3D space.

Figure 29. Positive Rules (Part 1). If the colour combination on the left-hand side is detected, the 9IM-Matrix can be filled according to the right-hand side. Combinations of mixed color cells (gray and/or black/white) never lead to filling the 9IM matrix, since they do not allow for a statement about the exact boundary position. For the same reason there is no color combination from which $\partial A \cap \partial B = \neg\emptyset$ could be derived.



Each octant pair provides a colour combination to which specific rules can be applied. These rules may lead to filling a 9-IM working matrix that is maintained by the algorithm to keep track of the knowledge gained about the topological constellation. There are 12 positive and 9 negative rules altogether (Figure 29, 30 and 31). A positive rule can be applied when a certain colour combination occurs, and a negative rule if certain colour combinations do not occur over an entire level. Positive rules lead to empty set entries in the matrix, negative rules to non-empty set entries.

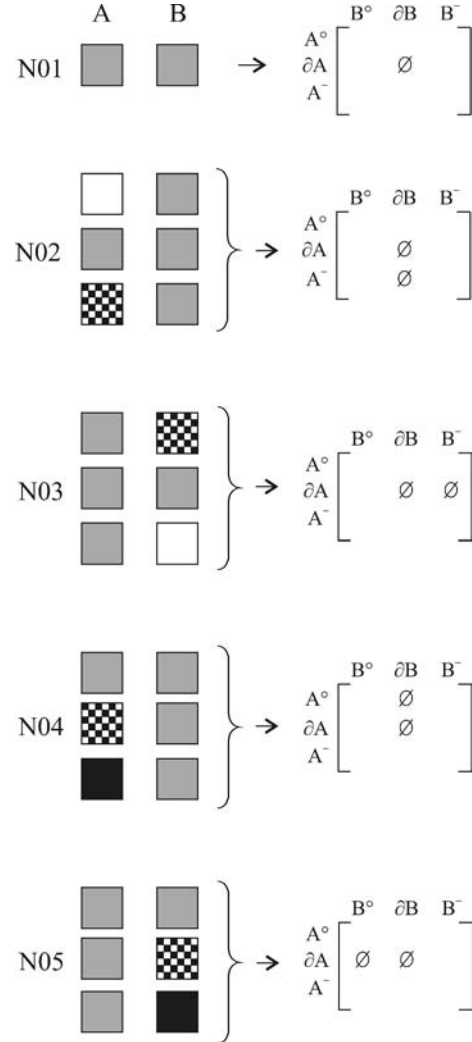
As in the case of the directional operators, the rules are derived from the semantics of the colours. A *white* octant, for example, is part of the *exterior* of an operand, and a *black* octant is part of its *interior*. If a *white* octant of the first operand occurs at the same place as a *black* octant of the second operand, it follows that the intersection between the exterior and the interior of the operands is non-empty.

The 9-IM working matrix is successively filled by applying these rules to all octant pairs. When processing the operator *whichTopoPredicate* the working matrix is compared with all predicate matrices of the formal definitions (Section 4.3.5). If the working matrix complies fully with one of them, the recursion is aborted and the algorithm returns the respective predicate. If there is any contradiction between the filled matrix and the matrix of a predicate, the respective predicate is precluded. If no unequivocal decision is possible for any of the predicates, a further refinement is necessary, i.e. octant pairs of the next level are created.

In the case of the predicate operators the 9-IM working matrix is checked against the corresponding predicate matrix only. If there is a contradiction the algorithm returns *false*, if it completely complies, it returns *true*.

If, after execution of all applicable rules, the current occupancy of the working matrix does not allow for validation or disproval of the/any predicate and the maximum refinement level is not

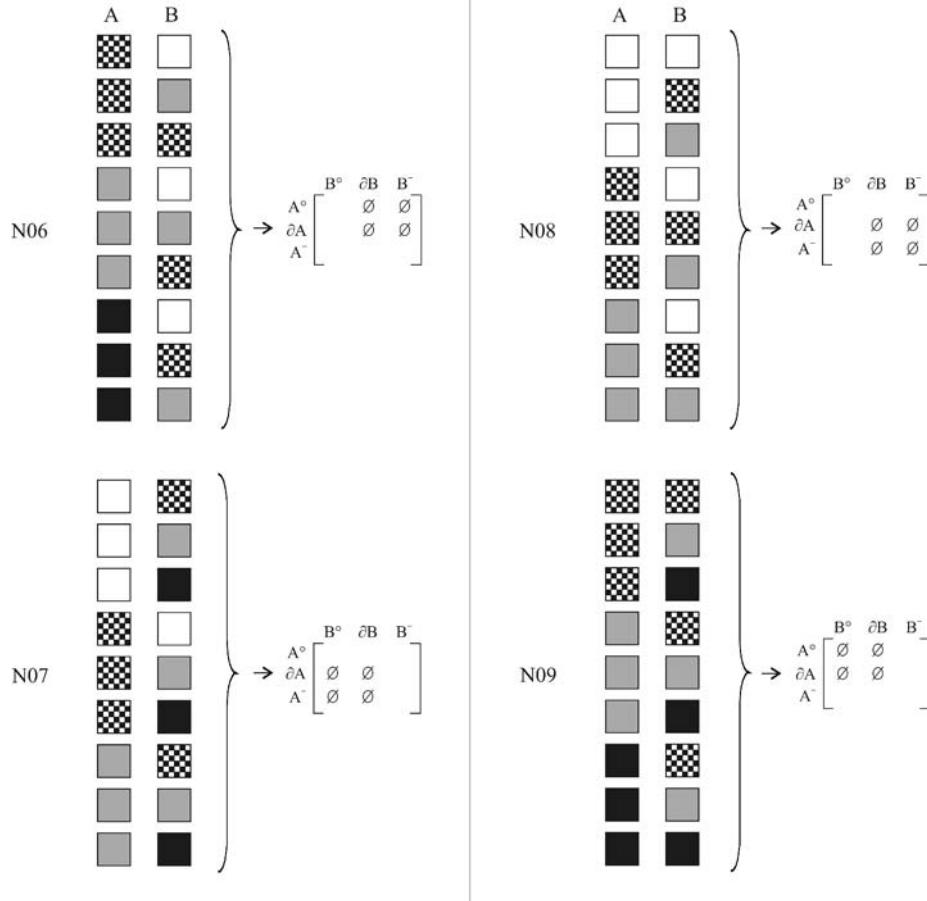
Figure 30. Negative Rules (1). If the colour combinations of the left-hand side do not occur across the entire domain, the 9-IM matrix can be filled according to the right hand side.



reached, child pairs are created and the algorithm calls itself recursively.

If the algorithm reaches the maximum refinement level and, in the case of *whichTopoPredicate*, none of the predicates is proved or, in the case of a predicate operator, the predicate under examination is neither proved nor disproved, a so-called predicate hierarchy is applied, which again ensures that the most probable situation is detected. This is discussed in the next subsection.

Figure 31. Negative Rules (2). If the colour combinations of the left-hand side do not occur in the entire domain, the 9-IM matrix can be filled according to the right hand side.



4.4.6 Fuzziness

The octree geometry representation shows a crucial peculiarity for the implementation of spatial operators: The boundary of an object encoded by an octree is not represented sharply, i.e. not as a set of points for each of which a neighbourhood exists that contains both interior and exterior points, but instead in the form of (grey) octants which define a boundary *layer*. The thickness of the layer shrinks with an increasing maximum refinement level (MRL): However, for finite values of the MRL it remains a layer.

This induces a certain fuzziness for all spatial operators. On the one hand such fuzziness results

in inaccurate results if the MRL is not chosen high enough. On the other hand it enables the spatial operators to react more “mildly”, thus corresponding better to the way human handle qualitative spatial relationships.

A typical example is the relationship *touch*. Even if two building elements “slightly” overlap, in certain application scenarios the user, or some analysis program, might want to treat them as being in touch. The same applies if there is a slight gap between the elements.

In the following paragraphs, each instance of impreciseness involved in the octree approach is discussed individually for the metric, directional and topological operators.

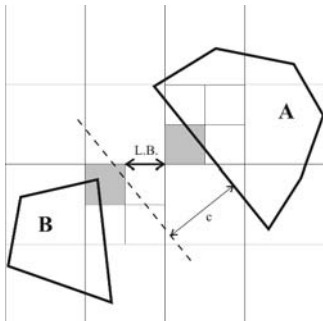
Metric Operators. The metric operator *distance* returns a lower and upper bound between which the real distance lies. This can be seen as uncritical, because it does not involve any error. The same applies to *maxdist*.

By contrast, the predicate operator *closerThan* and *fartherThan* may incorrectly return *true* or *false*, respectively, if the chosen MRL is not high enough, as shown in Figure 32. Note that, due to the underlying logic of taking into account the cell pairs' lower bound distances, *fartherThan* will never return *true* by mistake, not will *closerThan* return *false* by mistake.

In an alternative approach, one could consider to use a ternary instead of a Boolean value to be returned by *closerThan* and *fartherThan*, providing *unknown* as additional possible value. Unknown would be returned if the queried distance c lies between the lower and the upper bound calculated on the MRL. We will further examine this implementation option in future publications.

Directional Operators. The interpretation of non-resolved slot pairs on the final level depends

Figure 32. Situation where *closerThan*(A, B, c) erroneously returns *true*, and *fartherThan*(A, B, c) erroneously returns *false* if the maximum refinement level (MRL) is too low. This is caused by the implementation of the operators which relies on the calculated lower bound (L.B.) of the distance value on the MRL. In an alternative approach, both operators would return *unknown* when c lies between the lower and the upper bound.



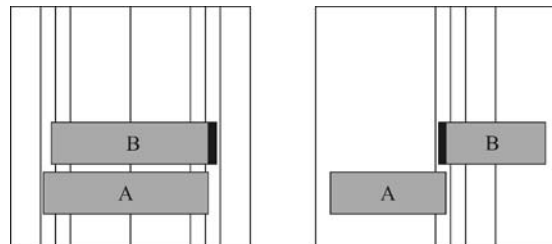
on whether the strict or the relaxed version of the directional predicates is being processed.

The different treatment of unresolved cases is chosen in such a way that it reflects the more probable situation: When applying the strict operator, one slot pair that *violates* the definition suffices to stop the algorithm and make the operator return *false*. It can therefore be assumed that the objects in question *fulfil* the definition if the MRL is reached and no such slot pair has been found. By contrast, when applying the relaxed operator, one slot pair that *fulfils* the definition suffices to stop the algorithm and cause the operator to return *false*. Thus, in this case it is assumed that the objects in question *violate* the definition if the MRL is reached and no such slot pair has been found.

According to this interpretation, the strict operators may incorrectly return *true* when the definition is actually violated (Figure 33, left) while, on the other hand, the relaxed operators may return *false* although the definition is actually satisfied (Figure 33, right).

Topological Operators. If, in the case of a predicate operator, the predicate under examination is neither proved nor disproved when reaching the MRL or, in the case of the *whichTopoPredicate* operator, none of the predicates is fully proved,

Figure 33. In the given examples, the critical parts (depicted in black) will not be detected by the slot-based algorithms if the maximum refinement level is not greater than 4. Left: The operator above *_proj_strict* will incorrectly return *true*. Right: The operator above *_proj_relaxed* will incorrectly return *false*.



the predicate hierarchy shown in Figure 34 is applied, i.e. the algorithm returns the highest non-disproved predicate of the hierarchy. The order of the hierarchy is chosen in such a way that, if the actual topological constellation complies with predicate *a*, all predicates above predicate *a* are disproved during successive refinement. On the other hand, the predicates below *a* are not necessarily disproved. In the sense of a “positivistic” approach it is assumed that the highest non-disproved predicate has been proven.

If both operands have the same dimensionality, *contain* and *within* are equivalent, i.e. for the validation of a “lower” predicate, both *contain* and *within* must be disproved. The equivalence of the predicates results from the fact that when disproving *equal*, either *contain* or *within* is disproved at the same time.

Applying the predicate hierarchy may result in the detection of an incorrect topological predicate if the MRL is too low. However, the hierarchy is chosen in such a way that these errors/misjudgements are acceptable, since they comply with the intuitive human understanding of qualitative spatial relationships. Figure 35 illustrates constellations where the application of the predicate

hierarchy results in the detection of an incorrect topological predicate.

Using the “positivistic” approach, the requirements of *logical consistency*, *mutual exclusiveness* and *complete coverage* are met by the system of topological operators, since in any case precisely one topological predicate is detected for any topological constellation no matter if the user applies the predicate operators or *whichTopoPredicate*.

4.4.7 B-Rep Approaches

The second general approach for implementing the spatial operators is based on the exact shapes of the geometric objects (the operands) given by their boundary representation (B-Rep). As opposed to the octree-based implementation, these algorithms work directly on the exact geometry description and accordingly return precise results.

Naive implementations on the basis of the B-Rep structure require a high computational effort or (e.g.) are restricted to convex bodies. In our approach we therefore use a hierarchical representation of the faceted objects. This makes it possible to exclude the irrelevant parts of the operands’ geometry at an early stage, thus

Figure 34. The hierarchy of the topological predicates for different type combinations. The algorithm returns the highest non-disproved predicate. The order of the hierarchy results from the observation that all predicates above a certain predicate *x* are disproved during the ongoing refinement if the actual topological constellation complies with predicate *x*. This hierarchy permits a fuzzy handling of topological relationships.

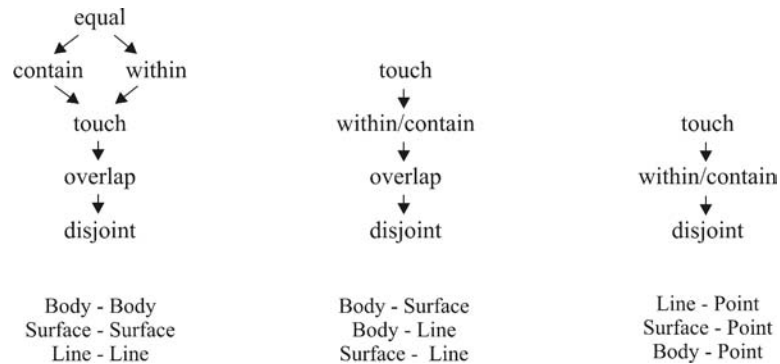
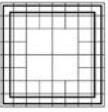
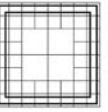
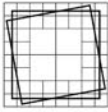
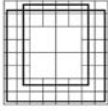
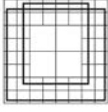
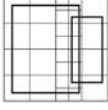
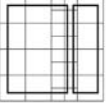


Figure 35. Misjudgements of the topological operators caused by inadequately refined resolution in the case of Body–Body constellations. The predicate assigned by the algorithm (horizontal) to the found situation (vertical) results directly from the design of the predicate hierarchy. The maximum resolution chosen for this example is represented by the smallest visible cell resolution. Empty table cells indicate that the corresponding misdetection does not occur.

	equal situation	contain situation	within situation	touch situation	overlap situation	disjoint situation
erroneously detected as <i>equal</i>						
erroneously detected as <i>contain</i>						
erroneously detected as <i>within</i>						
erroneously detected as <i>touch</i>						
erroneously detected as <i>overlap</i>						
erroneously detected as <i>disjoint</i>						

avoiding unnecessary computations. At the same time, parts that may have an impact on the result are examined in increasing detail. The principle employed here is also known as “divide-and-conquer” strategy.

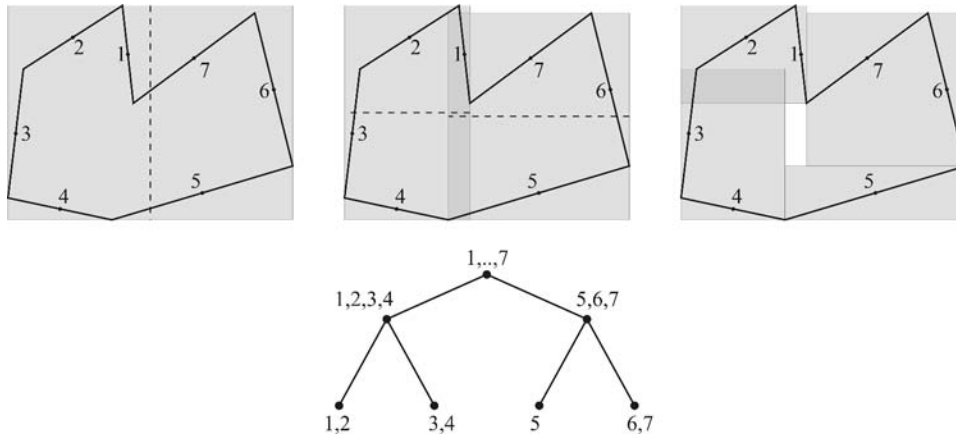
In the presented approach, AABB trees are chosen for the hierarchical representation. AABB trees are binary trees that recursively divide the space, along one coordinate axis on each occasion. A box-shaped hull volume (axis-aligned bounding box, AABB) that encloses the hull volumes of both child nodes is assigned to each node in the tree (Figure 36). The leaf nodes of the tree contain one or more facets of the geometric object, as well

as the bounding box containing these facets. It is important to note that an AABB tree, as opposed to the octree, is not a geometry representation, but a spatial indexing of the boundary representation.

The choice of employing an AABB tree is motivated by its simple structure not only enabling a fast generation of the tree but also permitting simple and consequently computationally cheap tests on the AABBs, such as intersection tests, for example.

There are various strategies for the concrete partitioning of the facets (Bergen, 1997). A commonly used partition rule considers the projection of all the facets on the longest axis of the AABB. If

Figure 36. Example of the generation of an AABB tree for a polygon in 2D. On each level, the space is divided along the longest axis. Each edge of the polygon is then assigned to one of the subspaces by considering the location of its midpoint. Afterwards an axis-aligned bounding box is created containing all edges belonging to one of the subspaces. For this bounding box, the process is recursively repeated, entering the next level of the tree.



the projection of the midpoint of a facet is located to the left of the projection of the midpoint of the entire AABB, the facet is assigned to the left-hand subspace, in the other case it is assigned to the right-hand subspace. Once all the facets have been classified, the process is recursively repeated for both the left and the right-hand subspace. The recursion is aborted as soon as only one facet is left in an AABB, or the maximum tree level has been reached.

The basic structure for implementing spatial operators using AABB trees is as follows: the first step is to generate AABB trees for both operands A and B of the spatial operator. Then the AABB trees are traversed in breadth-first manner and pairs consisting of one AABB from A and one AABB from B are created. Depending on the operator being processed some of the AABB pairs of the current level can be excluded from further examination, because they obviously do not have any impact on the result. All the other AABB pairs are further refined.

If both members of the AABB pair are leaf nodes in the corresponding tree, no further refinement is possible. In this case, pairs of the facets

contained in the AABBs are created. Depending on the operator being processed, precise tests, such as intersection tests, are now carried out on the facet pairs. This procedure makes it possible to reduce computationally expensive tests to a minimum.

Metric operators. For implementing the operator *distance*, the AABB trees are traversed in a similar fashion to the octree-based implementation, i.e. an upper and lower bounds are computed for each pair of AABBs and accordingly all irrelevant pairs and their children are pruned.

If an AABB pair is a potential candidate for the closest proximity and both AABBs of the pair are leaf nodes, we create the cross product of all primitives assigned to the two AABBs and, in a final calculation step, compute the exact minimal distance for all resulting pairs. The exact distance between two primitives under consideration is computed using the GJK algorithm for convex polyhedrons (Gilbert, Johnson, & Keerthi, 1988). Since an AABB generally encompasses a few triangles only, the computational effort is limited.

The computed distances between triangles may lead to a new minimum upper distance that can

be used to exclude other AABB pairs in the same way as in the octree-based approach. It is possible that an AABB pair is a potential candidate for the closest proximity, but only one box of the pair is a leaf and, therefore, only the second bounding box has two children. In this case, the two children of the second AABB are paired with the first AABB, respectively. Finally, the global minimum distance turns out to be the shortest distance between one triangle and another, as computed using the GJK algorithm.

Topological operators. In Figure 37 the algorithm for implementing the topological operator *whichTopoPredicate* is depicted schematically. In the first stage, an intersection test is performed to ascertain whether the two operands overlap, or not. It works in the same fashion as the algorithm implementing the metric operators, except that all distance calculations are replaced by intersection tests. A further refinement in the AABB trees is realized each time two AABBs intersect. On reaching the leaf nodes, facet pairs are created and tested on intersection. If an intersection is detected the predicate *overlap* can be returned.

If there is no intersection, the operands are either disjoint or one lies within the other. The

exact topological relationship, i.e. which of the predicates *contain*, *within* or *disjoint* can be applied, is determined by using a search ray and counting the number of intersection points. The ray test can also be implemented by applying a “divide-and-conquer strategy”: Intersection tests for the ray and the AABBs (Williams, Barrus, Morley, & Shirley, 2005) are executed until the final level is reached – only then are intersection tests performed for the ray and individual facets (Moeller & Trumbore, 1997).

The actual algorithm can be described as follows: First we choose an arbitrary axis-aligned ray starting at the surface of *B*, determine the intersection points of this ray and the objects *A* and *B* and then sort them according to their occurrence in the direction of the ray. By choosing the surface of *B* as origin of the ray, the ray is guaranteed to hit at least one object and will not miss both of them. Now the number of intersection points of the ray and object *A* which occur before the first intersection of the ray and object *B* are taken into account (see Figure 38).

If this number is odd, it can be stated that *B* is located within *A*, and the predicate *contain(A,B)* is returned. If the number of intersections is even,

Figure 37. Schema of the BRep-based algorithm implementing topological operators.

Intersection test				
Intersection?				
Yes	No			
	Ray test starting from B			
	Number of intersection points with A before first intersection with B			
	Even > 0	Odd	0	
			Ray test starting from A	
			Number of intersection points with B before first intersection with A	
			Even	Odd
Overlap(A,B)	Disjoint(A,B)	Contain(A,B)	Disjoint(A,B)	Within(A,B)

but greater than 0, the situation is vice-versa and the predicate *within*(A, B) is returned. If the number of intersection is 0, no topological predicate can be determined. Instead, a second ray test, this time starting at the surface of A , is required. An odd number of intersection leads to assigning the predicate *within*(A, B), whereas 0 or an even number of intersections lead to assigning the predicate *disjoint*(A, B).

Directional operators. BRep-based algorithms for the implementation of directional operators are still under development. However there are some promising approaches that again are based on the application of ray tests. Results will be presented in future publications.

4.5 Embedding Spatial Operators within a Query Language

The integration of the spatial types and operators defined in the previous section in one of the available query languages for Building Information Model discussed in Section 3 enables the user to apply both semantic and spatial conditions within a single query.

To find the most suitable of the options available, we experimented with three different query languages. For assessing the suitability of the query language basis we applied the following criteria:

1. **Extensibility.** The query language must allow for an extension of the type system or at least an integration of user-defined functions.
2. **Expressive power.** The query language must provide easy access to semantic data, including attribute values, collections, and navigation along references.
3. **Simplicity.** The query statement should be as short as possible, avoiding any syntactic overhead.
4. **Availability of processors.** There should be a number of processing engines available for

the query language, preferably under public license, to facilitate their use in research context.

The first criterion is the most crucial requirement: If the query language in question has a fixed set of applicable operators that cannot be extended, it is unsuitable as a basis for spatial query functionality. All other criteria are “soft” in the sense that they do not form an absolute requirement.

As explained in detail in Section 3, EXPRESS-X is the most appropriate option thanks to its conceptual closeness to the original data modelling language EXPRESS, resulting in a maximum of achievable expressive power and coupled with short, simple query statements. However, it lacks the essential means to integrate user-defined operators and can thus not be considered as query language basis.

We accordingly decided not to use EXPRESS-X, but to experiment with alternative query languages, namely SQL and XQuery, instead.

4.5.1 Embedding Spatial Operators in SQL

In a first attempt, we based the spatial query support on SQL, since it is one of the most widespread and powerful declarative query languages. Many SQL dialects allow for an extension of the available operators by means of user-defined functions, which may subsequently be used within the WHERE part of an SQL statement. For embedding the spatial operators we experimented with both versions of the SQL standard, the purely relational version SQL-92 and the object-relational version SQL:1999. Since by means of SQL:1999, a more sophisticated embedding is possible we will first describe this variant.

SQL:1999. As discussed in Section 3.4.2, SQL:1999 provides the user the possibility to define abstract data types (ADTs), thus extending the database type system in an object-oriented

way. These ADTs may not only possess attributes and references to other ADTs but also member functions (methods) that define the behaviour of the corresponding object instances. Accordingly, the spatial data types defined in Section 4.3.1 can be defined as ADTs providing the spatial operators as member functions.

The algorithms implementing the spatial operators that are presented in Section 4.4 require the explicit B-Rep geometry of the involved building components. Though building information models usually allow multiple ways to define geometry (extrusion, constructive solid geometry etc.), we have to assume the existence of a boundary representation here.

Taking the IFC data model as an example, a suitable place to introduce the spatial operators is the entity *IfcManifoldSolidBrep* which is used to model faceted BRep geometries that may contain voids. Using the capabilities of SQL:1999 the type can be easily extended by member functions representing the metric, directional and topological operators defined in Section 4.3. However, as presented in Figure 39, navigating from a building element object to its *IfcManifoldSolidBrep* representation involves 3 intermediate steps resulting in long and unhandy navigation expressions. The authors therefore propose the extension of the *IfcElement* class by the member function *shape()* that acts as short-cut and returns the corresponding *IfcManifoldSolidBrep* object.

By realizing this, spatial query functionality can be made available to end-users and third-party

programmers in an easily manageable manner. A specimen query that retrieves all columns that touch the slab whose ID is *Oid23089* then reads:

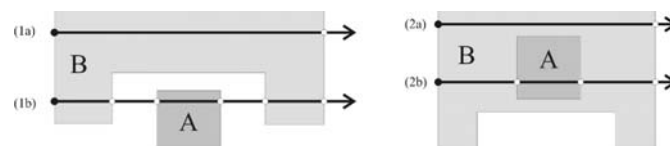
```
SELECT * FROM IFCColumn col,
IFCSlab slab3 WHERE col.
shape().touch(slab3) AND slab3.
id = 'Oid23089'
```

For a prototype implementation the authors used the commercially available ORDBMS Oracle 10g. For more detailed information on the integration of spatial operators in SQL using object-relational techniques, the reader is referred to (Borrmann & Rank, 2009; Borrmann et al., 2009).

The most important advantage of using an object-relational approach is the strong type safety provided by the declaration of user-defined types. The declaration of the *touch* member function, for example, forces the passed parameter to be of type *IfcElement* or one of its sub-types. Thus, type errors may already be detected by the query engine during the interpretation of the SQL statement and more specific error reports can be generated.

SQL-92. As for the desired purpose of a declarative spatial query language for BIMs, traditional database functionalities such as concurrency control, rights management and persistency are not of primary interest, the utilization of an in-memory database (IMDB) seems to be most appropriate.

Figure 38. Ray tests for determining topological relationships. The origin of the ray is marked by a filled circle, the intersection points by an empty circle. Ray (1b) correctly detects the predicate *disjoint(A,B)* and ray (2b) the predicate *within(A,B)*. No conclusions can be drawn, however, from the rays (1a), (1c) and (2a), since they do not hit operand A. In this case, a second test is performed, this time using a ray that starts at the surface of A.



These systems, which are normally completely embedded in the final application, usually provide SQL query and data manipulation functionality while avoiding the high overhead of hard-disk access. Unfortunately, there are no in-memory databases available today that provide the full range of the SQL:1999 standard, especially with respect to the possibility of defining ADT's.

We therefore decided in a second approach to base the spatial query functionality on purely relational databases. Here, a semantically weaker way of defining the spatial operators has to be chosen. All spatial operators are defined as global functions whose parameters are *strings* representing the operand's IDs. The specimen query then reads:

```
SELECT col.id FROM IFCCol-
umn col, IFCSlab slab3 WHERE
touch(col.id, slab3.id) AND
slab3.id = 'Oid23089'
```

4.5.2 Embedding Spatial Operators in XQuery

In XQuery, spatial operators are integrated in a similar manner as in SQL. It is an important

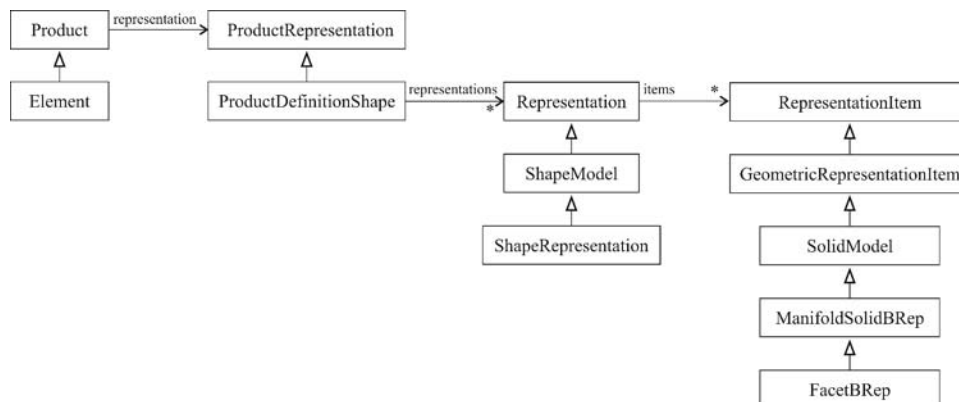
prerequisite that the XQuery engine supports the calling of external functions. If this fulfilled, the external functions are first declared in the prolog of the query:

```
declare namespace spatial
= 'java:de.tum.cie.Spatia-
lOperators'; declare func-
tion spatial:touch($arg1 as
xs:string, $arg2 as xs:string)
as xs:boolean external;
```

Afterwards they can be employed in the *where* part of the query:

```
let $uos:= $this/
ex:iso_10303_28/
ifc:uos for $column in $uos/
ifc:IfcColumn, $slab in
$uos/ifc:IfcSlab, where
spatial:touch($column/id, $slab/
id) and slab[@id=Oid23089] re-
turn <QueryResult>{$column}</
QueryResult>
```

Figure 39. Due to the complex structure of the IFC, access to a building element's geometry representation has to be realized using 3 intermediate steps.



4.6 Software Prototype

To prove the feasibility of the developed concepts we implemented a software prototype that offers spatial query functionality for building information models (Figure 40). It is capable to process IFC building models provided in either the STEP-P21 or the ifcXML file format. In order to avoid the laborious implementation of the geometry generation, we have chosen to take advantage of IFC-VRML files containing the explicit building geometry. Such files can be generated from an IFC model by using the *IFCStoreyView* program developed by the Karlsruhe Institute of Technology¹¹.

To realize the query support for STEP-P21 files the *exp2ddl* and *p21tosql* tools introduced in Section 3.4.1 have been employed. By the help of these tools, an in-memory database is created whose schema is capable to hold IFC data in a relational form. When reading the STEP-P21 file, the tables of the database are accordingly filled with data. At the same time the IFC-VRML file containing the corresponding explicit geometry representation is read into the spatial processing engine. The user can subsequently employ SQL-92 to query the semantic data of the IFC model

and use the spatial operators available as global functions.

If the user provides a building model in the ifcXML format, the XML file is read into memory using the library *XMLBeans*¹². Subsequently, the building model data is available for query processing employing the XQuery engine Saxon¹³. Again the geometry is read-in through a corresponding IFC-VRML file. All spatial operators are declared as external XQuery functions and will accordingly be called if they appear in a query.

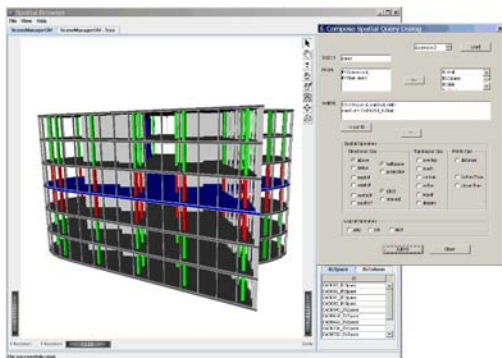
After processing either the SQL query or the XQuery, the resulting set of building elements is highlighted in the 3D viewer.

A serious condition for the correct functioning of the spatial query functionality is a high quality of the geometry provided in the IFC building model. If the model contains isolated or unconnected polygons or bodies with missing polygons, incorrect query results may be returned. For the future we therefore plan to develop a geometric pre-processor that is able to detect these kinds of imperfections beforehand and warn the user accordingly.

5 CONCLUSION

This chapter has discussed in detail the technical possibilities for querying Building Information Models applying both semantic and spatial constraints. The first section investigates the query technologies available for traditional, non-spatial conditions. The complex structure of the EXPRESS-based data models currently in use for building information modelling requires a language with a high expressive power that permits a simple, concise formulation of queries. Since decisive attributes are often linked to the desired entities by a number of intermediate steps, facilities for an easy navigation along references are particularly important. From a formal point of view, EXPRESS-X has been identified as the most appropriate query language option. Since there is

Figure 40. Screenshot of the prototype application showing the dialog for composing spatial SQL queries and the 3D viewer highlighting the result set.



only a very limited number of processing engines available, for one thing, and it lacks the required extensibility for integrating spatial query functionalities, for another, alternative options including SQL and XQuery are also presented here.

The second part focused on realizing the spatial query functionality. The proposed qualitative spatial operators form an intermediate level of abstraction between the technical representation of a building's geometry (using vertex coordinates etc.) and the way engineers and architects think about the geometrical and topological relationships between building components. By applying spatial operators the users can easily identify building components that fulfil certain metric, directional or topological conditions. The chapter provides detailed formal definitions of the semantics of the spatial operators and gives an overview on different implementation approaches.

For the future, declarative query support for building information models providing spatial and semantic conditions will be of increasing importance. On the one hand, the sound definition of the content of partial models is a crucial prerequisite for realizing BIM-based collaborative planning processes. On the other hand, it is expected that national and international regulation authorities will make extensive use of automated code checking procedures based on digital building models. For encoding the respective codes, rules and laws in form a readable by both humans and machines, a declarative query language providing both semantic and spatial constraints forms an excellent basis.

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KEY TERMS AND DEFINITIONS

Building Information Model (BIM): A computational representation of a planned or built building. The representation comprises the 3D geometry of the building elements and the spaces, as well as semantic (non-geometric) information, such as element types and material properties. Also there is a rich set of relationships between building elements stored in the building model. A BIM is modeled using object-oriented modeling techniques.

BIM Query: A BIM query is used to retrieve a well-specified subset of the entire building model. The query is formalized using either a query language or a schema representation. BIM queries are used in human-machine as well as machine-machine communication.

Semantic Query: A semantic query uses properties of BIM entities and/or relationships

between them as selection criteria that are defined in the BIM.

Spatial Query: A spatial query uses properties and/or relationships that are of spatial nature and are not explicitly available in the BIM. To process a spatial query the 3D geometry model is analyzed.

Spatial Query Language: A formal language that allows formulating spatial queries by providing topological, directional and metric operators for specifying selection criteria.

Topological Operator: Topological operators are used to query topological relationships between two entities of the building model. Topological relationships are invariant under affine transformations, such as rotation, translation and scaling (factor $\neq$ 0). To use topological relationships as selection criteria in a spatial query language, the large set of possible topological constellations is clustered and a human language denomination (*touch, contain, within, ...*) is assigned to each of these clusters.

Directional Operator: Directional operators are used to query directional relationships between two entities of the building model. Direction is a binary relation of an ordered pair of objects A and B, where A is the reference object and B is the target object. The third part of a directional relation is formed by the reference frame, which assigns names or symbols to space partitions. In the context of BIM queries, an *extrinsic* reference frame is applied, which is formed by the Cartesian coordinate system the BIM is placed in. The

space partitions can be created applying different techniques (e.g. halfspaces or projections); in any case, the denomination of the cardinal directions (*northof, westof, above, ...*) or combinations are assigned to them.

Metric Operator: Metric operators are used to query distance relationships between two building entities. Examples for metric operators are *distance, closerThan* and *fartherThan*.

ENDNOTES

- ¹ The respective entities in the IFC model have the prefix *IfcRel*.
- ² <http://www.coa.gatech.edu/~aisc/cisifc>
- ³ <http://www.steptools.com>
- ⁴ <http://www.pdtec.de>
- ⁵ <http://exp-engine.sourceforge.net>
- ⁶ <http://ems.eurostep.fi/PMQL/Doc/index.htm>
- ⁷ <http://www.blis-project.org/~sable/>
- ⁸ This is widely known as “impedance mismatch” between the object-oriented and the relational world.
- ⁹ Objektkatalog für das Straßen- und Verkehrswesen, <http://www.okstra.de>
- ¹⁰ <http://www.ispras.ru/~step/>
- ¹¹ http://www.ifcwiki.org/index.php/IfcStoreView_VRML_Export
- ¹² <http://xmlbeans.apache.org>
- ¹³ <http://www.saxonica.com>

Chapter 19

Basic Topological Notions and their Relation to BIM

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ABSTRACT

Each building sets up a topological space in the mathematical sense. Therefore every Building Information Model (BIM) has to store topological information. Such information can be found, for example, in the IFC (Liebich et al. 2005). The volume modelling part of the IFC uses a so-called 'IfcTopologyResource' which is a topological model on the local scope of each single building element. At a global scope, the 'IfcRelConnects' class and its subclasses are used for the connectivity of the building parts. This chapter presents a generalizing concept which handles both "local" and "global" connectivity information in a common way and provides means to mutually relate them.

1 INTRODUCTION

Even if the absence of a common concept for handling both "local" and "global" topologies is not considered a problem, ad-hoc-modelling of topological properties in BIM without adequate topological knowledge may end up with flaws. Such knowledge also helps distinguish spatial semantics from non-spatial semantics, and it avoids complicating the model. A good example for such complexity is the 'IfcRelConnects' class hierarchy: The class 'IfcRelConnectsElements' defines two attributes

'Related' and 'Relating' referencing two *elements* which are somehow connected. Another subclasses of 'IfcRelConnects', however, have a completely different signature and meaning: Namely, the class 'IfcRelSpaceBoundary' "relates" a room *element* to a *set* of boundary elements and a similar class 'IfcRelCoversSpaces' where a room *element* "is related" to a *set* of boundary surfaces. So we have an element-element, an element-set, and a set-element signature, and even a transposition of the meaning of "relating" and "related".

This small example shows that there exists a zoo of storage concepts for spatial data. Some of the enormous complexity of IFC, COMBINE

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II (Eastman 1999), and other BIM can surely be attributed to this. Then again, with all these numerous concepts at hand it is still difficult to precisely define the relation between rough sketches, working drawings, and the details used in such working drawings. These models also do not provide version control which keeps track of spatial changes without redundantly storing the unchanged parts of the model.

The primary aim of this chapter is to provide mathematical background on topology and demonstrate its potentials for BIM. Thus its use in BIM-research is advocated, as such background knowledge at hand may help to identify spatial properties and to handle them adequately. Additionally, this chapter advocates a separation of spatial modelling from other aspects of BIM.

The chapter also presents two simple straightforward topological data models: *topological data types* and *relational complexes*. These can be easily realized as conventional relational databases. The models might also be helpful to overcome the current heterogeneity in spatial data modelling. Indeed, they have initially been developed for *comparison* of spatial modelling approaches instead of providing a new one.

Additional knowledge on the theory of topological constructions is provided. This theory is needed because the proposed redefinition of standard relational database queries are topological constructions in topological databases. One of these topological queries will be shown to have a particularly useful application in a hypothetical BIM. The topological inner-join, which formalizes how sketches, working drawings, and libraries of details are related, will be presented.

2 BACKGROUND

Before we define our topological data model we want to introduce some basic concepts of topology. A large amount of the matter presented in

this section can be found in topology textbooks such as, Brown (1988).

A Naive Approach to Topology

Topology deals with spatial properties, for example, of being “completely within” a set of elements or points (a shape) or at least “close to” it. A *space boundary* of a room within a building, for instance, is “close to” that room but neither element of the room’s space boundary is “within” that room. A door, however, is “within” the shape made of the door itself together with the two rooms it connects. As every shape which has that door “within” itself intersects both rooms, the door is said to be “close” to either of these rooms. In fact, the elementary notions of topology are merely precise definitions of what can be considered “interior”, “boundary”, and “exterior”. We will now specify these concepts for the case of the three-dimensional Euclidean space into which each building is embedded.

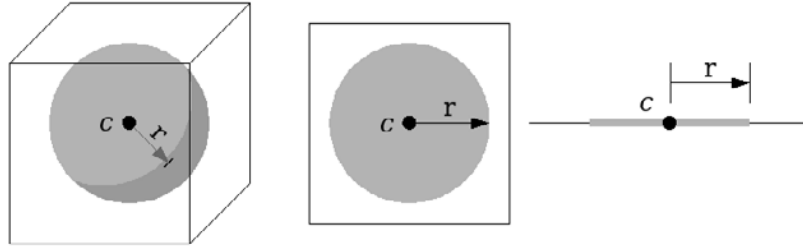
Euclidean Real Space and its Topology

If we define an arbitrary coordinate system then each point p in space can be expressed by three real numbers $p = (x, y, z)$ and hence we call the set $\mathbb{R}^3$ of all these three-tuples, the *three dimensional real vector space*, which is a common mathematical model of the space that surrounds us. A *shape* in space is simply a subset S of $\mathbb{R}^3$. The *Euclidean distance* $d(p, q)$ between two points $p = (x, y, z)$ and $q = (u, v, w)$ is known to be the function $d: \mathbb{R}^3 \times \mathbb{R}^3 \rightarrow \mathbb{R}$, defined as

$$d(p, q) = ((x-u)^2 + (y-v)^2 + (z-w)^2)^{1/2}.$$

We now call a real vector space together with the Euclidean distance the *Euclidean real space*. This space can be of arbitrary dimension—only the distance function must then be adjusted to this dimension in the straightforward manner.

Figure 1. The open balls $B_r(c)$ of different dimensions. The dimension of the surrounding space is indicated by boxes or a line. Naturally, the third dimension in the left picture is only an illusion.



With this distance function we will now introduce the so-called *natural topology* of the Euclidean real space. First we define a shape which we call *open ball*: Given a centre point c and a radius $r > 0$ we declare: The open ball $B_r(c)$ with centre c and radius r is the set of points p which have a distance to c strictly closer (less) than r . In symbols this reads

$$B_r(c) = \{ p \mid d(p,c) < r \}.$$

Note that the surface points of the open ball are excluded by this definition. Therefore it is called “open”. This is also a higher dimensional analogue to an open interval (a,b) in $\mathbb{R}$, whereas in the two-dimensional case an open ball is often called an *open disk*. Figure 1 shows some open balls of different dimensions.

The centre point of this ball is clearly “completely within” that ball and we will say that it is also “completely within” every set that is even bigger: Given a shape S in the space $\mathbb{R}^3$, we say that a point $c \in S$ is an *interior point* of S , if there is a radius $r > 0$ such that $B_r(c)$, the ball around c , is a subset of S , hence iff $c \in B_r(c) \subseteq S$ for some $r > 0$.

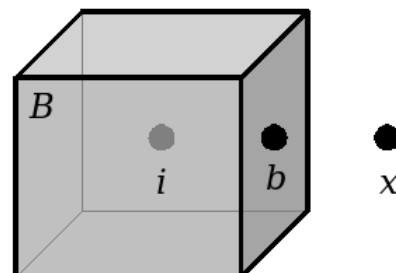
The notion of interior immediately leads to a complementary notion of exterior: A point is an *exterior point* of a shape S , if it is an interior point of the complement set $\mathbb{R}^3 \setminus S$ —the set of all points in space which do *not* belong to S .

Now the *boundary* (or frontier, surface) of S is the set of all points which are neither interior nor exterior points. It has the characteristic property that *every* open ball around a boundary point intersects both the shape *and* the complement of the shape S .

The interior and the boundary points of a shape together are considered *close* to that shape since every distance $\varepsilon > 0$, as small as it may be, is not too small for such a close point to have at least one point in the shape within that distance. Hence, the union of interior and boundary of a shape is called the *closure* of that shape.

A *topology* is nothing else than the set of all interiors of each subset (or shape) of the space. We will denote our topology defined by a distance function d by T_d . A *topological space* is a pair which consists of a set of elements—the points—together with the set of all the *open* subsets of this

Figure 2. Interior point i , boundary point b , and exterior point x , of a box B as a shape in $\mathbb{R}^3$.



point set. Our Euclidean real space as topological space is, hence, the pair $(\mathbb{R}^3, T_d)$.

It is a common exercise in topology lectures to demonstrate, that the interior of a shape S is the same as the interior of its interior. Such a set of points, which is the interior of itself, is called an *open set*. The open ball is an example of an open set. Its surface is the boundary and is called *sphere* $S_r(c) := \{p \mid d(p, c) = r\}$. Finally, the closure of a ball is called the *closed ball* $cB_r(c) := \{p \mid d(p, c) \leq r\}$ where the surface is *included* by definition. Each closed set is a complement of an open set and vice versa. A set may also be neither closed nor open, and it may also be as well closed and open at the same time—in which case it is occasionally called *clopen*.

Now our notion of an open set—a shape stripped off its surface—has three important properties:

- (1) The empty set $\emptyset$ is open and the entire space $\mathbb{R}^3$ is open.
- (2) The intersection of two open sets is open.
- (3) The union of an arbitrary set of open sets is open.

These properties are called the *topological axioms* and every set T_X of subsets of a point set X which has these three properties is called a *topology* for X . Accordingly, each pair (X, T_X) made of a set X and a topology T_X for that set is called a *topological space*. Our distance topology for the real vector space is a special case called *natural topology* of the real vector space. Note that the empty set $\emptyset$ and the entire space $\mathbb{R}^3$ are the complement of each other. Therefore they are both as well open and closed or—as some say—clopen. Now with these axioms at hand, we can forget our notion of distance and can define arbitrary topologies on any set in an abstract manner. A set can indeed have many different topologies: The reader may verify, that $\{\emptyset, \mathbb{R}^3\}$ also has the three properties mentioned above and, hence, is a topology for $\mathbb{R}^3$ and so is $\wp(\mathbb{R}^3)$, the set of all subsets of $\mathbb{R}^3$.

The former topology is called *trivial* or *minimal* and the latter *discrete* or *maximal*.

It is also possible to take an arbitrary point set X and an arbitrary set A of subsets of X and declare the sets in A be open. Then A , in general, is not a topology but there exists a uniquely defined minimal topology $T(A)$ which contains A as a subset. This topology is then said to be *generated* by A . Existence and uniqueness of $T(A)$ are easily seen: Take the set of all topologies for X containing A as a subset. Then this set is not empty because it contains the discrete topology $\wp(X)$ as an element. Furthermore, the intersection of an arbitrary set of topologies for a set X is again a topology for X . Now, $T(A)$ is simply the intersection of all these topologies containing A as a subset and, hence, unique. By this intersection it is also a subset of each topology which contains A as a subset and, hence, is minimal.

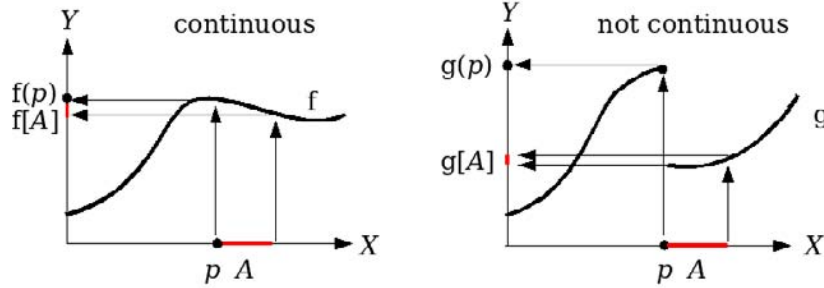
Continuous Functions

A *continuous function* is a function $f: X \rightarrow Y$ from the point set of one topological space (X, T_X) —the domain—to the points of another topological space (Y, T_Y) —the range—which respects the “close-to” relation between points and shapes. It does not tear off close points from shapes to which they are close. Hence if p is in the closure of S then the image point $f(p)$ in Y must be close to the image set $f[S] := \{f(x) \mid x \in S\}$ which is the set of all image points $f(x)$ of all x in S . If a function is continuous, then this is denoted by

$$f: (X, T_X) \rightarrow (Y, T_Y).$$

This is the most important type of functions in topology, and this is the same continuity of functions known in calculus as shown in Figure 3. A characteristic property of a continuous function is, that the inverse image $f^{-1}[B]$ (the set of all points in X , which have an image point $f(x)$ in B) of a set $B \in T_Y$ is open in the domain space.

Figure 3. A continuous function f and a function g which is not continuous. Whereas p is close to A , and this is respected by f on the left hand side, the image point $g(p)$ on the right hand side is not close to the image set $g[A]$.



We will later see how continuous functions are used to carry out topological constructions and then will define our topological database queries as such constructions. Now let us observe three important properties of continuous functions:

- (1) The identity function $\text{id}_X: (X, T_X) \rightarrow (X, T_X)$, $\text{id}_X(p) := p$, from a space to itself is always continuous.
- (2) The composition $g \circ f$ (pronounced “g of f”) of our function f with another continuous function $g: (Y, T_Y) \rightarrow (Z, T_Z)$, defined by $g \circ f(p) := g(f(p))$, is continuous: If p is a point in (X, T_X) close to some shape S in X , then, by continuity of f , the point $f(p)$ is close to $f[S]$, which is a shape in Y . But then by continuity of g we also know, that $g(f(p))$ is close to $g[f[S]]$ and hence $g \circ f(p)$ is close to $g \circ f[S]$. So the function $g \circ f$ respects the close-to relation and, therefore, is continuous, hence $g \circ f: (X, T_X) \rightarrow (Z, T_Z)$.
- (3) The composition of three continuous functions f, g , and h is associative, hence the functions $h \circ (g \circ f)$ and $(h \circ g) \circ f$ are equal, because $h \circ (g \circ f)(x) = h(g(f(x))) = h(g(f(x))) = h(g(f(x))) = (h \circ g)(f(x)) = (h \circ g) \circ f(x)$ for all $x \in X$.

It is these properties why continuous functions are also called *topological morphisms*. The first property is clear, but it should be noted that

this only holds if the topologies for domain and range are equal (or at least if the range topology is a subset of the domain topology). Note that the identities are neutral with respect to composition: $f \circ \text{id}_X = f = \text{id}_Y \circ f$ (easy: $f \circ \text{id}_X(p) = f(\text{id}_X(p)) = f(p) = \text{id}_Y(f(p)) = \text{id}_Y \circ f(p)$ for all $p \in X$).

We use a dot notation for function composition here because of its similarity to a frequently used notation in programming languages for similar purposes: If, for example, in Java “f()” is a method for an object x of type X which returns an object of type Y , and “g()” is a method for that type Y , then an expression like “x.f().g()” could be called the “method composition” $g \circ f$.

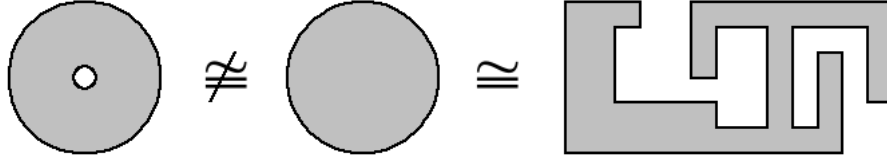
Topological Properties

Continuous functions are now used to define which topological spaces are considered essentially equal or *equivalent*:

First, of course, a space is essentially equal to itself and accordingly, as we already know, the identity function $\text{id}_X: X \rightarrow X$ is a continuous function $\text{id}_X: (X, T_X) \rightarrow (X, T_X)$ on the topological space.

Second, we consider two spaces (X, T_X) and (Y, T_Y) essentially equal if they can be “linked together” by continuous functions, which “cancel” themselves to the identities of each space if composed. Namely, if there exist two continuous

Figure 4. The middle and the right hand side spaces are homeomorphic hence have the same topological properties even if they do not look similar. The left hand space looks similar to the disk in the middle but it is not homeomorphic to the other shapes because of its perforation. So, the number of perforations is a topological property.



functions $f: (X, T_X) \rightarrow (Y, T_Y)$ and $b: (Y, T_Y) \rightarrow (X, T_X)$, one forth and one back, such that both compositions $f.b$ and $b.f$ are identities. In symbols this reads $b.f = \text{id}_X$ and $f.b = \text{id}_Y$. Then each point p in X has exactly one corresponding point $f(p)$ in Y and, conversely, it is itself the corresponding point of $f(p)$, as $b(f(p)) = b.f(p) = \text{id}_X(p) = p$. Additionally, an open set $U \in T_X$ has a corresponding set $f[U] \subseteq Y$. By $g[f[U]] = U$, this set $f[U]$ is the inverse image of U under the continuous function g and therefore it is open. Hence each open set has a corresponding open set $f[U]$ and also is itself the corresponding open set of $f[U]$.

Two spaces which can be “linked together” by such continuous functions are called *topologically isomorphic* or, short, *homeomorphic*. This is denoted in symbols by $(X, T_X) \cong (Y, T_Y)$. The involved “linking” functions are then called *topological isomorphisms* or *homeomorphisms*. Note that a space can always be linked to itself by the identity function and so it is indeed homeomorphic to itself. Each topological space is member of exactly one class of homeomorphic spaces and each property which distinguishes two different such classes is called a *topological property*.

It is a difficult computational problem to decide in general if two spaces are homeomorphic because endowed with this ability we would also be able to decide if two graphs were isomorphic and hence decide graph isomorphism. Moreover we will later see that the homeomorphism problem and the famous Graph Isomorphism problem

(Hoffmann 1982) are of polynomially equivalent computational complexity.

Alexandrov Spaces

There is an obvious asymmetry in the topological axioms because every union of open sets must be open, but on the intersection side only finitely many open sets need to have an open intersection. One might ask now what we get when we become stricter and insist that arbitrary intersections of opens sets be open, too. This leads to a special class of topological spaces called *Alexandrov spaces*.

First, we realize that the Euclidean space does not satisfy that property: A single point p as a set $\{p\}$ cannot be open because every open ball with centre p has an infinite number of points and hence is strictly bigger than $\{p\}$. However, the set of all open balls with centre p is a set of open sets but their intersection gives $\{p\}$ which is not open. Hence the Euclidean real space is not an Alexandrov space.

On the other hand, every topology for a *finite* set has this property because a finite set also has a finite number of subsets and hence can only have a finite number of open sets. Then an arbitrary set of open sets is finite as well and therefore its intersection is open. So every finite space is an Alexandrov space.

This is notable because every data to some data model constitutes a finite set and therefore

a topological data model must be Alexandrov. In particular, if a BIM is considered a topological space it has this property, too. For an effective encoding of such a topology an important property can be used, which already in 1937 has been found by Alexandrov: the specialization preorder.

The Specialization Preorder

Each topological space (X, T_X) has a “close to” relation between points and shapes mentioned above: A point $p \in X$ is *close to* a shape $S \subseteq X$ if and only if (short: iff) every open set U_p containing p intersects S . We then write $p \in \text{cl } S$. We now can restrict this to a relation $\leq$ on the points of X only, and then write $p \leq q$, iff $p \in \text{cl } \{q\}$ (Alexandrov 1937).

First, this relates every point to itself and the relation is *reflexive*. It is clear by intuition that every point is “close to” itself, but, as intuition can be misleading, we will briefly prove reflexivity: Every open set U_p which contains p intersects the set $\{p\}$, hence $p \leq p$. qed.

Second, the relation is *transitive*: If three points a, b, c are indirectly related $a \leq b \leq c$, then they are directly related, too, hence $a \leq c$, because by $a \leq b$ every open set U_a which contains a also contains b , but by $b \leq c$ every such open set also contains c and so we have $c \in U_a$, hence $a \leq c$.

So we have a reflexive and transitive relation (a *preorder*) $\leq$ for every topological space, which is (nowadays) called the *specialization preorder*.

In the case of non-Alexandrov spaces, different topologies can have the same specialization preorder. Alexandrov spaces, however, are always uniquely distinguished by that relation. For example, in the Euclidean space two different points cannot be close. Hence, the preorder of the natural Euclidean topology is the identity relation. However, the Alexandrov topology with the identity relation as its specialization preorder is the discrete topology.

Now with the specialization preorder $\leq$ of (X, T_X) we already have an effective method to

store a finite topological space into a relational database: Define a table, say X , where each record represents a point of X as an entity type and another table, say R_x , where each record represents the pairs (a, b) having $a \leq b$ as a relation type of cardinality $n:m$. This already gives a straightforward data model for topological spaces: (X, R_x) is a *database representation* of (X, T_X) . In fact, the topological databases presented later are only a slight generalization of this idea.

This also gives an asymptotical upper bound for the storage complexity of topologies: If n is the number of elements in our topological space then the storage complexity for every topology for X is in $O(n^2)$. We will later see that no better asymptotical upper bound for *arbitrary* topologies can exist (Paul 2008), so improvement of the storage efficiency of this model is only possible by constant factors or by restricting oneself to “docile” topologies which themselves have less storage complexity.

Now given the database representations (X, R) and (Y, S) of two topological spaces (X, T_X) and (Y, T_Y) , then a function $f: (X, T_X) \rightarrow (Y, T_Y)$ is continuous, iff for each pair $a, b \in X$ with $a R b$ we also have $f(a) S f(b)$.

Topological Constructions

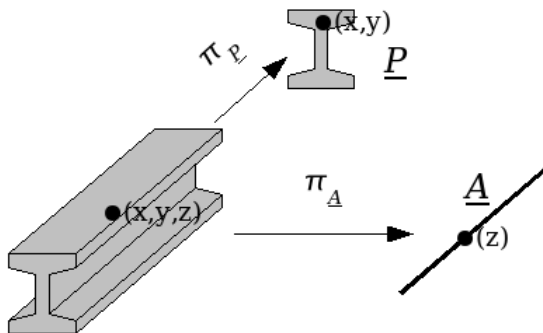
The basic idea of topological constructions is, that one or more topological spaces $(X_1, T_1) \dots (X_n, T_n)$ are passed to an operator f which takes their point sets as input and returns a resulting set $Y = f(X_1, \dots, X_n)$. Then a suitable topology T_Y for Y has to be defined, such that (Y, T_Y) can be considered the resulting *space* of $f((X_1, T_1) \dots (X_n, T_n))$.

An example is extrusion of a profile along an axis: one topological space involved in extrusion is the one-dimensional extrusion axis (A, T_A) ; and the other space is the two-dimensional extruded profile (P, T_P) of, say, some beam in a building structure. This results in the three-dimensional beam (B, T_B) as a topological space. The resulting point set of extrusion is the Cartesian product

of the input point sets, hence $B = P \times A := \{(p, a) \mid p \in P, a \in A\}$, and its topology is the so-called *product topology*.

Now, how can such a suitable topology be found? We first observe that each point in B is somehow related to the input points: A point $((x, y), z) \in B \times A$ (or short (x, y, z)) in our beam is combined by the (x, y) -coordinate pair of the profile and the z -coordinate is taken from the extrusion axis. Hence from our point set of the extruded beam we have two functions f_p, f_A back to the input spaces, defined as $f_p(x, y, z) := (x, y)$ and $f_A(x, y, z) := z$, the projections. So we have two functions $f_p: P \times A \rightarrow (P, T_p)$ and $f_A: P \times A \rightarrow (A, T_A)$ from a common domain set $P \times A$ to individual range spaces. This configuration is called a *source*. Clearly, with the discrete topology $\wp(P \times A)$ both maps would be continuous, hence $f_p: (P \times A, \wp(P \times A)) \rightarrow (P, T_p)$ and $f_A: (P \times A, \wp(P \times A)) \rightarrow (A, T_A)$. But we want our topology to depend on the input data as much as possible, while keeping these maps continuous. So we have to decrease our topology by removing as many open sets as possible until we reach a minimal topology which keeps both maps involved continuous. This topology is uniquely determined by the maps and the input topologies (the source) and is called the *initial topology*

Figure 5. The extrusion of a profile P along an axis A has two functions pointing back onto the input spaces. These induce a topology on the starting (initial) side of the arrows.



induced by these maps—a topology for their common domain. Existence and uniqueness can be shown in a similar manner as with the topology $T(A)$ generated by a set A : Take all topologies for $P \times A$ which leave all involved maps continuous. Then their intersection also has this property, is unique, and is minimal.

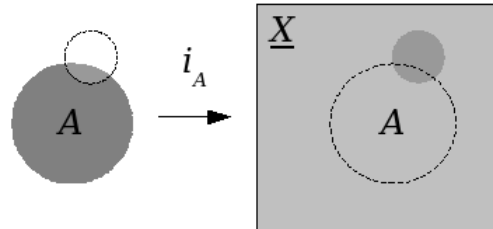
Another example of an initial topology is the subspace of a topological space. Given an arbitrary set of elements S from a topological space (X, T) , we would like to get a suitable topology for S . Now X and S are related by a map $i: S \rightarrow X$, which is simply defined as $i(x) := x$, hence shares some similarity with the identity. This is called the *inclusion map* from S into X . As the topology for the range X is known, our topology is the initial topology of i , which is usually denoted by $T|_S$, pronounced “ T restricted to S ”. $T|_S$ is simply the set of intersections of each set in T with S .

The term “initial topology” alludes to a converse situation, called *sink*, where the input topologies are at the domains side of some functions to one common range. In this case we would always obtain continuity if we used the trivial topology. But, as we want the topology to depend on the input data as much as possible, we have to augment that topology until we reach a maximal topology which still leaves all maps involved continuous. This topology is then called the *final topology*. It is more easily computed than the initial topology and simply consists of all subsets S of the range set which have an open inverse image $g_i^{-1}[S]$ in each domain space.

In general, topological constructions are based on either initial topologies for sources or final topologies for sinks. Figure 7 gives a diagram with an overview.

We will now dedicate a separate part of this chapter to a final topology which links the infinite Euclidean space to a topology for the finite number of building elements or, shortly, which defines the topology of an instance of a BIM.

Figure 6. The subset A of X has a function pointing back from A into the original space X . It simply assigns each point to itself. Note how an open set in X (small grey disk) turns into an open set in A (small grey clipping).



The Quotient Topology

Each building occupies a space (X, T_X) and is a combination of building elements which constitute a set, say A . Each element $e \in A$ occupies a part of the entire space. The set A may as well be a set of so-called “topological primitives” like lines, faces, edges or vertices from volume modelling or also a set of building elements like walls, slabs, and windows. We will now postulate, that this can be considered a *partitioning* of the space in the strict mathematical sense: Each part has at least one point, no two parts share a common point in space and all parts together occupy the whole space;

there is no gap and no overlapping. Then at each location where two elements are joined it must be decided which element a point in the joint belongs to—to one of the joined elements or to a separate joint object between them. We will denote this set of subsets, each occupied by an element in A , by X/A . Then we have a function $p: (X, T_X) \rightarrow X/A$, $p(x) := [x]$, where $[x]$ denotes the set of all points that belong to then same building element as the point x does. Note that the set X/A is finite, hence can only have Alexandrov topologies.

Then the final topology for p is called the *quotient topology* for X/A because a partitioning of a set is called a quotient set. It is the topology

Figure 7. Initial and final: On the left hand side, a family of maps $f_1 \dots f_n$ goes from a common point set domain X into a family of spaces $Y_1 \dots Y_n$. This is called a *source* and defines the initial topology for X . The other side shows the converse situation called *sink* where it is the spaces that are at the domain side of the arrows $g_1 \dots g_n$ having a point set Z as their common range for which they define a final topology.

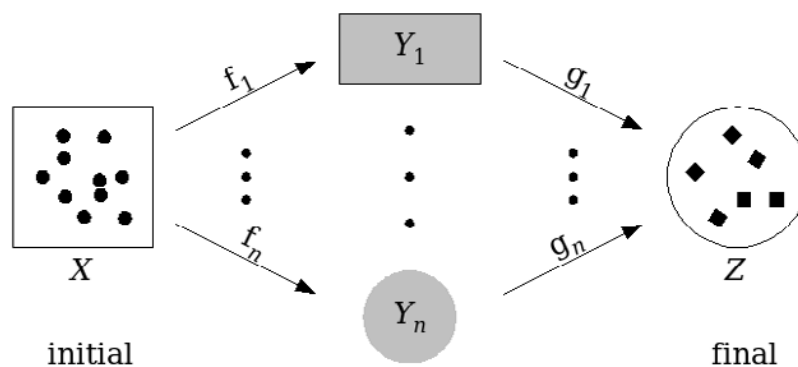
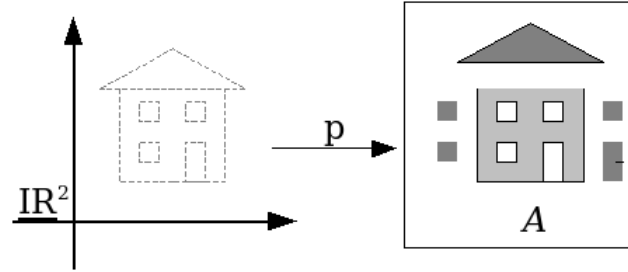


Figure 8. Elements of a building located in the real space (here in 2D, hence an example from Flatland). The function p points from the space onto the set of building elements. Note that each boundary line is attached to exactly one object. Otherwise p would not be a map because a boundary point in $\mathbb{R}^2$ would then be assigned to more than one object.



for the mutually disjoint shapes of the building elements in A . If we replace X/A by A we get a similar topology for the building elements themselves, a representation of which we already can store in a relational database, if we do not insist too much in efficiency.

As (real world) buildings are conceived at different levels of details, there must be coarser and finer partitionings piled atop and linked by a chain of quotient maps (Figure 11). To reduce storage complexity and the risk of inconsistent data, however, not all of these partitionings can be explicitly stored into a database—some of them should be computed by other data given. Later this will be discussed in more detail.

Topological Databases

We will now generalize the concept of storing topological spaces in a relational database, such that we can increase efficiency. Then we will demonstrate that the improvement in efficiency can only be by a constant factor. In general, storage complexity cannot be better than $O(n^2)$. However, in the special case of a BIM, the topologies are docile and will only have linear storage complexity.

The improvements of a relational representation of an Alexandrov topology are straightforward. As every element is “close to” itself, the

“diagonal” entries (a,a) can be deleted from the stored relation. A second improvement would be to remove all pairs (a,c) , if (a,b) and (b,c) are already stored until no more such pair is left. Codd (1979) calls this the OPEN operator and the re-computation of these (a,c) the CLOSE operator.

To allow these improvements we let R be an arbitrary relation on a set X . Then, we call (X, R) a *topological data type* and a set of topological data types with possibly some additional consistency constraints a *topological database* (Paul 2008, Bradley & Paul 2008). This still is nothing more than another name for a simple directed graph. Before we show how this is related to topology, we need some preliminaries:

The *transitive closure* of a relation R is the minimal transitive relation R^+ which contains R as a subset. This is exactly the relation computed by Codd’s CLOSE-operator. The *transitive and reflexive closure* R^* of R is R^+ with the diagonal entries (a,a) for all $a \in X$ added.

The set $\text{St}_R(x)$ of an element $x \in X$ is the set of all elements y where $x R y$ holds. We call this the *star* of x with respect to R . The star $\text{St}_R[U]$ of a set U is the union of the stars of the elements in U . With this operator we can define a topology: If X is a set and R a relation on X then the set $T_R := \{U \subseteq X \mid \text{St}_R[U] \subseteq U\}$ is an Alexandrov topology for X . Note that R need neither be transitive nor reflexive. The specialization preorder of T_R is

the transitive and reflexive closure R^* of R . So every other relation B between R and R^* , i.e. $R \subseteq B \subseteq R^*$, generates the same topology. This is an interesting property because sometimes it may be desirable to keep some redundant information—in this case, elements from $R^* \setminus R$ —in a database to speed up queries. This redundant information does not affect any topological property.

A *continuous database map* is a map $f: X \rightarrow Y$ between two topological data types (X, R) and (Y, S) such that $f \times f[R] \subseteq S^*$. The map $f \times f$ is the direct product of f with itself:

$$f \times f: X \times X \rightarrow Y \times Y, (a, b) \mapsto f \times f(a, b) := (f(a), f(b)).$$

It can be shown that, first, these are indeed the continuous maps between the topological spaces represented by the topological data types and that, second, it is in general necessary to compute the transitive closure S^+ of S in order to recognize this continuity. In relational databases such maps may be foreign key references or 1:n associations or, short, any kind of relation between database tables which qualifies as a map in the mathematical sense.

Relational Complexes

The previously presented notion of a topological data type does not store the information how elements are oriented—an information which is frequently found in volume modelling concepts as, for example, in boundary representation modelling. The orientation of an edge connecting two vertices, for example, is the specification which vertex is considered the starting vertex and which vertex is the ending vertex. On the other hand, the orientation of a face is a specification which side is the “front” side and which is the “rear” side of that face. The difference between the topological data type presented above and the extension to be presented here is similar to the difference between an undirected graph and a directed graph.

Such orientation information is easily stored: Let (X, D) be a topological data type with point set X and relation D . We first assign a dimension value to each element in X , simply by assuming the relational schema of X was extended by an integer attribute, say *dim*. The elements of dimension 0 are called *nodes* or *vertices*. If they have dimension 1 they are *lines* or *edges*. A dimension of 2 is attached to *faces* whereas *volumes* (e.g. rooms) are of dimension 3. There is no upper limit on dimension and a hypervolume is merely a record where the dimension attribute has value 4.

We then set up the first consistency rule:

- (1) All $(a, b) \in D$ must be strictly ordered by dimension i.e. $a.\text{dim} < b.\text{dim}$. So a vertex can be close to an edge but no edge can be close to a vertex.

With this rule our specialization preorder becomes antisymmetric, hence, a partial order and the associated topological space is then said to be T_0 or Kolmogorov.

The second extension to the relational scheme of (X, D) is the assignment of an integer value to each pair $(a, d) \in D$, say via an additional integer attribute α . Thus an entry in D looks like (a, b, α_{ab}) . This expresses which “side” of some boundary element a is “seen” by its bounded element b . If a exposes its “front” side towards b then $\alpha_{ab} = +1$ and if b sees the “rear” side of a then $\alpha_{ab} = -1$. We may also say “initial” and “final” side in case of an edge-vertex relation and “left” and “right” side in case of a face-edge relation. In case of a loop the boundary element a may be attached to both sides of the bounded element b element. In this case $\alpha_{ab} = 0$.

Then D can be considered a big $X \times X$ -matrix where rows and columns are not identified by numbers but rather by the elements in X . Each entry at row r and column c is the α -value of (r, c, α_{rc}) , if such record exists in D and is considered zero otherwise.

We now define two more consistency rules:

- (2) For all $(a, b, \alpha_{ab}) \in D$ where the dimensions of a and b differ by more than 1 the value α_{ab} must be zero.
- (3) For all entries (a, c, α_{ac}) in the matrix product $D \cdot D$ the value α_{ac} must be zero.

Rule (2) expresses the fact that it does not make sense, for example, to define a “side” of an edge with respect to a volume bounded by that edge. With rule (3) our relation D represents the matrix of the boundary operators of a chain complex (Hatcher 2002). Rule (3) expresses the fact that the boundary of an element—be it an edge-loop around a face or a face-shell around a volume—always “circumscribes” that element. The (algebraic) boundary of an element c is merely the c -column of matrix D . Figure 9 shows an example of a rectangle.

Complexity of Topological Data Types

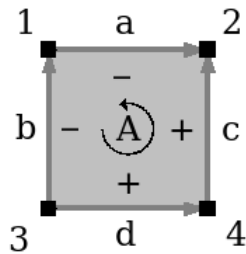
We will now show, that $O(n^2)$ is the best asymptotic storage complexity for all topologies of a finite set X of cardinality n . It is well known, that such a set has at least $2^{\lfloor n^2/4 \rfloor}$ different topologies (Erné

1974). This can easily be demonstrated: X always has two disjoint subsets E and V of size $\lfloor n/2 \rfloor$. Then $E \times V$ is of size $\lfloor n^2/4 \rfloor$ and each subset R of $E \times V$ can be considered a relation on X . Now there are $2^{\lfloor n^2/4 \rfloor}$ such relations and each of them is transitive and irreflexive and therefore generates a unique topology for X . qed. Hence, even the most space efficient data structure which can store all topologies for this set must have at least this number of different states. If all states are somehow coded binary, the code must then be of size $\geq \log 2^{\lfloor n^2/4 \rfloor} = \lfloor n^2/4 \rfloor$ in the worst case. So, the worst case size of each data structure for arbitrary topologies is asymptotically bounded from *below* by n^2 and is therefore in $\Omega(n^2)$. Hence no better upper bound than $O(n^2)$ can possibly exist.

In a BIM, however, all possible topologies are not likely to come up and in practice the storage complexity will be linear. This is due to the mostly “orthogonal” situation in a building, where, for example, at most six edges are likely to meet at a common vertex.

We will briefly discuss the time complexity of the homeomorphism problem and show, that this problem is essentially as hard as graph isomorphism. An *undirected simple graph* is a pair (X, E) of two disjoint sets X and E where the elements in E are one- or two-element subsets $\{x, y\} \subseteq X$. An

Figure 9. The boundary relation of the complex to a square. The orientation of face A is indicated by the bent arrow. For each edge with compatible direction, the face-edge entry is $+1$, otherwise it is -1 . An edge-vertex entry is positive at a final vertex and negative for an initial vertex. Even if the illustration is kept in 2D, there is no upper limit on the dimension of this concept.



a	b	α
a	A	-1
b	A	-1
c	A	+1
d	A	+1
1	a	-1
1	b	+1
2	a	+1
2	c	+1
3	b	-1
3	d	-1
4	c	-1
4	d	+1

element $\{x,y\} \in E$ is called "edge" and is said to connect a with b . Two graphs (X, E) and (Y, F) are *isomorphic*, if there exist two functions $f: X \rightarrow Y$ and $b: Y \rightarrow X$, which cancel to identities if composed and which respect edges, hence $\{f,f\}[E] \subseteq F$ and $\{b,b\}[F] \subseteq E$, where $\{f,f\}(\{x,y\}) = \{f(x),f(y)\}$. The *graph isomorphism problem* (GI) is the computational problem of writing a program which gets two somehow encoded graphs (X, E) and (Y, F) as input and returns a Boolean value "true" if both input graphs are isomorphic and "false" otherwise. There are similar definitions for directed graphs, where the edges are pairs (a,b) instead of sets $\{a,b\}$ to represent the orientation. GI is a hard problem somewhere between (or maybe "between") P and NP. A broad discussion of this problem can be found in (Hoffmann 1982).

We will now show that GI and the homeomorphism problem are polynomially equivalent. First we define a relation $a R_x \{b,c\}$ iff $a \in \{b,c\}$ on $X \cup E$. A vertex a is "close to" an edge $\{x,y\}$ if that edge connects the vertex to some other vertex. Then the so-called edge-graph $(X \cup E, R_x)$ is a topological data type which can be computed from (X, E) in polynomial time. Furthermore, the associated topological spaces $(X \cup E, T_{R_x})$ and, accordingly, $(Y \cup F, T_{R_y})$ are isomorphic iff the corresponding graphs are isomorphic. Hence GI can be polynomially reduced to homeomorphism. On the other hand two topological data types (X, R) and (Y, S) represent homeomorphic spaces iff the two *directed* graphs (X, R^*) and (Y, S^*) are isomorphic. Now it is known that the computation of the reflexive and transitive closure R^* of a relation R can be carried out in polynomial time and that the directed graph isomorphism is polynomially equivalent to undirected graph isomorphism. Therefore homeomorphism can also be polynomially reduced to GI. Hence GI and homeomorphism are polynomially equivalent or, in other words, homeomorphism is a GI-complete problem.

We introduced this time-complexity consideration as a preparation to the queries part which

follows: Topological *predicates* are still missing in this query language. If one tries to define such a predicate, however, it is advisable to first consider its complexity. Otherwise programming efforts towards such a predicate may turn out to be not feasible.

3 TOPOLOGICAL DATABASE QUERIES

As said above, topological database queries still do *not* focus on querying topological predicates such as "Which two rooms are connected to a given aisle?" The topic of querying spatial *predicates* is covered by (Borrmann & Rank 2010) and (Egenhofer 1991). Egenhofer defined the famous 9-intersections—a family of topological predicates like "meets", "overlaps" etc. between two shapes A and B by considering some of the 9 possible intersections of interior, boundary and exterior of A with interior, boundary and exterior of B and asking, which of them is empty and which is not. The aim of this section, however, is to adopt the standard relational algebra for databases to the topological databases. In short: We do not explicitly ask here for topological properties but want to get as many of them as possible into the query results.

Of course, our concept will be based on the theory of topological constructions. The queried topological data types and the query results are linked by maps and the resulting topology will then be either initial or final. We will give here, without proofs, the basic operators of relational algebra—union, intersection, set-difference, projection, renaming, selection, and Cartesian product—as topological constructions. The topological versions of the operators are always written underlined here to indicate the difference to the basic operators. Despite their simply being the "translation" of the standard relational algebra operators into the category of topological databases, some of these operators are not provided

by current spatial database management systems (DBMS).

From now on, we will adopt the notions ‘source’ and ‘sink’ to topological data types, and we will call a relation which generates a final topology a *final relation* and, accordingly, speak of *initial relations* in the converse case. Note that the relations, unlike the topologies, are not necessarily uniquely defined. In general, final relations are easier to compute than initial relations which often necessitate transitive closure computation—except if the maps are surjective. This is an interesting correspondence to the fact that the construction of final topologies is easier than the construction of initial topologies. The Cartesian product, however, is an example of an initial topology which can be constructed without transitive closure computation.

We will assume here that a topological data type (X, R) consists of a database table X and a relation R on X which itself contains pairs of entire records of X . This violation of database design principles is deliberate because the formal definition of the queries becomes easier this way. Of course, in a realistic database design these definitions must be adopted, and a future spatial DBMS should handle this automatically.

Union, Intersection, and Set Difference

The following operators can be either used in queries but also define how to add and remove data from and to the database, and are therefore essential for every (spatial) DBMS.

Let (X, S) and (Y, T) be union compatible topological data types, which means, that the relational database schemes of X and Y are equal, and so are the schemes of S and T .

Union

The characteristic maps of the union are the inclusion maps $i_X: X \rightarrow X \cup Y$ and $i_Y: Y \rightarrow X \cup Y$, with

the union $X \cup Y$ as the *common range* of these maps—a sink having a final relation $S \cup T$. The union of topological databases simply is

$$(X, S) \sqcup (Y, T) := (X \cup Y, S \cup T).$$

Intersection

Conversely, the characteristic maps of the intersection are the inclusion maps $j_X: X \cap Y \rightarrow X$ and $j_Y: X \cap Y \rightarrow Y$ with the query result at the common domain side. Hence, we have source and need an initial relation which we do not get by simply intersecting the relations. However, $S^+ \cap T^+$ —the intersection of their transitive closures—is an initial relation of these maps. So intersection of topological data types is

$$(X, S) \sqcap (Y, T) := (X \cap Y, S^+ \cap T^+).$$

Set Difference

Set difference also has an initial topology coming from the characteristic map $i: X \setminus Y \rightarrow X$ and can be defined by

$$(X, S) \setminus (Y, T) := (X \setminus Y, S^+ \setminus (Y \times Y)).$$

Note that the topology T of the subtracted space has no influence on the result.

Projection, Renaming, Selection, and Joins

These operators are the parts of the famous “select-from-where” statement in SQL. Note that the Cartesian product of two cubes gives a six-dimensional hypercube and is beyond the upper dimension limit of three or four (3D + time) of current spatial DBMS.

Projection

Projection π_A of a table X on attributes A maps each tuple t from X to a projected tuple $\pi_A(t)$, with those attributes from t stripped off which are not in A . For example, $\pi_{\{x,z\}}(1,2,5) = (1,5)$, if x, y , and z are the attribute symbols for components of the 3-tuple. This projection is also the characteristic map $\pi_A: X \rightarrow \pi_A[X]$, hence projection is a sink and can be defined as

$$\underline{\pi}_A(X, R) := (\pi_A[X], \pi_A \times \pi_A[R]).$$

Note that a final relation of any sink $f: (X, R) \rightarrow Y$ is simply $f \times f[R]$.

Renaming

Renaming is also defined on a per-tuple basis similar to projection. It is only mentioned here for completeness, because a flawless database design according to the usual design principles can simply reuse the input relation R for the output relation without any modification.

Selection

Selection generates a subset of the tuples and hence its topological counterpart generates a subspace. We again assume that (X, R) be a topological data type, with our deliberate design flaw in that R consists of pairs of tuples from X . Additionally let Θ be a predicate to the schema of X . The characteristic map of selection is the inclusion map of the selected tuples in $\sigma_\Theta(X)$ back into the input relation X , in symbols $i: \sigma_\Theta(X) \rightarrow X$, $i(t) := t$. This is a source with initial relation $R^+ \cap (\sigma_\Theta(X) \times \sigma_\Theta(X))$. Note that this intersection is only possible because of our design “flaw”. Practical design would force to dereference the foreign key references from R to X , hence, complicate the formula without providing additional insights. So topological database selection is

$$\underline{\sigma}_\Theta(X, R) := (\sigma_\Theta(X), R^+ \cap \sigma_\Theta(X)^2).$$

Cartesian Product

The Cartesian product has already been shown to carry an initial topology. This, however, can be computed without any transitive closure computation:

$$(X, R) \times (Y, T) := (X \times Y, (R \otimes T^0) \cup (R^0 \otimes T))$$

where R^0 and T^0 are the identities $R^0 := \{(a, a) \mid a \in X\}$ and T^0 likewise defined. The product relation $R \otimes T$ is simply achieved by rearranging the elements $((a, b), (x, y))$ from the Cartesian product $R \times T$ into $((a, x), (b, y))$ to be able to consider it a relation on $X \times Y$.

Join

Joins, like equi-joins and natural joins, can be achieved by composing “selection” and “Cartesian product”. We will later demonstrate how these topological joins may be helpful to remove redundancies from BIM data. We will only allow *inner* joins because the characteristic maps of an outer join are *partial* maps from the join result back to the input relations. Therefore they would induce an initial topology for partial maps which, according to Paul (2008), in general is not unique. This non-uniqueness, however, depends on the author’s preferred definition of “continuous partial map”. With a different definition (Brown 1988, p. 155) such an outer join would be possible, though not necessarily of more practical use.

Cartesian Product in Relational Complexes

If our topological data types are relational complexes we should take care that the result also represents a complex. For example, the select operator has to be modified to compute the topological closure of the result. Then the selected subspace is

guaranteed to be a complex. Sometimes, however, selection already returns a complex even if the resulting space is not closed in the input space, in which case closure may be omitted. In contrast to the above listed topological query operators we still have no such comprehensive list for the relational complexes, which we consider an open research question.

The *Cartesian product* of two complexes, however, has already been described by Eilenberg & Zilber (1953). We will present the relational complex version here. Let (X, D) and (Y, B) be two relational complexes. Then we define XY as the set of tuples $x \otimes y := (x, y, \dim_x + \dim_y)$ for all $(x, \dim_x) \in X$ and $(y, \dim_y) \in Y$. Then the boundary matrix $D \otimes B$ according to the Eilenberg-Zilber-theorem is

$$D \otimes B(x \otimes y) = D(x) \otimes y + (-1)^{\dim_x} x \otimes B(y),$$

Where the notation $M(x)$ of any matrix M shall denote the x -column of M assuming a relational database schema $M[a, b, \alpha]$. In SQL this column is retrieved by

select a, alpha from M where b = x ;

If we denote the unity matrices for X by B^0 and D^0 likewise we have with

$$D \otimes B(a \otimes b) = D(a) \otimes B^0(b) + (-1)^{\dim_a} D^0(a) \otimes B(b)$$

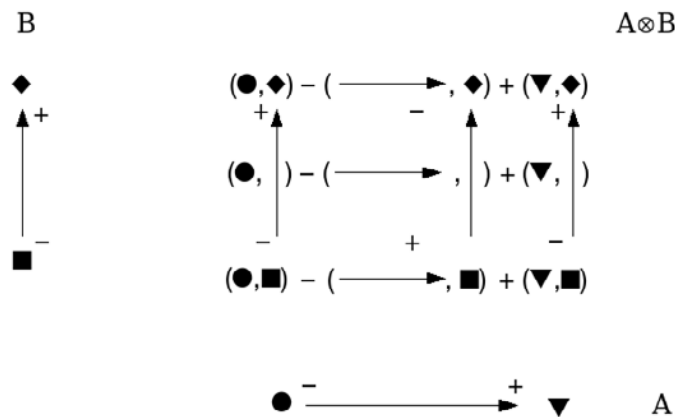
an obvious analogue to the set theoretic product relation defined above. Hence the relation $D \otimes B$ is defined as

$$D \otimes B = \{((a, y), (b, y), \alpha_{ab}) \mid D(a, b, \alpha_{ab}) \text{ and } y \in Y\} \cup \{((x, c), (x, d), (-1)^{\dim_x} \cdot \alpha_{cd}) \mid x \in X \text{ and } B(c, d, \alpha_{cd})\}.$$

So Eilenberg & Zilber's formula in SQL is:

```
create view DoxB as
select D.a as x1, B0.id as y1,
D.b as x2, B0.id as y2
, D.alpha as alpha
from D, X as B0
union all
```

Figure 10. The product of two closed edges A and B gives a rectangle $A \otimes B$. The pair $(\rightarrow, \uparrow)$ of the horizontal edge element " $\rightarrow$ " in A and the vertical edge element " $\uparrow$ " from B represents the interior face. This pair is of dimension 2—the sum of the dimensions of its components. In $((\rightarrow, \blacklozenge), (\rightarrow, \uparrow), -1)$ and $((\rightarrow, \blacksquare), (\rightarrow, \uparrow), +1)$ the α -values are the inverted α -values of $(\blacklozenge, \uparrow, +1)$ and $(\blacksquare, \uparrow, -1)$ in B because the dimension of $\rightarrow$ is odd.



```
select D0.id as x1, B.x as y1,
D0.id as x2, B.y as y2
, (1 - 2*MOD(D0.dim, 2)) *
B.alpha as alpha
from Y as D0, B;
```

assuming $(X[id,dim], D[a,b,alpha])$ and $(Y[id,dim], B[x,y,alpha])$ are the relational schemes for the input complexes. The schema of the resulting relational complex is then

```
(XY[xid,yid,dim],
DoxB[x1,y1,x2,y2,alpha]).
```

Note that this operation is not commutative, hence $D \otimes B \neq B \otimes D$. Figure 10 shows this product of two edges—essentially the rectangle from Figure 9.

Equi-Join, Fibre Products, and Details Libraries

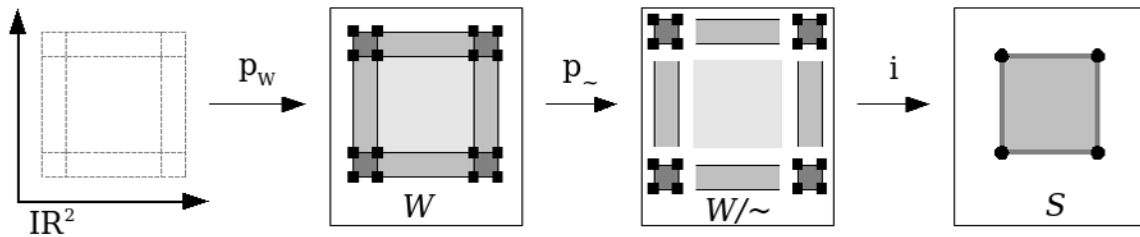
With Cartesian product and selection we also have the equi-join of two tables. We will now see its possible application: relate coarser conceptual sketch views with finer working drawing views of one topological database representing a building. Figure 11 shows such a sequence of successively coarser spaces.

The finest view (where “fine” means “of many details”) of a building model is the collection of its elementary spatial objects: volumes, faces, edges, and vertices. These objects are called “topological primitives” in volume modelling and “cells” in topology. We will call this finer view a *working drawing*.

In planning, these cells are grouped into objects like beams, columns, walls, or windows and the layout of most of these groups repeat within the building. Hence, they are often redundant in the working drawing. Such redundant information should be factored into a layout collection and a coarser view (where “coarse” means “of few details”) of the building model. Then each element of the coarser model must have a reference to these detail layouts. We call the coarser view a *sketch* and the collection of layouts a *detail library*.

With a collection of details alone, we are not able to reconstruct the working drawing and must also define how two such details are connected, thus converting the detail library into a topological space. The topology of a detail itself (as a subspace) defines its layout and the additional topological information defines the connections between two such details. We will formalize this: A *detail library* is a surjective continuous map $p: (D, T_D) \rightarrow (I, T_I)$, where T_I is the final topology of p . We call D the detail layouts and I the detail index—the set of the detail identifiers. The original image $p^{-1}(i)$

Figure 11. A sequence of spaces, linked by maps. The map p_w defines the final space W (the working drawing) which consists of the “topological primitives”: edges faces and vertices. $p_{\sim}$ maps W onto a quotient by grouping primitives. The map i assigns each such group a “primitive” in S (the sketch). Note the similarity of many elements in $W/\sim$. We call the composition $i.p_{\sim}: W \rightarrow S$ a sketch map.



of an detail identifier $i \in I$ is the set of all detail elements $d \in D$, with $p(d) = i$ as a subspace of D called the *fibre* of i with respect to p . Now taking a sketch (S, T_s) , we are able to define a continuous map $u: (S, T_s) \rightarrow (I, T_I)$, indicating which detail in I is used by a sketch element in S . Then two elements in S which are connected can only use two details in I where such a connection is specified. So continuity becomes an interesting consistency rule for practical planning. Note that u is a total map, hence every element must use a detail (in SQL enforced by NOT NULL statements). Therefore the library has to explicitly specify default details, maybe named “unspecified wall” or likewise, to be used as defaults. Then, as p and u are maps, we can define the equi-join $D \times_{p=u} S := \{ (d, s) \mid p(d)=u(s) \}$, the topology for which is initial with the projections

$$\pi_D: D \times_{p=u} S \rightarrow D, \pi_D(d, s) := d \text{ and } \pi_S: D \times_{p=u} S \rightarrow S, \pi_S(d, s) := s.$$

This construction is called fibre-product, as it is the union of the Cartesian products of the common fibres of each element in I . If the maps p and u are relational database projections, this fibre product is called equi-join.

Figure 12 illustrates the concept with the example from Figure 11. Note, that there still seems to be redundancy in Figure 12 and it would be interesting to investigate first, if this, indeed, is a redundancy and, second, how it might then be removed.

4 TOPOLOGY IN THE IFC MODEL

It is advocated here, that spatial modelling be factorised out of a BIM and be delegated to an underlying generic spatial data model. Therefore we will see here where topological information can be found in the IFC model or, in other words, where the IFC can be considered a topological data type.

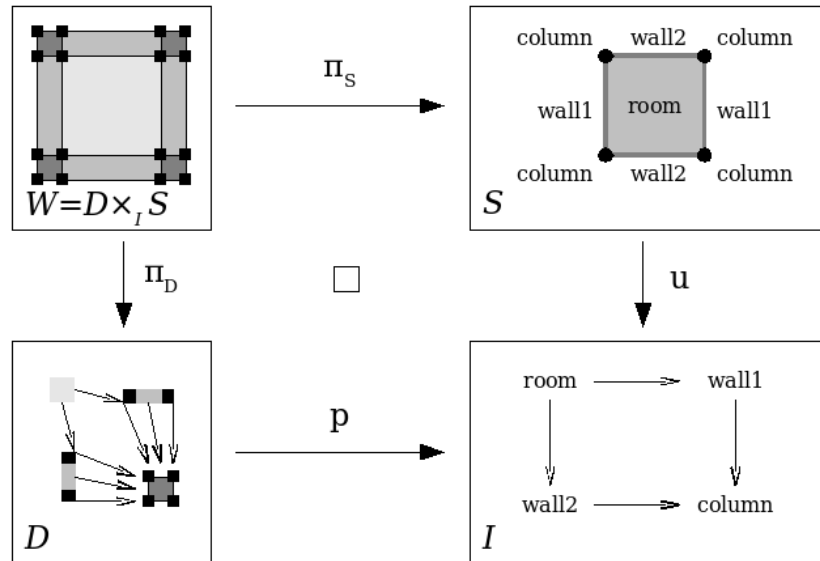
‘IfcRelConnects’ is the general abstract class expressing “connectivity” within a building. The instances of ‘IfcRelConnectsElements’ indeed are the pairs (Relating, Related) of our topological data type, hence

(IfcElement \ IfcRelConnectsElements, IfcRelConnectsElements)

would already be a topological data type which, however, is too simple and contradicts the intended semantics. This is mainly due to the fact that, first, an IFC-file cannot be considered only as one topological data type but rather as a family of data types linked together by references, hence a *database*. Second, the semantics of classes derived from ‘IfcRelConnects’ vary. We will now discuss some IFC types which are similar to the “close to” relation R of a topological data type (X, R) . We will call elements of X *entities*, and refer to the elements in R as *pairs*. Let *rel* be an instance of type ‘IfcRelConnects’. If *rel* is of class

- *IfcRelConnectsElements*, then it must be distinguished, if the optional ‘IfcConnectionGeometry’ is specified or not. In the former case this geometry object must be considered an entity, otherwise *rel* itself would represent that entity. Let *elt* be said entity—either *rel* or the specified geometry—then the pairs (*elt*, *rel.RelatingElement*) and (*elt*, *rel.RelatedElement*) are to be added to the relation.
- *IfcRelConnectsWithRealizingElement*, then it is similar to ‘IfcRelConnectsElements’. For each realizing element *elt* the pairs like those in the former case have to be added to the relation.
- *IfcRelConnectsPortToElement*, then the pair of the attribute values (RelatingPort, RelatedElement) has to be added to the relation.

Figure 12. The equi-join $D \times_I S$ of the sketch S with references $u: S \rightarrow I$ to the identifiers I of the detail library $p: D \rightarrow I$ in standard notation for a fibre product. Usually diagrams of fibre products (as this one) are denoted by a little square in the middle. Note the symmetry in D (wall1 and wall2 are equal) which might be a redundancy.



- *IfcRelConnectsPort*, then *elt* has to be considered a building *entity*, and the pairs (*elt*, *elt.RelatingPort*) and (*elt*, *elt.RelatedPort*) have to be added to the relation.
- *IfcRelCoversSpaces*, then for each element *rc* in *rel.RelatedCovering*, the pair (*rc*, *elt.RelatedSpace*) has to be added to the relation.

There are still more such classes and it should be obvious by now that there is much heterogeneity within the IFC with regard to modelling topological properties.

Yet another important topological type of the IFC are relations which stem from ‘IcfRelDecomposes’. This kind of relations has to be modelled as continuous database maps *between* different topological data types, because they actually represent a partitioning of a set of more primitive elements into higher aggregates. Additionally ‘IfcProduct’ has an attribute reference composition ‘Representations’ (another example of function composition) which basically has the same semantics as ‘IcfRelDecomposes’: It decomposes IFC products into “topological primitives”. These primitives and the relations among them can be found in the ‘IfcTopologyResource’ itself, which is used for boundary representation of geometric objects. The entities ‘IfcEdge’, ‘IfcVertex’, ‘IfcFace’ can, of course, be stored as entities into a relational complex and the topological references among them into its boundary relation. Note, that the alpha values of a boundary matrix have the same semantics as the ‘Orientation’ attribute in an ‘IfcFaceBound’.

5 RESEARCH QUESTIONS

Approaches towards programming efforts of these topological data types are presented by the author (Paul 2007). An abstract topological data

type view on b-rep models is straightforward and easily coded in Java. It is also very easy to attach simple geometric data like vertex location. However, there are still open research questions to be solved in order to bring this theory into a working spatial database management system.

The first interesting task would be completing the list of query operators for *relational complexes*. First, geometric volume modelling is based on complexes and, second, they can represent important information like “which is the front side of a wall” or “into which room does a door open”.

It is also important to discuss the formal justification of this model which is based on the assumption that a building is a *partition* of space. Although this should be considered the *canonical* perspective, other perspectives would be helpful for practical planning. However, these should then always be related to such a partitioning.

The equi-join of topological data types promises an integrated detail library atop a common generalization of extrusion. It is not clear, however, if this simple approach is already feasible or if additional provisions have to be made. Note that the example presented on Figure 12 still seems to have redundancies. Nevertheless, it is the detail library which could be the most attractive part of the presented topological modelling approach, and it seems to be missing in current spatial DBMSs.

Another promising application would be a spatial revision control system similar to the well known CVS for text documents (Vesperman 2003). Windisch & Scherer (2008) present a versions control system atop the IFC model.

One could also use this concept for higher dimensional spaces and use it to store four-dimensional space-time databases, for example, a construction scheduling. Note that the model has no upper dimension limit and only one elementary spatial data type.

Additionally, a relational view on spatial modelling could also be a starting point to merge the well-known *scene graphs* from virtual reality (VR)

with relational design principles—in particular to remove the restriction to a tree structure. It is noteworthy, for example, that Java3D (2008) provides a class named ‘Link’ which can be used to overcome this restriction: With references via ‘Link’ and ‘SharedGroup’ a Java3D scene graph can be made confluent. Hence a concept which removes this restriction at all would be consequent. In particular this might turn into a direct link from BIM to VR.

6 CONCLUSION

This chapter advocates a spatial data model with one interface as a separate component of a BIM. It shows that topology is easily combined with the relational data model. This results into one unifying approach to modelling spatial relations of type “connected-to”, “bounded-by” or “part-of” etc., which may be a good starting point for the development of the generic spatial database component of a BIM—either developed from scratch or atop existing spatial DBMS. The next steps would be to complete the model by adding the missing queries based on algebraic topology and then incorporate *geometric* properties as, for example, proposed in (Paul & Borrmann 2008). A BIM can then be a system of specialized instances of such a spatial model.

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KEY TERMS AND DEFINITIONS

Topology: A structure for a given set (of points or elements) which specifies interior, frontier and exterior of subsets of that set. Formally, a set of subsets of that given set which satisfies the topology axioms (the set of all possible interiors).

Topological Space: A set together with a topology for that set.

Continuous function: (continuous map): A function from the points of one topological space to the points of another space which respects the relation of points being close to shapes of that space. Also a generalization of “part_of”-relations.

Specialization Preorder: A relation $\leq$ within a topological space relating each element to the elements it is close to. For example, a door is close to each of the two rooms it connects, hence $\text{door} \leq \text{room1}$ and $\text{door} \leq \text{room2}$. Also a generalization of “connected_to”-relations.

Topological Construction: General theory of constructing new topological spaces out of given ones by first operating on the point sets and then finding the topology for the resulting set that fits best.

Topological Data Type: A graph used to store the preordered sets (see: specialization preorder) defined by finite topological spaces. The graph itself need not be a preordered set.

Topological Database: An integrated family of topological data types, hence a family of topological data types eventually satisfying some additional consistency constraints.

Topological Database Query: The topological construction derived from a relational algebra query operation and adopted to topological data types.

Complex, Algebraic: A series $\cdots \rightarrow V_i \rightarrow V_{i-1} \rightarrow \cdots$ of vector spaces connected by linear functions $d_i: V_i \rightarrow V_{i-1}$ such that each composition $d_i \cdot d_{i+1}: V_{i+1} \rightarrow V_{i-1}$ of two consecutive functions always returns zero. Then each image vector $d_i(v_i)$ is considered a “cycle”, as $d_{i-1}(d_i(v_i))=0$

Complex, Topological: A topological space which has an algebraic complex associated in a straightforward manner. Then the boundary of an element is considered to “circumscribe” that element (as a cycle): For example, the surface of a body circumscribes its volume.

Complex, Relational: Extension of a topological data type: A topological data type which represents both a topological space and its associated algebraic complex.

Chapter 20

Geospatial Views for RESTful BIM

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ABSTRACT

In the near future Building Information Modelling will be applied in different areas of the AEC industry. Building Information Models (BIMs) will be used as resources to enable interoperability of software and 'Building Information Modelling' based Integrated Project Delivery will be realised as a common process of managing a project over a single shared information backbone. Thus, facilitating the collaborative use of shared BIMs is becoming important in parallel with the industrial demand in the field. Some urban management tasks such as disaster management, delivery of goods and services, and cityscape visualisation are managed by using Geospatial Information Systems as the current state-of-art, as the tasks in these processes require a high level and volume of integrated geospatial information. Several of these tasks such as fire response management require detailed geometric and semantic information about buildings in the form of geospatial information, while tasks such as visualisation of the urban fabric might require less (geometric and semantic) information. Today service-oriented architectures are becoming more popular in terms of enabling integration and collaboration over distributed environments. In this context, this short chapter presents an enhancement for a BIM Web Service pattern (i.e. RESTful BIM) that will help in facilitating information transfer from Building Information Models into the geospatial environment. The chapter starts with the background section later provides a review on the RESTful BIM pattern. Geospatial Views that can be developed for the RESTful BIM will be elaborated on later in the chapter.

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1 INTRODUCTION

Building Information Models (BIMs) and Model Based Engineering in general have become an active research area in Construction Informatics in order to tackle the problems related to information integration and interoperability. The industrial rationale behind the rise of the trend towards BIMs and model based engineering is the inadequate interoperability in the industry. Gallaher *et al.* (2004) indicated that US\$15.8B is lost annually in the U.S Capital Facilities Industry due to the lack of interoperability. Today, BIMs are seen as the main facilitators of integration, interoperability, collaboration and process automation. The key reason behind the advent of BIMs is enabling interoperability (seamless exchange and sharing of information) between various different applications used in the construction industry and throughout the lifecycle of the building. Building Information Modelling is applied in many different areas, i.e. either BIMs are used as a resource to enable interoperability or Building Information Modelling has been realised as a process of managing a project through a single shared information backbone. Over the last decade, the Industry Foundation Classes (IFC) developed by International Alliance of Interoperability has matured as a standard BIM in supporting and facilitating interoperability across the various phases of the construction life cycle.

On the other hand, geospatial information and Geospatial Information Systems (GISs) are used in various fields related to urban built environment ranging from three dimensional cityscape visualisations to emergency response management. Until recently, the transfer of semantic information and spatial relationships from building models to the geospatial environment could not be accomplished. This was mainly due to two reasons:

- Firstly, inability of standard CAD models to store semantic information and spatial

relationships due to their lack of object oriented data structures.

- Although BIMs contain geometric and semantic information about the building elements in an object oriented data structure, the geospatial information models handled and treated the data in a different manner than BIMs, and were insufficient in representing all the aspects of the Building Information Models.

The combination of both these factors made it difficult to, transfer information from building models to geospatial environment and represent buildings within geospatial information models. This in turn, prevented a complete automation of several processes where detailed geometric and semantic information about buildings is required (to be held in the geospatial environment) (Isikdag, 2006).

Focusing beyond data integration towards remote communications, the development in web technologies has resulted in the emergence of service-oriented architectures that makes it possible for remote applications to inter-operate using standard web interfaces. The service orientation enables loose coupling of applications over the web, i.e. several applications can communicate and interact with each other without the need of knowing the details of their working environment. Each of these applications (or data layers) that take part in such a web-based interaction in a serving form (either as a data/component or application service) is known as a web service. Software architectures built upon web services are known as Service Oriented Architectures (SOA). Although the trend in the software industry is towards enabling application interoperability over web services (or SOA), the AEC industry is still not fully benefiting from the service oriented approaches, as the focus of the industry is still very data integration oriented.

The pattern RESTful BIM presented in this chapter is designed for facilitating service-oriented

and model based interoperability in the AEC industry. RESTful BIM pattern focuses on enabling interoperability through a fine-grained web interface in a service/resource-oriented nature. The Geospatial Views that will be elaborated later in the chapter facilitates the presentation of the Building Information in the geospatial environment by using RESTful BIM. The following section summarises the background of the research, while the latter sections introduces the patterns that have been defined.

2 BACKGROUND

Building Information Modelling can be defined as a new way of creating, sharing, exchanging and managing information throughout the entire building lifecycle (NBIMS, 2007). In this context, a BIM can be defined as a computable representation of all the physical and functional characteristics of a building and its related project/life-cycle information, which is intended to be a repository of information for the building owner/operator to use and maintain throughout the life-cycle of a building (NBIMS, 2006). More recent definitions of these concepts can be found in the Preface of the Handbook. Today, the key BIMs in the AEC industry are the Industry Foundation Classes (IFC) and the CIMSteel Integration Standards (CIS). IFC is the effort of IAI/buildingSMART whose goal is to specify a common language for technology to improve the communication, productivity, delivery time, cost, and quality throughout the design, construction and maintenance life cycle of buildings. CIS are open standards for the digital exchange and sharing of the engineering information relating to a structural steel framework. Both of these standard Building Information Models are defined using STEP description methods, and can be shared and exchanged in the three STEP implementation levels (Isikdag et al, 2007). The object model of the BIMs (i.e. the logical data structure that defines all entities, attributes and

relationships) is represented within a schema. The model data is usually created by a CAD / BIM application and stored in a physical files (for exchange) or databases (for sharing). Three key methods for sharing and exchanging BIMs were identified in Isikdag et al (2007) as:

- *Data Exchange* by using physical files
- *Data Sharing* through physical files and Application Programming Interfaces (APIs)
- *Data Sharing* through databases

Data Sharing through databases is usually accomplished by using a central database (also known as the Product Model Server or BIM Server), within which users can manage the model by using database front-ends or interact with the model by using standard or proprietary database Call Level Interfaces –CLIs (or APIs). The information in a BIM can be simplified at the data level by defining and using a subset of the model, i.e. the Model View. As explained in Isikdag et al (2008), Model Views can be generated in advance (i.e. Schema Level Views) or by selecting specific building elements from a BIM in runtime (i.e. Instance Level Views).

Web services can be defined as components and resources that can either be, invoked over the web or reached by standard web protocols using standard messages. These services provide standard web based interfaces to currently used applications in order to enable them to, exchange data over the web by using standard protocols and expose their functionality over the standard web based interfaces. Most of the web services that are currently implemented have transformed the interfaces of the legacy systems. As mentioned in Pulier and Taylor (2006), exposing a web service mostly involves enabling the older software (or the data layer of the legacy system) to receive and respond to web message requests for its functionality. He (2003) indicated that two constraints exist for implementing the Web Services:

- Interfaces must be based on Internet protocols such as HTTP, FTP, and SMTP
- Except for binary data attachment, messages must be in XML.

Two definitive characteristics of web services are mentioned as Loose Coupling and Network Transparency (Pulier and Taylor, 2006).

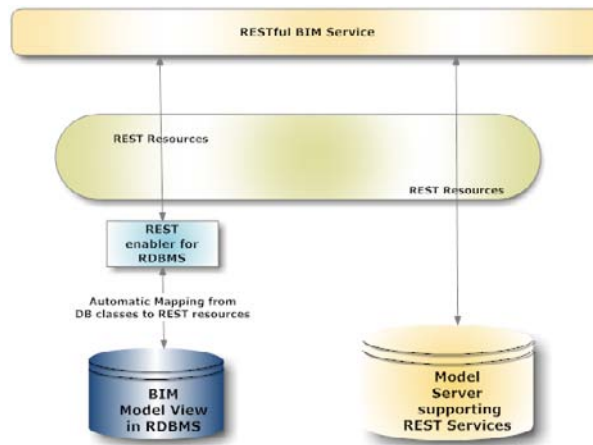
- As explained by the authors, in a traditional distributed environment computers are *tightly coupled*, i.e. each computer connects with others in the distributed environment through a combination of proprietary interfaces and network protocols. Web services in contrast, are *loosely coupled*, i.e. when a piece of software has been exposed as a web service it is relatively simple to move it to another computer.
- On the other hand, as web services' consumers and providers send messages to each other using open Internet protocols, web services offer total *network transparency* to those that employ them (Pulier and Taylor, 2006). Network transparency refers to a web service's capacity to be active anywhere on a network or group of networks without having any impact on its ability to function. As each web service has its own Universal Resource Indicator (URI), web services have similar flexibility to web sites on the Internet.

Two styles of Web Services exist today, namely SOAP and REST. SOAP is a web service style based on using the SOAP (Simple Object Access Protocol) protocol for exchanging XML formatted messages between the networks by using Hypertext Transfer Protocol (HTTP). On the other hand, REST is an architectural style where the web service operates by calling resources over the web. The terms REST and RESTful web services have been coined following the PhD dissertation of Roy Fielding (Fielding, 2000). As explained by

Pautasso (2008), REST was originally introduced as an architectural style for building large-scale distributed hypermedia systems. According to the REST style, a web service can be built upon resources (i.e. anything that is available digitally over the web), their names (identified by uniform indicators, i.e. URIs) representations (i.e. meta-data/data on the current state of the resource) and links between these representations.

Traditional approaches for reaching and updating information in the Building Information Models are mostly focused on exchanging physical files between applications and using shared (central) databases to manage the shared information within the models. In addition, the use of Model Views (i.e. static or dynamically selected subsets of models defined according to needs of a specific information exchange scenario) is encouraged for facilitating the model-based information management throughout the entire building lifecycle. In fact, recent R&D efforts such as SABLE (Sable Web Site, 2005) have shown that it is possible to use Service Oriented Architectures to interact with BIMs and for sharing and exchanging building information. Although the approach might cause problems regarding versioning and ownership, if managed successfully it will provide significant benefits as it will, prevent data overloading in databases, enable efficient use of hardware and network resources, and will be a step towards the Distributed Building Information Modeling. The following sections summarises the RESTful BIM pattern (which is elaborated in Isikdag and Underwood, 2009), and later discusses the role of Geospatial Views in transforming the building information into geospatial information systems using RESTful BIM. The REST style pattern explained in the following section will enable the exposition of all objects in a Building Information Model as a set of web representations. This exposition will enable the users to work directly with every object of the Building Information Model over the web without the need for knowing where, how, and in what form the BIM is stored.

Figure 1. The implementation of RESTful BIM pattern



3 RESTful BIM

As mentioned previously, in order to enable this one-to-one interaction with Building Information Model objects (such as every single building element), the system developers will need a fine-grained interface (i.e. similar to a database Call Level Interface) in the web level. Developing this interface manually for every object in the Building Information Model or Model View (especially when the model views are at instance level or dynamic) is not a simple task. One solution to this problem is leaving the SOAP approach which is commonly used to expose manually defined web service interfaces, and focusing on RESTful, i.e. resource oriented approach for creating the finest-grained interfaces.

In this context, the RESTful BIM pattern focuses on the exposition of all Building Information Model objects as web resources. As depicted in Fig.1, the exposition of BIMs as REST style web services can be accomplished by two methods. The first method is storing BIMs in a relational database and exposing every object of the model as a representation using a REST enabler interface. The second method is storing the BIM in Model Server(s) and directly exposing every object of

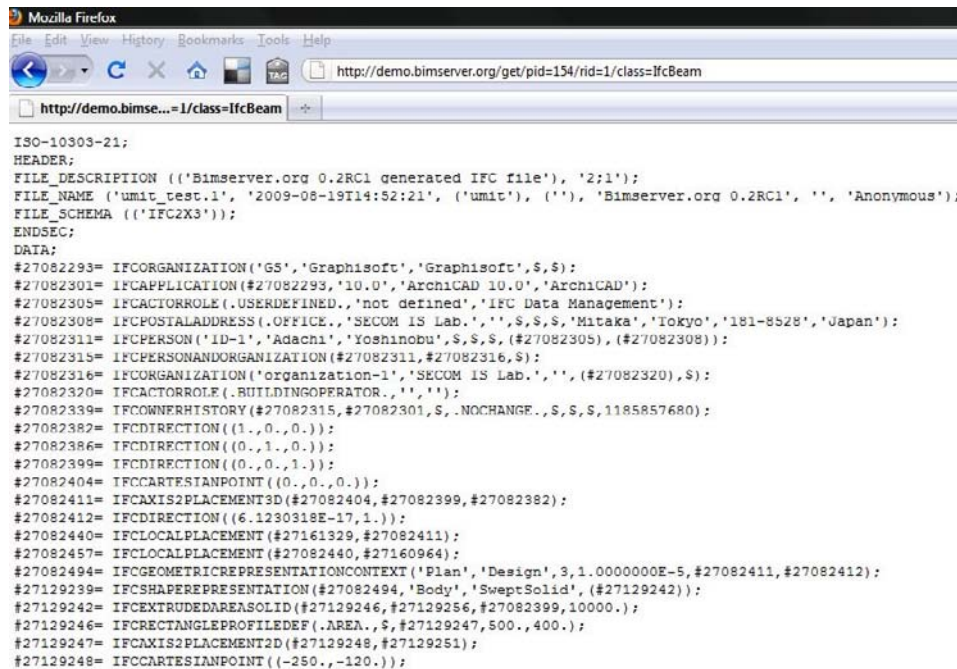
the model as a representation in a REST Web Service.

As mentioned in Isikdag and Underwood (2009), the finest-grained web interface to the model will enable the client application to directly interact with every model object. Recent technological developments have resulted with interfaces that make it possible to automatically map the entities in a relational database to REST resources. Thus, today it is possible to automatically generating REST resources from a BIM that is residing in a relational database. This process is very straight-forward and simple using REST enabler interfaces such as sqlREST (sqlREST, 2008).

Once deployed, the sqlREST generates a (REST) resource for each entity (i.e. table) in the database and each instance (record) in the tables. Every kind of resource has an XLink attribute href with an URL. For example, when an IFC model residing in a relational database is exposed, the highest level set of resources will be provided as:

```
<resource>
<IfcColumn xlink:href="http://
```

Figure 2. The result of a BIMserver (REST style) query to acquire the instance of IfcBeam class



```
localhost/sqlrest/
IfcColumn/">IfcColumn</IfcColumn>
<IfcBeam xlink:href="http://
localhost/sqlrest/
IfcBeam/">IfcBeam</IfcBeam>
...
</resource>
```

An implementation of the second method is realized by the BIMserver project (BIMServer, 2009). The BIMserver is a non-profit open source BIM server which is being developed by TNO, Netherlands. The core of the server is based on the IFC standard, i.e., the server can handle the IFC files. Once a file is uploaded to the server, it is possible to update the model based on model revisions (the server keeps a log of versions), and it is possible to get the final model in form of either an IFC P21 physical file or in a form of an IFCXML file (i.e. the XML representation of IFC model). The strength of the project lies behind its RESTful architecture. A set of any object group

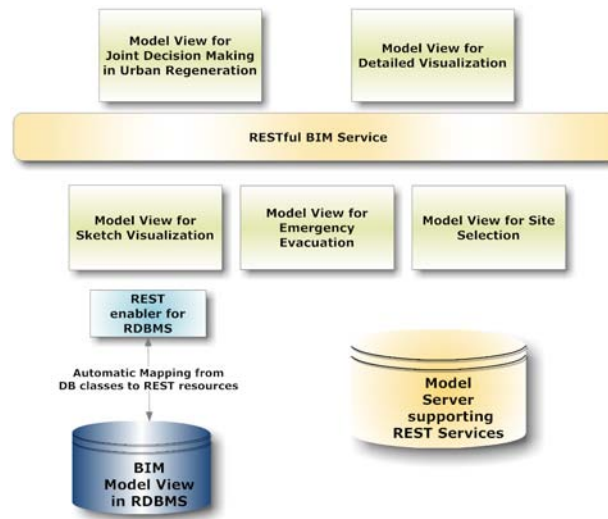
(i.e. IfcBeam, IfcColumn, etc.) can be returned as a result of a REST query. Fig.2 depicts the results of a REST query for acquiring the instances of IfcBeam class.

In contrast to the automatic exposition of BIM in Model Servers, there are tools for creating the resources manually (for generating coarse-grained interfaces), and the most commonly known tool is RESTlet (RESTlet, 2008). On the other hand, if the BIM is residing in an XML file, it can either be imported into a RDBMS or a Model Server and the representations (i.e. model data) can be reached from on-the fly generated resources. Another option in this case is generating resources and reaching representations by using DOM and REST API as interfaces.

4 THE GEOSPATIAL VIEWS

The literature on the integration of Building and Geospatial Information Models is increasing. Zlatanova and Prosperi (2006) present a broad

Figure 3. The Geospatial Views for the RESTful BIM pattern



perspective on the data integration between AEC and Geospatial domains. The reader can refer to Isikdag (2006) along with other chapters in this section of the Handbook for more information on implementation of BIMs in geospatial environment. The implementation on the geospatial side involves the use of 3D Geospatial Models to represent building information. More information on the 3D Geospatial Models can be found in Abdul-Rahman and Pilouk (2007). In addition Isikdag and Zlatanova (2009) provide an extensive review on the opportunities that the implementation of Building Information Models in geospatial environment will bring. Differences between Building and Geospatial Information Models usually forces developers to make geometric and semantic simplifications when transferring information from Building Information Models into the Geospatial Information Systems. The data models needed for emergency response and cityscape visualisation are typical examples of where this simplification is required. The simplification is required to represent the buildings either within the context of City Models developed in advance, i.e. CityGML (CityGML,2009) by static information mapping at the schema level or for dynamically

generating the objects (i.e. emergency response) at the instance level. The usual practice of model mapping today is doing it in a local environment and the use of web services for this purpose is not common. The geospatial views that will be developed for this purpose will act as a catalyst in this transformation process. The geospatial views of the Building Information Model will provide the selected set of building elements based on the applications' purpose.

The views can be one-tier up of the web service, which means that the selection (filtering) of objects is accomplished based on the result of a REST query or can be a tier down of the service layer, in this situation the filtering of objects is done at the database level and the view is presented as a result of the appropriate REST query. The model views can be generated by data mapping (using conventional languages such as EXPRESS-X, or new generation languages such as XSL) by the help of database APIs or by the Model Server itself. The views can be tailored for different application aspects such as emergency evacuation, cityscape visualisation, site selection or joint decision making. In all different views the types of selected elements can be different. The next step for the

transformation of the Building Information Model into a geospatial model is geometric and semantic simplification which will be accomplished by using the objects of the Model View.

5 CONCLUSION

Several different urban management tasks ranging from three dimensional cityscape visualisations to emergency response management are benefiting from the use of Geospatial Information Systems as the current state-of-art require high level and volume of integrated geospatial information (together with detailed geometric and semantic information about buildings). However, until recent years the transfer of building information into the geospatial environment has not been possible due to the lack of semantic information in early building models and due to incompatibilities between the data models in the two different domains. In fact, this situation is now radically changing and recent research has demonstrated that the transfer of digital Building Models into the geospatial environment is possible. The next task ahead is enhancing the applicability of this transformation and making it applicable and feasible within the large scale enterprise architectures. A way of achieving this is concentrating on service oriented architectures in sharing the Building Models. In fact, the AEC industry, although having their own valid reasons behind it, is still very much focused on establishing data and process level integration. For example, industry professionals and researchers are still very engaged in developing schema standards for exchanging (geometric and semantic) building information (i.e. IFC, CIS2) instead of working on application and service oriented integration strategies.

The study discussed in this chapter provides an overview of how service oriented architectures (especially the REST architecture) can be used to facilitate the transfer of information from Building Information Models into the geospatial

environment. In this context, the pattern enhancement explained in this chapter might contribute to the efficiency in transferring information from Building into Geospatial Information Models. The pattern enhancement explained in this chapter portrays that it is technically possible to build up highly customisable BIM based service oriented architectures using the REST style which can act as a backbone for digital urban models. Although the SOAP style is more mature as the current state of the art, the REST style (i.e. resource-oriented) architecture also provides a lot of opportunities in information transfer and transformation as it can enable finest-grained interactions at the web level.

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KEY TERMS AND DEFINITIONS

Web Service: A system or a software which supports interaction over the WWW. The interfaces of web services are generally defined by commonly recognised standard web languages.

Simple Object Access Protocol (SOAP): A protocol and a messaging method specified to exchanging information using web services. The SOAP protocol depends on XML as its message format.

Representational State Transfer (REST): The architectural style for building large-scale distributed hypermedia systems. According to the REST style, a web service can be built upon

resources, their names, representations and links between the representations. WWW is a system built according to the REST architectural style.

RESTful BIM: The web service (design) pattern developed by Isikdag & Underwood to facilitate RESTful sharing of Building Information Models.

Model View: A subset of the Building Information Model which can either be generated in advance or on-demand.

Model Server: A storage environment or a server that facilitates the collaborative use of

Building Information Models

EXPRESS-X: A Model mapping language developed with the purpose of transformation of models defined according to ISO 10303 standard.

Chapter 21

BIM and Geospatial Information Systems

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ABSTRACT

Historically and traditionally, location based information merely represents a feature's location in a real world setting. Advances in information technology (IT) and data collection techniques have revolutionised the Geographical Information System or Geospatial Information Systems (GIS) industry. The relatively recent explosion in data storage and processing capabilities has led to more detailed and accurate data being collected. This provides a far greater data rich environment and more opportunities for exploiting this information. It is not enough to only know where something is. Questions like but what is it, what's nearby and what are the associated attributes 'are more relevant now. A data rich Geospatial Information System allows for detailed spatial (location based) queries to be performed to explore and analyse these geographical relationships. In parallel to this information explosion, the built environment has started to embrace this revolution. In essence, a building is a component of a larger group of features which is linked by infrastructure and other elements to create a holistic system. The common factors which connect this system together all have an associated location. When viewing a building in isolation it is clear that it is made up of a number of different individual features. Information about these features is a key part to its design, construction, operation and maintenance. The term (BIM) Building Information Modelling refers to the information system which is developed to manage built features. Of course a building doesn't float in space; it is closely related to other features and infrastructure. This chapter will explore the value of integrating BIM and Geospatial Information Systems into a single system, why this is important, and how this can be achieved.

1 INTRODUCTION

There has undoubtedly been a growth in the use of Geospatial Information Systems (often referred

to as GIS) and BIM over the last few years. In the last few years the GIS market has evolved from technology that was once specialised to becoming part of the enterprise. As D.Duffy (2003) says,

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“according to Daratech, a Cambridge, Mass., market research company, the total revenue from GIS software topped \$1 billion in 2001, which represented a growth of 9 percent in 2001 over 2000”.

It can be argued that there are a number of reasons for this growth such as:

- The convergence of related technologies which benefit from location (spatial) information;
- Realisation of benefits and efficiencies that are the result of a more collaborative approach;
- Greater emphasis on managing information as an asset which is re-usable;
- The traditional CAD/BIM and GIS silos moving closer together with the emergence of people with both skill sets working on common platforms
- Interoperability barriers are starting to be removed; there is a more standards driven approach to data collection and storage which is helping to provide a framework for data exchange.

A building, however big, small or complex is one component of the wider built environment. Even as a single entity it creates a vast amount of information just by existing. Any works that are planned or any maintenance and operational schedules require information about the components which combined together make up the structure. In a true architectural sense a building is not designed as a single entity. Consideration is given to its context within the direct locality as well as the wider environment. It is not as simplistic as, BIM is inside the building and the geospatial (GIS) space is everything outside the building.

Chances are the “building” is physically connected to a combination of “assets” outside which provide water, energy and communications. These

“assets” are then connected to other buildings and assets and so the networked system continues. Looking at it this way it seems obvious that an integrated system would be the most sensible approach.

2 COLLABORATION

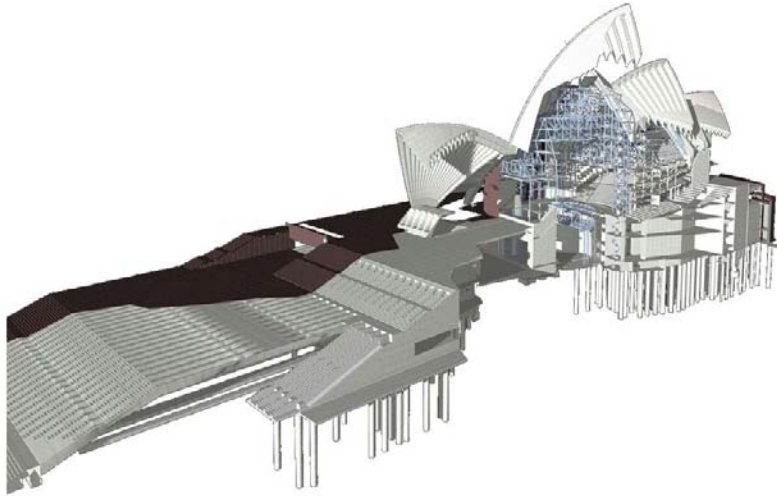
Collaboration is a phrase that has crept into the AEC vocabulary and is now part of the common vernacular. From the latin *collaborare* the definition is to “work together”. There is often agreement during a project inception meeting that project work streams should collaborate more combined with talk of using common systems and standards. What is sometimes lost at this point is why this is important and what the benefits are in terms of real measurable business returns. The short sighted approach is to ignore these ideas of collaboration to focus on the “deliverables”. After all, this is how performance is measured. You don’t often hear of clients being glad about costs spiralling upwards because the suppliers decided a BIM was required or a complex geospatial system would solve all the projects problems. Often the long game isn’t considered. As Simon Rawlinson (2006) states

“Fragmentation of the process and the continued separation of commissioning, design, construction and operation take away the incentive to use BIM for facilities management”.

The perception of low level collaboration will hinder the investment and development of the joined up BIM. This will be discussed later in this chapter.

Stepping back and consider the vision. Putting any known barriers aside what is the BIM and geospatial vision. You could sum it quite simply as “one version of the truth”; a single information portal which provides an accurate, query-able data hub relating to all aspects of the built environment.

Figure 1. Adapted from Arup BIM example of infrastructure and buildings operating as a system



The data is provided, updated, used and managed by all of the stakeholders. The process begins as soon as the building is considered and used right through until de-commission.

In broad terms, some of the advantages of this BIM approach are summarised as follows:

- Owners, designers and engineers get lower net information costs and risks
- First responders can contribute to the design to make buildings safer
- Efficient monitoring lowers operating costs
- Better views of facilities lead to better decisions
- Realtors, appraisers, and bankers save money
- Regulations compliance costs are lower
- Subcontractors' costs and risks are reduced

Source: OGC(2007)

As the OGC (2007) states,

“US Presidential Executive Orders 12906 for Spatial Data and 13327 for Real Property Asset Management both promote creation of a common

infrastructure to facilitate efficient and effective information sharing, reuse and application for a variety of needs. A BIM links to, and makes use of, geospatial information such as: property boundaries, zoning, soils data, elevation, jurisdictions, aerial images, land cover, land use, etc. And it includes data of interest to buyers, owners, lenders, realtors, first responders, repairers, occupants, safety inspectors, lawyers, emergency planners, and people working on neighboring facilities”

It could be argued that the “stuff” outside the building is well managed and available through traditional GIS in various formats and versions. As James Fee said in an interview with V1 Magazine (Fee, 2008)

“people are always saying that GIS is outside the building and CAD is inside the building, and well we all know that isn't necessarily the case. That's over simplistic. GIS goes inside of a building and CAD goes outside of a building. So there is that interaction between the two and where that happens is going to depend on how far each one goes. At what point do you say this should be done in a

GIS 3D model and at what point do you say this should be done in a BIM 3D model?"

There have been considerable advances in this area to develop complex data models which are used to accurately visualise and model the natural environment. What are the challenges to apply this logic to buildings? Surely a building can be "mapped" and managed in a similar way to other assets found outside. The geographical extents are different but the theory is the same. During the design and planning process plenty of data is created and used but more importantly the final position and specification of all the separate components is known and documented. What happens to this data? Actually isn't the BIM just a by-product of the design process which should just slot neatly into its place in the world. Arguably this is what should happen, but why is this not the case?

The business drivers for integrating and using these two technologies should be clear and well articulated in such a way that there is a compelling case for their inclusion at the earliest possible moment. But what are the business drivers for this integration into a single system? Are these attractive enough to become common practice and if they are why isn't this happening. Is the industry ready for change or maybe more importantly are the different technologies which need to be used truly ready to be integrated into a holistic system? Whose responsibility is it that this should happen; the designer, the contractor or the asset manager?

These are some of the questions which will be explored within this chapter.

3 SETTING THE SCENE

At this stage it is worth reflecting on the areas of technology that this focuses on and considering some of the wider opinion.

As referred to earlier, the term Geospatial Information Systems is used to describe the software,

hardware, data and people that are utilised together to analyse and manage location based data. This broad definition includes all of the Geographical Information Systems (GIS) technologies, earth observation techniques, spatial database engines, web protocols and standards provided by the likes of the Open Geospatial Consortium, the AGI and Inspire (Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE) was published in the official Journal on the 25th April 2007. The INSPIRE Directive entered into force on the 15th May 2007).

The GIS industry itself is a billion dollar technology juggernaut. Its roots might be in the natural environment, but applications now include asset management, defence, site development, acoustic modelling and the evaluation of risk to name but a few. For the first record of a truly operational GIS you have to go back to 1962. Dr Roger Tomlinson established a GIS in Ottawa, Ontario for the Department of Forestry and Rural Development to manage land inventory data. This system built on standard mapping applications by providing capabilities for overlay and measurement.

As with any technological business there are many different software options. However, the common denominator will always be the data. This will be discussed in more detail later. Simplistically, all the software really provides is, a way to consume this data (in whichever format is being used). As can be expected there is a conundrum of different read and write possibilities for the data formats depending on the software being used. The wider advent of standards and web based services has helped overcome some of the interoperability problems but this still is an issue.

Origins of BIM

In GIS terms, BIM has been around for far less time. But like GIS you could equally argue that building information has been managed for many

years. It is widely thought that there are two origins for the term BIM:

- The first comes from Autodesk (BIM White Paper, 2002) as a term to describe “3D, object-oriented, AEC-specific CAD”.
- The second comes from Professor Charles M. Eastman at Georgia Institute of Technology (1999). This is based on the opinion that the term Building Information Model is basically the same as a Building Product Model, which Professor Eastman has used extensively in his books and papers since the late 1970s. (‘Product model’ means ‘data model’ or ‘information model’ in engineering.)

Whichever is the case, there is some agreement that the term BIM was popularised by Jerry Laiserin “as a common name for a digital representation of the building process to facilitate exchange and interoperability of information in digital format”. According to Jerry Laiserin and others, “the first implementation of BIM was under the Virtual Building concept by Graphisoft’s ArchiCAD, in its debut in 1987”.

The information has existed, buildings have been built and information has been created during this process, this isn’t new. The Romans had detailed plans about their structures (indeed, metadata still exists today)! The practice of managing all of this information within an organised “database” which can be queried and used to manage the operation of the building is somewhat more contemporary. As with many industries there are always drives towards efficiencies and techniques that can be adopted to ensure that lean approaches are used. When considering the costs associated with designing, constructing and operating a building, savings that can be made run into the millions. The realisation of these savings is one of the driving factors behind the emergence and consideration of the BIM approach.

What is sometimes overlooked when looking at any technology is probably the most important component of all, the people. It is the people and personalities which make ideas become a reality and make change happen. Unfairly the CAD/BIM and geospatial (GIS) communities have in the past been described as the hard hats vs. the bobble hats. In the past the background and agendas of the people working in both of these industries has been poles apart, often not even working in the same coordinate system. Thankfully this is now changing. Partly driven by the software vendors themselves (for example AutoDesk, Bentley, ESRI and Intergraph), both of these application areas are able to interoperate within a common set of standards and data models. This move has provided the tools to make the theory become a reality. It has become evident that many of the basic skills needed are transferable between the two communities.

4 GENERAL ANALYSIS

Those dealing with and those who are responsible for managing information and data at this type of scale can clearly see the benefits of adopting an integrated approach. Common sense would point towards this. What is the benefit of storing information which is influenced by so many other factors in isolation? During this section some of these benefits will be explored further in order to try and build an argument for adopting this approach.

As with any digital project when any new infrastructure is planned and designed, no matter how complex, during this process the volume of associated information grows, often at an alarming rate. Just ask your IT analysts how much disk space is being consumed on a daily basis. This information broadly falls into two categories; that which has been produced as a direct result of the design and that which has been gathered to help the design process. Either way there is a cost in

generating this information, depending on the size of the project this can run into the many millions of pounds. It is often the silent asset in terms of investment but holds the highest value.

As Mark Reichardt(2008) quoted,

“In 2005, the European Commission’s European Construction Technology Platform (ECTP) published a document titled “Challenging and Changing Europe’s Built Environment - A vision for a sustainable and competitive construction sector by 2030”. The report, prepared by members of the construction industry, states, “for Europe to face its major technological, economic and social challenges, we must be proactive in understanding and communicating within our sector. An important task is to turn the sector around to becoming knowledge-based. By improving the construction process, we hope to achieve reductions of up to 30% of lifecycle costs, 50% of delivery time and 50% of work-related accidents.”

A 2004 study of office buildings, undertaken by the North American Continental Automated Buildings Association (CABA), found that over a 30-year period, initial building costs account for only two percent of total building costs, while operations and maintenance costs equal six percent and personnel costs equal 92 percent (Fuller and Petersen, 1995). This is somewhat staggering.

An example could quite easily be a large site development project which might constitute the re-development of a derelict site there are a number of data products which will be required; utilities data, topographical survey, contamination survey, geotechnical information and landownership. Traditionally these data products would sit within the “geospatial information” silo, and may be accessible to the GIS team and possibly others. Who needs access to this data; the architect, the structural engineer, the contractor or the facilities manager? You could easily argue that they all need access at some point, together with many other

disciplines (or work streams) depending on the complexity of the project.

Maybe the question then is what happens to this information during a project? Theoretically once it has been gathered (remember a cost is incurred here) it should be used as many times as possible, to leverage as much return on the investment as possible. How many examples amongst the industry are there where duplicate surveys have been carried out to collect similar data or surveys have been carried out to collect data that has already been commissioned previously during a prior project stage.

If you develop this train of thought further there is an obvious business driver here. By investing in the technology which is available to manage data of this type you are able to leverage far more benefits from that data, many times, during the project lifecycle. More of a collect once use multiple times philosophy.

Importance of Interoperability

Interoperability is one of the major challenges if not the biggest challenge of all. It is well documented that in the NIST report (2002) “the cost of inadequate interoperability in the US capital facilities industry is \$15.8 billion”. As Geoff Zeiss (Director of Technology, Autodesk) (2008) points out

“discontinuity hurts everyone, it costs time and money. Everyone involved with buildings and infrastructure must have seamless access to design and geospatial information. As the industry strives for making the process more efficient there will be greater emphasis placed on converging the technologies and the information these technologies use”.

It is clear to see that a collaborative BIM and geospatial system helps to drastically reduce this figure quoted in the NIST report. There is a clear benefit here. By working in a joined up

Figure 2. Projects involve collaboration at a number of levels



way there are clear savings which can be made by standardising these technologies.

The development and the adoption of standards will be a vital part of this process. Open Geospatial Consortium (OGC) is an international voluntary consensus standards organization. In the OGC, more than 360 commercial, governmental, non-profit and research organizations worldwide collaborate in an open consensus process encouraging development and implementation of standards for geospatial content and services, GIS data processing and exchange). OGC has a 3D information management working group with a heavy focus on the convergence of AEC and geospatial trends and technologies. The IAI (International Alliance for Interoperability) uses the IFC standards (Industry Foundation Classes) to coordinate change and improvement.

Information accessible through the OGC Web Site(2009) explains the stance the OGC are taking with BIM and why a standardised approach is important. As the OGC states:

"In AEC and related domains, stakeholders with a wide range of business goals or governance goals

want to bring "business process reengineering" into the world of AEC and facilities management. Old business processes no longer make sense when computers and networks can be deployed to do things better and faster. It's valuable to note, too, that new opportunities for profit or public service arise as information and communication technologies (ICT) are integrated into workflows. BIM standard efforts involve standards from a variety of organizations, all of which are communicating with members and driven by pressure from stakeholders to improve efficiencies in virtually every commercial and public activity that involves the built environment. Their concerns encompass the planning, design, construction, management, renovation, repurposing, decommissioning and ultimate demolition of buildings, bridges, power stations, airports, highways, fuel storage facilities, refineries and ports. The stakeholders believe that BIM standards will save billions of dollars and provide an improved quality of life".

It is worth at this stage highlighting the excellent "joined-up" approach the OGC are taking. It sometimes feels like the industry is awash with

standards. Importantly these BIM standards build upon existing industry standards, such as:

- The International Alliance for Interoperability IFCs
- Standards of the National Institute for Building Sciences
- ISO standards
- Open Standards Consortium for Real Estate (OSCRE) standards
- Open Geospatial Consortium (OGC) standards
- The FIATECH capital investment roadmap
- Efforts like CSI OmniClass taxonomies, COBIE (Construction to Operations Building Information Exchange).

All of the BIM Standard approaches that are being made in the US, Europe and across the globe take the stance that digital data is, accessible in a shared way, and easily interoperable across different communities and stakeholders information systems. It should also be based on the use of open standards which can be defined in the most appropriate language.

For example National Building Information Model, Version 1, Part 1, Overview and Methodologies(2009), is a working document which is using a network of voluntary contributors to help shape a US national BIM standard.

In theory, the use of standards and best practice are a great way to reduce issues around interoperability, after all if everyone works to the same standard then the information should be able flow freely making it easier to converge different technologies together in order to achieve some of the efficiency benefits and drive forward innovation. Right? Maybe this isn't always the case.

The Importance of Change

As with any type of change there is resistance to it, this is human nature and not exclusive to this

subject. In essence the convergence of geospatial systems and BIM is a convergence of technology that as been around for a while, often competing within a very competitive market worth many billions. Conservative attitudes exist, which make it challenging to make and implement changes to workflow, roles and responsibilities. Clients often expect "more for less" which doesn't create an environment where implementing new working practices is easy. In some respects even though the advantages seem to be clear it isn't always the push that the industry needs to make the step to incorporating this technology into "a business as usual" practice.

As Sam Bacharach *Converging on the Market: CAD, Geospatial, 3D, Visualization and BIM* (2007) states in his paper "the challenge is daunting. The different technology domains and application domains have different vocabularies, geometries, computing paradigms, data formats, data schemas, 'scales' and fundamental world views. They also have different requirements for accuracy, "verisimilitude" (realism) and animation performance."

Sam goes on to explain the market reality in terms of the situation on the "coal face". There is a transition toward far greater productivity within the workflow. The move being from traditional hardcopy drawings to digital drawing files eventually to the use of web services. Obviously this takes time. As with any change of this scale there is an element of risk taken on by the user which can only be overcome when they are sure that it is going to work and they are fully confident in the process. While this build up of confidence is happening software vendors will continue to develop software based on user requirements. There is a lag in the process, it is almost impossible to expect a user to continually change their working practice and take on new processes when their routine may continually change.

Sam goes on to state that "Our business relationships also shape our thinking. Most architects and builders are still in between paper

Figure 3. Resistance to change



and digital files. It's easiest to do business with people in the way they know how to do business. Architects usually design with CAD, but often they still communicate with paper (or drafting film), partly because the computer systems used to specify component suppliers, contractors and city officials often don't interoperate very well. Increasingly, however, the systems do interoperate, at least through file transfers. But the digital files that get transferred are not as secure as paper: it's easier to trust a paper document. One can know with some certainty who created it, when it was created and when it was last updated.

Despite these obstacles, businesses that work together on big projects increasingly exchange digital information using a variety of formats and extranets. They typically rely on some combination of industry standards and ad hoc agreements to avoid incompatibilities. This saves a lot of printing, scanning and redrafting, and it enables exchange of files via the Internet. This step toward digital communication helps designers leverage their investment in CAD and helps construction contractors realize the benefits of CAD"

It could be argued that barriers from technology are the easy part! IT is always advancing, there is more PC power available now, bandwidth is increasing, and computers get faster. On the same curve as this are the demands we are expecting

from our IT. The demands we place on IT are often ahead of the curve.

Whichever way you look at it information (data) is central to this issue. As Mark Reichardt (President and CEO, Open Geospatial Consortium, Inc.) (2008) said

"The goal is not only to reduce waste, but to increase the value of information. The value of information extends well beyond its original purpose, because, for almost any AEC or geospatial information, there are many likely or possible future uses as well as possible immediate secondary uses".

The message being that information that is needed and created in one phase of a project is also needed for the rest of the project lifecycle and beyond. Logically this would make sense. Why re-create information if it already exists. As discussed previously this only adds to the overall costs and project overhead.

Earlier in this section we touched on an example of a site development project in the context of the different users of information and the types of information that will be required; the reason being to consider the commercial gains from re-using data. However, it isn't as clear cut as this. At a high level there are advantages from being

able to understand the “site” better. The old adage “better information for better decision making” applies here. But what does this mean in reality? Utilities data is a prime example. Their precise location, connectivity and associated attributes is often one of the vital pieces of information that is required. The location being where they are now and where the location of new utilities will be as the buildings are designed. This is especially relevant when considering connectivity which then has an impact on the other components of the associated infrastructure (any new roads, structures, drainage etc). Correctly understanding these complex spatial relationships and being able to share this information with reference to the new building and locality is of vital importance. The inaccurate collection or communication of utilities data will result in design changes, clashes and possible health and safety risks.

Bearing all of this in mind it seems sensible that this type of data should therefore be stored and managed in a combined system which is accessible to and compatible with not only the GIS systems but also the building design itself.

Buildings Data

So far we have mainly focussed on the buildings relationship within its locality and some of the related data, but what about the building itself? As mentioned previously the same theories which can be applied to geospatial data with reference to how it is collected, managed and used can be equally applied to the building itself, admittedly this is on a smaller geographical scale but arguably it is more important at this scale. In broad terms the design of a building is comprised of a number of different components which are designed by a number of different disciplines all of which depend on each other to understand how the design should develop, information on the different components and the associated attributes of these components. For example what are the weight, thickness, and material of the air-con ducts? In many cases this

information is not always communicated in the most efficient way. This is either because of different formats being used, different data models or lag in when the component is designed and when the information is available. Within the BIM environment there is a common collaborative system for storing and accessing the design data. This allows far greater options for understanding the design as it evolves but also a number of other notable benefits.

Clash detection is a well documented example where BIM excels. One of the reasons that this is a good example is that clash detection relies on a multitude of other components to work. Clashes are often only clearly visible when these components are brought together into a common system and analysed together. The impact of clashes can result in costly design changes and impacts on the overall programme. Obviously being able to understand where clashes might occur is heavily reliant on accurate data. A collaborative BIM approach would clearly help here. Providing the information is supplied in the correct format these detections can be carried out as part of an automated process. So the benefit here is not only being able to carry out the clash detection but being able to do it quickly.

This leads nicely on to another area of consideration, project management, in particular the programme and the costs. Planning a construction process is notoriously difficult. Industry reports suggest that resources are only used at 40%-60% efficiency. 4D modelling is a tool that provides an interactive ability to visualise, inform and rehearse construction sequences driving more efficiency into the construction process. The 4D acronym has developed within the industry to describe the addition of time to existing models. In simplistic terms the 3-D model contains “objects” controlled and driven by a timeline. The application of the “fourth dimension” allows the sequence of objects to be manipulated with almost limitless permutations. As more detailed programmes are required the model can be used to describe a complex

sequence of building activities without the need to understand pages of charts; the aim being to optimise the construction timeline and highlight bottlenecks and site constraints.

The next stage is often referred to as “5D”; the addition of cost data. The power of 5D scheduling allows the exploitation of the different objects and enables reporting of the subsequent costs at any particular point in time. The analysis of task occurrences and their relationship to one another allows the investigation of almost a limitless number of possibilities.

By understanding the building within its real world context and having a greater appreciation of its relationship with related features it is easier to plan and manage the entire development from a project management and cost management aspect. Currently workflows are governed by the availability of data and the format that the data will arrive in. As has been mentioned previously, a great deal of time has to be factored into the programme to deal with resolving issues around data formats and how these can be overcome. Often this time is repeated from project to project and results in a very clear cost. There would be a very real value associated to reducing the time spent doing these tasks. This time could then be spent actually making use of the data. Spending time making sure that the two technologies are integrated would have a major impact in this area.

A recent UK government report (2008) (Place Matters: the Location Strategy for the United Kingdom) of location based information stated that within the geospatial industry 80% of time is spent collating and managing information while only 20% is spent actually using the information.

Large buildings projects commonly require many different disciplines working together as part of project team; often requiring data and information from each other to complete specific tasks. The inability to efficiently share what is often very dynamic data can have impacts on the overall project programme and delivery. This

is particularly true when considering BIM and Geospatial Information Systems. The project critical path often includes a number of different inputs which require either traditional geospatial information or information about the building design. How this collaboration works is often absolutely critical to the success of a project. As more emphasis is placed around getting a better understanding of the urban environment there will be more demand for greater integration of these technologies.

The question is how attractive is this, is there a chance that it will become part of the business as usual approach. There does seem to be some logic to this approach and some pretty obvious drivers here. There is an aspect of introducing change and trying to adopt a new set of standards and procedures. One of the issues to consider is where will this change be driven from. In some ways this is more of a technology push rather than a change which is being requested by the business itself. The technology does already exist and there are a number of different options available depending which vendor you speak to. It isn't always straightforward to implement change when it comes from a technology push. This change could come to market quicker if the change is requested contractually the same as any other contractual element. If this was the case then there would be more of an incentive to change working practices and procedures. What would be the incentive for doing this? It is well documented and referred to in this chapter that there are a number of benefits that the client or end user of the development would see. As discussed, these could either be as a result of saving time or saving through the re-use of data.

There is a direct link with the growing demand for “smart infrastructure” in order to tackle environmental issues. This is more efficient and environmentally friendlier systems for managing, among other things, commuter traffic, food distribution, electric grids and waterways. IBM

have branded this campaign as a “smarter planet” as a method for using technology to monitor and manage the planet.

On reflection there are numerous reasons for the AEC industry to adopt an integrated BIM geospatial approach. Some of these are described below:

- Leverage greater value from the information that is produced during the entire project lifecycle. Information produced during the design process is “carried through” to construction, operation and maintenance
- By understanding the building within its real world context and having a greater appreciation of its relationship with related features it is easier to plan and manage the entire development from a project management and cost management aspect
- The information that is collected and stored within the BIM system can be used to overcome issues such as clash detection and the impact of design changes
- Design changes can be rapidly evaluated
- Large building projects commonly require many different disciplines working together as part of project team. Often requiring data and information from each other to complete specific tasks. The inability to efficiently share what is often very dynamic data can have impacts on the overall project programme.

Considering all of the literature, examples and reasons for change on the one hand it is hard to try and understand why the industry hasn’t made the change and fully adopted a combined BIM and Geospatial Information System solution. Undoubtedly there are numerous projects which would benefit from this. As this chapter has already discussed, there are well documented reasons for adopting this approach but crucially it is worth considering if these are truly attractive enough to become common place and more importantly

common practice with the AEC industry. If there is a lack of traction for this approach there will be no change.

This isn’t necessarily a bleak picture. The industry has already gone through massive change over the years. Looking back the CAD and geospatial revolutions both happened at the same time as other advances in mainstream IT and the rise of the internet also happened. This mix of technology has brought us to where we are today. The technology is now there to put in place the theories which have been discussed for some time. In the past the CAD and GIS (representing geospatial information) silos have been very separate. As has been discussed there has been little common ground between the two technologies. This maybe due to the origins of the software and the different markets they traditionally operate in. In recent history the two have moved closer together to the point now where many offer similar technologies. It is becoming increasingly difficult to draw the line between that which is CAD and that which is GIS.

The rise of the use and availability of web services and the various exchange data formats which are now available has helped to reduce some of the barriers which used to exist around interoperability between the two systems. Data is the key and more importantly in a truly interoperable standard web services empower the user (client) to choose the product which they want to use to consume the data. This approach not only makes for a rich tapestry of available data for the traditional geospatial scenarios but also for buildings. Sharing and collaboration is easier as is availability. Including the addition of “cloud computing” and the relative ease of data transfer across the enterprise.

This all sounds very good and positive but whose responsibility is it to enforce this change and make sure that the standards are met. Should this be a technology push or is this a pull from the industry. It was discussed earlier in the chapter the reluctance for the adoption for new work

processes until a level of confidence is reached. Given that this is the case should it therefore be the responsibility of the client to make sure that contracts are written in such a way to specify the standards that should be used together with a set of deliverables that can then be used to make sure that the benefits of this approach are realised.

It could well be argued that until this is the case that the change will be stifled. Arguably, the majority of benefits from the integration are benefits which are client side and only really come into effect once the building has been designed, is being constructed, and maintained. The maintenance and operation stage is the longest phase and also often is “worth” more than the actual construction. Bearing this in mind it seems clear that there should be motivation from clients to include explicit terms in contracts that make sure that the right standards are met in order to make it possible for an integrated approach to BIM and geospatial information later on in the lifecycle.

5 ANALYSIS OF FUTURE TRENDS

At this stage it is worth looking ahead to some of the possibilities given the greater collaboration between these two areas. If BIM and geospatial systems do truly align what will be happening in the future and what will this mean?

One obvious result would be that there is far greater integration with other applications which is driven by the benefits gained from having a standardised approach to data. There would be far less reliance on vendor specific proprietary data models and more use of standard exchange formats, data sharing and the use of web services to “feed data” into applications. This is starting to happen now and is seen by many as the next major step forward. The increased availability of an internet connection, increases in bandwidth and advances in web protocols will make it far easier to provide access to data rather than passing around numerous “files” of data. Underpinning

this society of data sharing will be the application and use of standards, which will enable data integrity to remain in place.

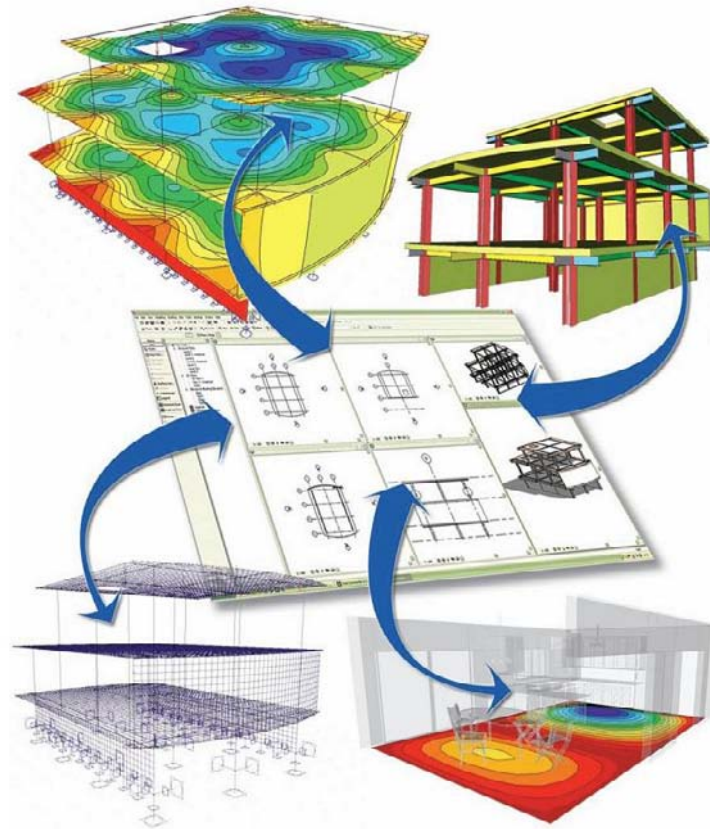
An integrated design team would no longer have to be uploading and downloading data files but could work far more efficiently and collaboratively by sharing data within this standard set of procedures. This would not only be within the confines of geospatial systems but also as part of the building design process itself. Data feeds will become more data rich and will also include some live feeds of data, and feeds of future predictions based on the design itself. In effect, modelling will be done on the fly based on the available data and made available using the same protocols.

We have seen with the popularity of Google Earth and similar applications that there is an increased hunger for location based content but not just the traditional map marker and some attributes. More data will be made compatible that can be used within these types of environments. This will include not only design data but also the scenario modelling results and the impacts of the design in time. This information will be used to assess and model far more complex situations. The value being that it will help provide us with a far greater level of understanding about a site than we already have. The impacts on the environment will be far more understood.

Data licensing and data ownership issues will be more widely understood. Currently artificial barriers exist which restrict the availability of data. These barriers often occur because little is known about any licence restriction surrounding the data. As data becomes freely available in a format which can be easily used so there will be far more innovative applications for that data.

Any new buildings or site developments will be able to easily make use of the data that is available having confidence that it is in the correct format. The benefits of an integrated approach will be seen across the industry as efficiencies will become clear; far less time will be spent on issues with data interoperability as data sharing

Figure 4. Adapted from image taken from SCIA, Scientific Applications Interoperability Diagram (2008)



and collaboration will become far easier. As was mentioned earlier, this will most likely help to assist with the growth of smart infrastructure and smart cities.

The current design process is often very time consuming and iterative. Design teams meet, conceive options, and then have to go away investigate and test these options. A week or two later the design teams might meet up again and the process will repeat itself. Making use of the data that is currently available, “real-time” analysis would be used to test and review options quickly. For example, computational fluid dynamics (CFD) is used to assess the environmental performance of space. This is presently a very time consuming process. Advances in IT and with an increase in

data interoperability mean these processes will run much faster with routines being able to be run and assessed on the spot. This will streamline the whole design process.

The optimisation process uses computational routines to assess and sort options to find an optimal set of solutions. Any number of parameters in the design process can be varied, including for example views, daylight levels, thermal efficiency and costs. Design parameters can be incorporated into complex algorithms that will find the best set of solutions to meet the objectives which are set by the design team. Once this computational solution is set and built, alternative designs can be explored. This process is commonly used within the aerospace and automotive industries and is now

beginning to take a hold in the building industry. This approach is appealing to architects because it provides an objective basis for design. One of the benefits is that options can be very quickly assessed.

How we understand urban environments is becoming more critical than ever now in our quest for a low carbon and low consumption future. An integrated urban modelling approach for understanding the interactions between all the components of a city and how everything performs is going to be critical. This involves taking steps towards multi-parameter real-time quantitative simulation of the urban environment. The goal is to bring together discreet quantitative analytical solutions (urban design, moving vehicles, moving people, acoustics, lighting and climate) into a unified real-time interactive environment to demonstrate performance based design. This could be to other designers, city planners or clients.

A great deal of the design process is based around previous experience and past performance; producing a good design with the right feel for the space. It would of course be tremendously useful if it were possible to experience the space before it is built. The most basic of these “virtual reality” type experiences is a fly through that provides some kind of feel of space and a sense of proportion, but this does not really engage all of the senses. It is becoming increasingly possible to provide an accurate aural footprint of a space using acoustic simulation rooms such as sound labs. The trend in this area will lead to the use of rooms that can be used to simulate the appearance, sound, air movement and temperature performance of a space providing a true immersive experience.

All of these future developments will become common place and part of a business as usual approach to these types of projects. The adopted system will be the collection of software applications which are bound together by some standardised data protocols and standards. Using this technology in an integrated way to understand

the urban environment will no longer be seen to be the future but it will be the “way things are done”; demanded by clients and common practice amongst designers, engineers and project managers. The rise in the innovative uses for this data will come about because there will be more possibilities due to the way the information can be made available and accessed.

6 CONCLUSION

This chapter set out to examine the value of integrating BIM and Geospatial Information Systems into a single system; why this is important and how this can be achieved. It is clear to see that these two technologies are coming closer and closer in terms of philosophies and functionality.

This convergence is for a number of reasons, arguably the key drivers and business reasons for this change are focussed around more efficient way of working, reducing unnecessary costs and leveraging more return from the investments made in these technologies. As has been mentioned the value can not only be discussed in terms of £’s and \$’s saved but also the longer term benefits from managing data better as a long term asset in the same way that “physical” assets are managed.

It is worth reflecting the importance of data and how this continues to underpin all of this technology. Interoperability and standardised approaches which are industry wide should be adopted where appropriate. These not only provide a framework which is understood and accepted but also “oils the wheels” which helps advance the collaboration which needs to be encouraged.

This approach can really be summed up as an approach which works towards total engineering, a term used by Ove Arup. Total engineering really sums this approach up well and also helps to describe some of the values and benefits which this chapter has been describing. In order to realise the values and benefits some change must happen. This

is often the difficult bit as this impacts often on large organisations and large costly projects which have very real deadlines and deliverables.

The benefits and value are often only realised if this shift and change is put in place. For this to happen there must be confidence that this will work and that the investment made will actually return benefits. There are increasingly more examples and evidence to support the benefits and value claims that have been made in this chapter which should help to re-enforce the time and effort which is necessary to drive this exciting and worthwhile technology forward.

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KEY TERMS AND DEFINITIONS

BIM: The process of generating and managing building data during its life cycle.

GIS: Captures, stores, analyzes, manages, and presents data that refers to or is linked to location.

OGC: An international voluntary consensus standards organization for geospatial information

IFCs: Data model is a neutral and open specification that is not controlled by a single vendor or group of vendors. It is an object oriented file format with a data model developed by the International Alliance for Interoperability (IAI) to facilitate interoperability in the building industry.

Spatial Query: A spatial query is a special type of database query supported by geodatabases. The queries differ from SQL queries in several important ways. Two of the most important are

that they allow for the use of geometry data types such as points, lines and polygons and that these queries consider the spatial relationship between these geometries.

Earth Observation: Gathering of information about planet Earth's physical, chemical and biological systems. It is used to monitor and assess the status of, and changes in, the natural environment and the built environment.

Coordinate System: Enables every location on Earth to be specified in three coordinates, using mainly a spherical coordinate system.

Interoperability: Process of enabling different data formats to interoperate together and reduce the number of formats required within a workflow.

Section 7

State of the Art

Chapter 22

BIM Adoption: Expectations across Disciplines

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ABSTRACT

This chapter presents a comprehensive analysis of the current state of Building Information Modelling (BIM) in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry and a re-assessment of its role and potential contribution in the near future, given the apparent slow rate of adoption by the industry. The chapter analyses the readiness of the industry with respect to the (1) tools, (2) processes and (3) people to position BIM adoption in terms of current status and expectations across disciplines. The findings are drawn from an ongoing research project funded by the Australian Cooperative Research Centre for Construction Innovation (CRC-CI) that aims at developing a technological, operational and strategic analysis of adopting BIM in the AEC/FM industry as a collaboration platform.

1 INTRODUCTION

BIM (Building Information Modelling) is an IT (Information Technology) enabled approach that involves applying and maintaining an integral digital

representation of all building information for different phases of the project lifecycle in the form of a data repository. The building information involved in the BIM approach can include geometric as well as non-geometric data. Geometric data refers to information such as 2D drawings, 3D models, and

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their dimensional and spatial relationships. Non-geometric data can refer to textual data such as annotations, reports and tables; visual data such as sketches, graphs and images; multimedia data such as audios and videos, as well as other forms of information generated during the building project lifecycle. BIM is expected to envision efficient collaboration, improved data integrity (Ellis, 2006), intelligent documentation (Popov et al, 2006), distributed access and retrieval of building data (Ibrahim et al, 2004b) and high-quality project outcome through enhanced performance analysis, as well as multi-disciplinary planning and coordination (Fischer and Kunz, 2004; Haymaker et al, 2005; Haymaker and Suter, 2006).

While the potential benefits of the BIM approach in terms of information sharing and management, as well as project collaboration, and coordination may seem evident, the adoption rate of BIM has been rather lethargic. A number of factors, such as a lack of awareness and training, the fragmented nature of the AEC/FM industry, industry's reluctance to change existing work practice and hesitation to learn new concepts and technologies, and lack of clarity on roles, responsibilities and distribution of benefits, have been identified in the literature as major barriers to BIM adoption. Most of the earlier research on BIM adoption has focussed on specific disciplines of the AEC/FM industry where surveys and questionnaires have generally been used to collect the research data. The findings reported in this chapter forms an important part of an action-oriented research that aims at the development of a technological, operational and strategic analysis of adopting BIM in the AEC/FM industry. This chapter builds on the earlier research on BIM adoption but uses Focus Group Interviews (FGIs) as the main method of data collection. FGIs differ from surveys and questionnaires, not only because they enable the collection of more in-depth research data on BIM adoption, but they also provide a forum for the different disciplines of the AEC/FM industry to share and clarify their views on

various BIM adoption issues, such as a common understanding of benefits, hurdles, requirements and expectations of BIM.

FGIs were conducted with experts from major AEC/FM practices and associates including architects, engineers, contractors, consultants, project managers, facility managers, delegates from government agencies, academics and software application vendors. A comprehensive background study of BIM literature and current commercial BIM applications had been conducted beforehand to identify key issues, put forward topics for discussions during the FGIs, and serve as a benchmark for the analysis and comparison of the collected FGI data. A coding scheme has been designed specifically to analyse the FGI data. The design of the coding scheme has been based on the dominant themes identified through the initial open analysis of the FGI data and the background study. The coding scheme is developed (1) to identify the priority issues across different AEC/FM disciplines regarding BIM adoption; and (2) to determine the current level of awareness, knowledge and interest in BIM across the disciplines. Through the FGI data analysis, this chapter identifies the key issues that need to be addressed for BIM adoption. The chapter concludes by highlighting the current and future extension of the research and by analysing the readiness of the industry with respect to the (1) tools, (2) processes and (3) people to position BIM adoption in terms of current status and expectations across disciplines.

2 BACKGROUND

The background study involves a critical review of available BIM literature together with a comprehensive desktop audit of current commercial BIM applications.

The BIM literature review provides a context for the research. The review also offers a comprehensive understanding of common practice in the AEC/FM industry, and informs on the

potential issues that may arise during building project development and collaboration when new technologies are adopted.

A desktop audit of current commercial BIM applications provides an understanding of the different approaches to BIM implementations, which offers the insight into development and various trends of tools supporting BIM. A detailed overview of the capabilities and limitations of those tools is also obtained, which can serve as a benchmark for technology adoption.

2.1 Summary - Literature Review

An extensive literature review on BIM has been conducted. As BIM as an emerging research field has limited existing studies, the literature review goes beyond academic research papers to also include white papers and technical reports from major vendors that are involved in developing BIM related applications (i.e. Autodesk; Bentley and Workman, 2003; Greenway Consulting, 2003; Graphisoft), guidelines and reports generated by government and other regulatory bodies (i.e. AGC, 2007; GSA 2007), and articles in well respected online newsletters (i.e. <http://www.aecbytes.com>) that reflect the latest development in BIM.

Though there have been a few examples of adopting BIM or BIM-related concepts in the real world projects (Campbell, 2007; Bentley News, 2006; Khemlani, 2007b; 2007c) by developing or adapting parts of the current practice towards a BIM approach, the general rate of BIM adoption has been very low. Lack of initiative and training (Bernstein and Pittman, 2004), the fragmented nature of the AEC/FM industry (Johnson and Laepfel, 2003), varied market readiness across geographies, and industry's reluctance to change existing work practice (Johnson and Laepfel, 2003) have been identified as some of the reasons for this low adoption rate. These issues have also been echoed by Khemlani (2004b; 2006). In an industry where most projects are handled in multi-disciplinary and multi-organisational teams, the lack of clarity on

roles, responsibilities and distribution of benefits in adopting the BIM approach is an important inhibiting factor (Holzer, 2007).

From a technical aspect, a recent survey by AECbytes (Khemlani, 2007d) provides a good overview of the current status of BIM in the AEC/FM industry. Some of the findings from the earlier studies have also been reinforced by the survey result. The major findings of the survey are listed below.

1. Collaboration is still primarily based on the exchange of 2D drawings, despite the fact that most disciplines are now working in 3D environments.
2. There has been a greater demand for more advanced and more comprehensive object libraries and modelling capabilities in computer packages.
3. There has been an increasing demand for technologies that support distributed teamworks.
4. Tool preference varies with the size of the firm and organisation: in general, smaller firms often prefer more intuitive project environments. Larger firms that are more likely to be involved in complex and large scale projects prefer tools with greater flexibility for customising their own project environments.
5. 3D visualisation is not a major concern any more: most users who participated in the survey would like to gain more out of the accurate building information model beyond visualisation.
6. There is an urgent need for better training material and technical support.
7. Support for analysis, performance simulation and data interoperability is important, but is not a burning issue as per the survey.

2.2 Summary – Desktop Audit

A desktop audit of different types of commercial BIM applications has been conducted, which involves live demonstrations and trials, data collection from product brochures (i.e. Gehry Technologies; Autodesk Navisworks; EPM Technology, 2004) and analysis of tools as published by other influential sources (i.e. CyonResearch, 2003; STATS BYGG, 2006). Categories of applications that have been evaluated include BIM model servers, discipline specific design tools, planning tools, analysis tools, design review and viewing tools, facility management tools, product libraries and so on. The desktop audit provides an overview of the technological capabilities and limitations of the applications and their roles in BIM, and indicates the development trends of commercial BIM applications. The main issues identified from the desk audit are highlighted below.

Overall status: A wide range of applications are currently available for various purposes that form a part of the BIM approach, ranging from application suites to very specific tools for design, analysis and product libraries (Khemlani, 2007a). There is a rapid growth in the number of supporting technologies but only a few are Industry Foundation Classes (IFC) compatible (Khemlani, 2004a), which means that the vast majority can only be integrated with specific tools that accept their data formats. Tools for early design phases and integration of conceptualisation tools are lacking at the moment (Pentilla, 2007): the popular design tools such as ArchiCAD, Autodesk Revit and Bentley are generally inadequate in supporting sophisticated conceptual design activities.

New trends: web-based product services can be very useful and efficient for the AEC/FM industry (Campbell, 2007; Ibrahim et al, 2004a) and their numbers are growing, benefiting from the recent trends such as the development and application of object-oriented modelling that has gained a widespread acceptance within the industry. The concept of **object intelligence** in

building modelling has enabled intelligent relationships beyond spatial connectivities between objects and between their properties to be specified within building models. More importantly, they support modelling constraints (Eastman et al, 2004; Lee et al, 2006) that enabled the emergence of more efficient analysis tools (Bajzanac, 2005; Mitchell et al, 2007) to automate various processes that were previously primarily manual and time consuming.

Lack of support for integration: Examples of BIM in practice suggest that in the present state there are indeed technologies available that can potentially improve the work process in the AEC/FM industry and gradually advance towards BIM. However, the lack of tools supporting the integration of different project phases has been a major concern (Khemlani, 2007a; Holzer, 2007). As more specific BIM applications are being developed targeting specific processes and aspects of the project, and more importantly allowing the integration with other applications and with other processes, the support for integration must improve in order to cope with the demand.

The desktop audit also highlights the following issues that need to be considered for the technical implementation of BIM:

- **Centralised database vs. distributed database:** Is a distributed database the better option for building projects? What are the coordination and maintenance issues in using distributed databases against using a centralised database? What are the different types of database technologies available? For example, Bentley has adopted the distributed database approach, which makes information sharing especially effective and practical for complex and large-scale projects. However, the distributed database approach requires a greater effort in ensuring data integrity across different locations. In contrast, information sharing is easier done in a centralised

database as adopted by other vendors such as ArchiCAD and Autodesk Revit. For a detailed discussion on database technologies, see You et al (2004).

- **Intelligent building information:** How much intelligence is appropriate? There is a trade-off between modelling constraints, and project creativity and flexibility (Eastman et al, 2004; Khemlani, 2007b; 2007c). Some consider object-oriented modelling using intelligent objects as the core of the BIM approach because it enables the specifications of intelligent object relationships. Furthermore, they also enable writing rules that integrate modelling constraints; for example, to make certain modelling actions invalid if they are in conflict with the rules. However, at times creative design involves overlooking the generic rules in order to achieve novelty and hence it is important not to over constrain the project process and data. The trade off between the modelling constraints (to ensure model validity and integrity), and project creativity and flexibility (to support the emergence of potential creative project outcomes) is a critical issue for the quality of the building project.
- **Detailing:** The level of detailing in building models is a critical decision making process on the technical implementation of BIM. It is important that the model is detailed enough to ensure that all the relevant disciplinary data can be generated and validated. However, details that may be redundant in terms of their usability should be identified and minimised to optimise the model size and to avoid information overload.
- **Design model vs. construction model:** Some industry practices suggest that the two kinds of detailing in models that are required for design and construction purposes are significantly different and hence

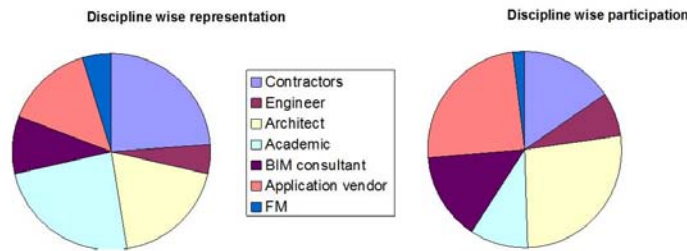
developing separate models for each purpose may be a better option. Others believe that this may lead to redundancy and a single model with efficient versioning can better serve the purpose. As the organisations gain experience working with BIM it is suggested that they should explore the benefits and drawbacks of the two different approaches and decide on the suitable approach that best addresses their needs. Similarly, as more experience is gained in using BIM the “best” practices will evolve over time.

- **Changing tools and changing roles:** Is there a role change for the involved professions due to the introduction and adoption of BIM? With the changing tool capabilities and the variations of information support provided by the tools, the roles and responsibilities of the involved disciplines may also change over time (Eastman et al, 2004a). For example, by adopting BIM, designers such as architects may be able to receive feedback on technical aspects of the design at a much earlier stage with the access to the analysis tools and data that were previously not available to their disciplines, through the building information models. This will provide them with greater capability and independence in design decision making on some technical aspects, which previously relied on other professions or consultants.

3 RESEARCH DATA COLLECTION AND ANALYSIS

The main findings on BIM adoption within the AEC/FM industry, as reported in this chapter, build on the earlier research of BIM adoption but apply Focus Group Interviews (FGIs) as the main method of data collection. As pointed out in the Introduction, the advantages of FGIs over

Figure 1. Discipline-wise representation and participation in the two FGIs



surveys and questionnaires include not only the collection of more in-depth research data on BIM adoption, but also provide opportunities for the different disciplines within the AEC/FM industry to discuss their views on various BIM adoption issues such as common understanding of benefits, hurdles, requirements and expectations of BIM. A coding scheme has been specifically designed to analyse the FGI data.

3.1 Focus Group Interviews

Two FGIs have been conducted in two major Australian capital cities, namely Sydney and Brisbane. Through the two FGIs, the research team was able to bring together important players and associates that cover all major sectors of the AEC/FM industry, including architects, engineers, contractors, consultants, project managers, facility managers, delegates from government agencies, academics and software application vendors. With the active participation of these representatives, the main goal of the FGIs is to uncover and analyse industry perception of BIM adoption across different disciplines. Discussions in FGIs, as confirmed in the earlier BIM literature review, suggest that reasons for the low adoption rate of BIM in the AEC/FM industry are not only technological. Other factors that influence BIM adoption include work practice, organisational structure, business interest, user training and so on. It has also been recognised that the introduction and adoption of BIM would require a different approach to building

data organisation and structuring. Some legal and contractual measures will also be required to deal with work practice and security related issues.

The FGI discussions were recorded on tapes and then segmented. The segmented data were analysed firstly using an open analysis to identify main themes. Based on the main themes identified a coding scheme was developed and applied to the segmented data for detailed analysis. Each FGI gathers international leading organisations that have adopted BIM to a certain extent in a group environment for moderated discussions lasting approximately two to three hours. The discussions were chaired by the research team. The two FGIs involved 21 participants in total. Break-up of the discipline-wise representation and participation is shown in Figure 1 and Table 1.

It is noted that the government architect present in the Brisbane workshop has a dual role. On one hand he participates in the general architecture-related discussion, and on the other hand he provides information and leads the discussion on government regulations regarding BIM. As a result, his contributions (127 segments) are significantly larger compared to other participants.

Participation is measured as the frequency of issues raised or discussed by representatives of a specific discipline. Through the analysis of the FGI discussions, the industry needs, concerns and expectations regarding BIM adoption have been identified. The FGI discussions show that the level of BIM awareness, knowledge and interest across the disciplines differ, nevertheless the main

Table 1. Break-up of the number of segments by discipline in the two FGIs.

Participation (Sydney)	no.	Participation (Brisbane)	no.
Contractor	72	Contractor	37
Engineer/ design manager	8	Engineer/ design manager	50
Architect	51	Government architect	127
Academic/ research	8	Academic/ research	60
BIM consultant	72	BIM consultant	51
Application vendor	13	Application vendor	84
Facility manager (FM)	14		

issues inhibiting BIM adoption are often shared across disciplines. These issues are presented in the Main Findings section.

Coding Scheme

The coding scheme applied for the FGI data analysis has been developed based on the dominant themes identified through the initial open analysis of the FGI data and the earlier background study. The coding scheme has been applied to; (1) identify the priority issues across different AEC/FM disciplines regarding BIM adoption; and (2) understand the current level of awareness, knowledge and interest of BIM across the disciplines.

The coding scheme has five main categories; discipline, context, type, content, and keywords. These categories and their sub-categories (if applicable) are shown in Figure 2. **Comment** is only used for the research team to write down any observations worth noting during the FGI discussions or data segmentation and analysis.

Because knowledge on BIM varies across

different disciplines within the AEC/FM industry, **Discipline** category is therefore used to code the FGI data based on the disciplinary and functional background (roles in the industry) of the participant. The marking of each segment, based on the disciplinary background, gives useful information about the importance of the different aspects of BIM (in terms of the content) within each discipline.

Context category is used to mark the circumstances under which a given segment of data has been discussed. Sub-category classifications within the Context category include:

- “Initiated”; marked if the segment of data started a new subject of discussion in the FGIs.
- “Reply”; marked if the segment of data answered a question posted earlier in the FGIs.
- “Follow up”; marked if the segment of data contributed to an ongoing subject initiated earlier in the FGIs.

Figure 2. The coding scheme

Discipline	Context	Type	Content	Comment	Keywords
	initiated reply follow up chair	suggestion/ ideas concern opinion/ viewpoint observation/ analysis query inform strategy wishlist	technical cultural/ work practice structuring / Data organization training legal/ contractual organizational- team process/ method Business case		

- “Chair”; marked if the segment of data was given by the moderator to control the flow of discussion.

For the FGI data analysis, the above sub-categories can imply the following:

- A subject initiated by a specific discipline is in general expected to be in higher priority for that very discipline. For example, the discussion on the lack of support for conceptual design in BIM was initiated by an architect, and therefore it can be considered as an important concern for the architecture discipline. On the other hand, the issue of the changing format of Industry Foundation Classes (IFC) specifications was initiated by an application vendor who, as a BIM service provider, has been undertaking the management of IFC data for clients.
- In general, the identification of a discipline that replies to a specific question can suggest that the discipline has knowledge, or at least awareness, of the specific topic. For example, when various questions about data security on the BIM model server were raised, the replies mostly came from the application vendors. This is because, compared to other participants, application vendors have more understanding of this issue, as various security concerns regarding information sharing would have been addressed during the development and commercialisation of the applications.
- “Follow up” allows for identification of other disciplines that participate in the discussion on a specific topic. For a discipline that has not participated in a specific topic at all, it may suggest a lack of knowledge, relevance or interest for that particular discipline on the specific topic. For example, the discussion on tool support for the conceptual design phase has very little or no

participation from the contractors and civil engineers, while the main participants are architects, academics, and application vendors, which may indicate there is a lack of interest of conceptual design supports in BIM from the contractors and engineers.

- “Chair” marked segments refer to statements used to moderate the discussion, and even if it started a new topic it may not be suggestive of further meanings. Rather, such changes in discussion topic are either forced due to time constraints or used to maintain the discussion within the scope of the research.

Type category is used to classify the segmented data based on the perceived purpose of the statement. The sub-categories for Type are: “suggestion/idea”, “concern”, “opinion/viewpoint”, “observation/analysis”, “query”, “inform”, “strategy” and “wishlist”.

The classification within **Content** category of the coding scheme is expected to enable the clustering of data in order to identify issues being discussed based on different aspects of BIM. Content category can therefore identify dominant topics by clustering the segmented data based on the subject of discussion. There can be at least eight sub-categories within the Content category. They are “technical”, “cultural/work practice”, “structural/data organization”, “training”, “legal/contractual”, “organizational-team”, “process/method”, and “business case”.

Discipline, Context and Type categories can be combined in order to cluster the segmented data such that the pattern of BIM awareness, knowledge and interest across related disciplines can be identified.

Finally, marking **Keywords** allows the identification of key issues across all categories, and the priority of these key issues can also be set by evaluating the frequency of their data occurrence. For example, the categorisation may suggest that technological issues are the most prevalent top-

ics in discussion, or that there are more concerns about data management issues by architects and application vendors. A detailed analysis suggests that most concerns about BIM data structure and organisation are related to version management. This is done by listing the keywords of each data segment. In this case, version management as a

keyword has the highest frequency of occurrence. Similarly, other specific issues within each coding category can also be identified such that we can set priorities for these aspects to be further examined.

The annotations and examples of each coding category are presented in Table 2.

Table 2. Annotations and examples of each coding category

Coding categories		Annotations and examples
Discipline		Industry role of the participant. e.g. architect, facilities manager, application vendor, etc.
Context		Circumstances under which the statement was given.
	Initiated	Starting a new subject of discussion e.g. <i>"Let us discuss (the) role of BIM in conceptual design"</i>
	Follow up	Continuing the ongoing subject of discussion. e.g. <i>"...yes, for example..."</i>
	Reply	In response to a specific question. e.g. <i>"...for that automated model checkers are there to..."</i>
	Chair	Monitoring the discussion, most often given by the moderator. e.g. <i>"...let us move to other issues"</i>
Type		The purpose of the statement.
	Suggestion/idea	e.g. <i>"...replace (the) document by information as (the) document has a connotation to it."</i>
	Concern	e.g. <i>"...(the) frustrating part is having different regulations across States."</i>
	Opinion	e.g. <i>"...as industry picks up they will be forced to adopt..."</i>
	Observation	e.g. <i>"In civil works, disciplines tend to work in isolation."</i>
	Query	e.g. <i>"What happens when the project phase changes?"</i>
	Inform	e.g. <i>"...for that automated model checkers are there to..."</i>
	Strategy	e.g. <i>"...one way is to force them."</i>
	Wishlist	e.g. <i>"The EDM model server will have to support..."</i>
Content		The main subject of the data segment.
	Technical	About tools (format/standard, feature and capability, and so on). e.g. <i>"...current systems (are) not capable of dealing with different levels of details."</i>
	Cultural/work practice	e.g. <i>"...not willing to change the way they work."</i>
	Structural/data organization	Ways of organising data (format, format and the grouping of data, and so on). e.g. <i>"...we can have things like private and public space (for storing building data)."</i>
	Training	Knowledge and skill acquisition. e.g. <i>"...architects learn many techniques in training that are not used with these tools."</i>
	Legal/contractual	e.g. <i>"...(the) organization that owns the information has the rights to change permissions."</i>
	Organizational- team	About collaboration and teamwork. e.g. <i>"What you will see is relevant to what your role is (in the project team)."</i>
	Process/method	Protocols, procedures and methodology. e.g. <i>"...you often start with the architect... in the sense it starts with a 3D model with different disciplines adding info(mation)..."</i>
	Business case	Industry incentives and business drivers. e.g. <i>"...who builds the model...who benefits from it... there is something about willingness."</i>

Table 3. Example of coded data segments

Comment/ segment	Discipline	Context	Type	Content	Keyword
"...(the) frustrating part is having different regulations across States".	Engineer/ design manager	Initiated	Observation	Legal/ contractual	Regulations
"How do we get one agreed standard?"	Contractor	Follow up	Query	Culture/ work practice	Standard
"Force them to do that ..."	Engineer/ design manager	Reply	Opinion/ strategy	Culture/ work practice	Force

Examples of coded segments are shown below in Table 3 to demonstrate the use of the coding scheme and its categories.

In the first segment shown in Table 3, a design manager from the civil engineering discipline started this particular topic of discussion, which is a concern related to legal and contractual issues and based on his observation from the practice. Accordingly a value of "1" is added under each of the relevant coding categories or sub-categories. Similarly, each other data segment is coded and marked. By counting the number of "1" marked against each coding category or sub-categories the total number of data segments that fall under each category or sub-category can be obtained. This coding scheme enables the analysis and comparison of the collected FGI data. Keywords are noted and grouped under common themes. The number of occurrences for each theme can be noted to prioritise the key issues. By applying this coding scheme for data analysis, the prioritised key issues across different AEC/FM disciplines regarding BIM adoption can be identified. The analysis can also offer insights on the level of awareness, knowledge and interest of BIM across all AEC/FM disciplines.

4 MAIN FINDINGS

By applying the coding scheme presented above, three different kinds of correlations can be mapped from the collected FGI data. The **Discipline vs.**

Content mapping can suggest the dominant issues regarding BIM adoption across different disciplines; the **Type vs. Content** mapping indicates BIM awareness, knowledge and interest about the content; and the **Discipline vs. Type** mapping indicates BIM awareness, knowledge and interest across different disciplines. These three types of correlation mappings, together with the key issues that emerged from the analysis, will be presented below.

4.1 Data Correlation Mappings

The correlation mapping of the data segments shows that the level of awareness, knowledge and interest on BIM adoption across different AEC/FM disciplines vary quite significantly. Figure 3 shows the **Discipline vs. Content** mapping. Architects and application vendors were the two most active groups with their discussions primarily focusing on technical, process/method, and cultural/work practice related issues.

- Technical aspects of BIM were the dominant subjects in both FGIs. Most of the technical discussions from the architects and BIM consultants are related to concerns, queries and suggestions, demonstrating their strong interests in BIM but also a possible lack of confidence in applying current technologies.
- Most process/method and cultural/work practice related discussions raised concerns,

suggestions and information sharing, demonstrating a keen interest across disciplines in BIM adoption but a general lack of knowledge in terms of how it may fit into each of their current practice. Design disciplines discussed these issues more than any other disciplines.

- Application vendors mostly provide information on technical aspects of BIM applications, often in response to the queries and concerns of other disciplines, thereby suggesting a lack of awareness amongst other participants.

The same technique was applied to develop the **Type vs. Content** and the **Discipline vs. Type** mappings. From the **Type vs. Content** mapping, the following observations are highlighted:

- Concerns are primarily on the technical, cultural/work practice and process/method related issues, with the technical concerns topping the list.
- In both FGIs discussions on the technical aspects of BIM centres on providing and sharing information (“inform” sub-category) and quite often involved the application vendors.
- While very few strategies were discussed

in the first FGI, there were relatively more strategies discussed in the second FGI. The strategies discussed are mainly concerning technical, process/method and business case related issues.

- Wish lists are features that the participants would like to see and they mostly relate to the technical capabilities of BIM. While there are very few wish lists from the first FGI, the number of wish lists in the second FGI is considerably high. The greater participation by academics and researchers in the second FGI could be the reason, as they often initiate such queries for the industry players to brainstorm.
- On numerous occasions, participants confirmed that both technical as well as process/method related issues are the key to the development and implementation of BIM, and especially important for project collaboration.

From the **Discipline vs. Type** mapping, the following observations are highlighted. The numbers of segments for each type by discipline are listed in Tables 4 and 5.

- Among all participating disciplines, architects were once again the most active group.

Figure 3. Content discussed across different disciplines

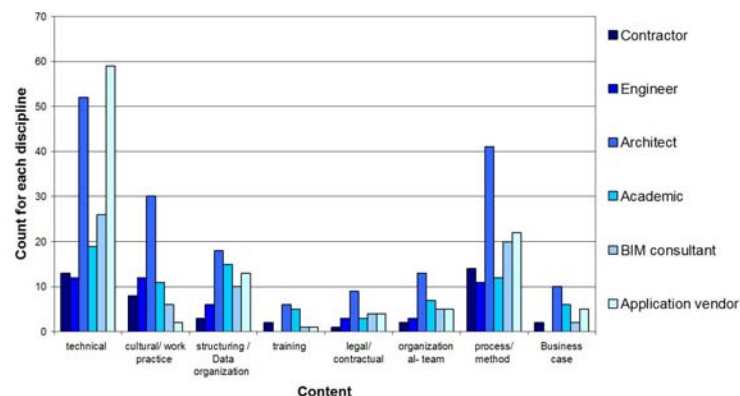


Table 4. Numbers of segments for each type by discipline (Sydney)

Discipline vs. Type (Sydney)	Suggestion / idea	Concern	Opinion / Viewpoint	Observation / Analysis	Query	Inform	Strategy	Wish List
Discipline	By Type – Number of Segments							
Contractor	1	6	18	2	9	5	1	4
Engineer/design manager	5	9	16	9	1	11	11	8
Architect	8	1	16	12	2	15	2	2
Academic/research	0	1	2	1	2	1	0	0
BIM consultant	7	3	26	8	2	26	11	2
Application vendor	1	0	4	0	5	2	1	0
Facility Manager	0	1	3		5	2	0	4

They top the list in stating their opinions (“opinion/viewpoint” sub-category) about BIM in general. The issues are mainly based on technical, structuring/data organization, and process/method related topics.

- Most of the concerns were also raised by the architects. They were also interested in discussing strategies in both FGIs.
- Application vendors spent most of their time providing and sharing information (“inform” sub-categories). One particular vendor also spent considerable amount of time discussing strategies, primarily related to BIM model servers from a service point of view.

- Beyond the active participation of the above two disciplines, design managers also participated generously by providing information on current processes and work practice.

4.2 Key Issues

This section presents the key issues discussed during the FGIs. These issues are grouped based on their relevance to the Content code sub-categories. Some overlaps are possible because they are listed in the order of their importance as reflected in the FGI discussions.

Table 5. Numbers of segments for each type by discipline (Brisbane)

Discipline vs. Type (Brisbane)	Suggestion / ideas	Concern	Opinion / Viewpoint	Observation / Analysis	Query	Informing	Strategy	Wish List
Discipline	By Type – Number of Segments							
Contractor	6	4	10	2	5	2	8	6
Engineer/design manager	4	5	14	11	3	7	8	1
Government architect	13	31	50	17	11	8	27	12
Academic/ researcher	12	11	11	4	18	6	14	6
BIM consultant	8	3	15	3	1	22	9	1
Application vendor	8	8	8	5	4	60	28	1

4.2.1 Work Practice and Process Related Issues

Data organisation: Digital storage is the current dominant form of data storage as it allows greater flexibility and economy of physical space. Therefore, digital data management and organisation is becoming ever more important for the industry, particularly from the work practice perspective. Standard practices and procedures need to be developed to address data representation, usability, classification and grouping; as well as to deal with possible data explosion. Version management, as singled out below, is one of the most important issues being discussed, and is closely related to data organisation.

Version management: There are three different version management issues being discussed.

1. When application vendors develop a new **version of the application**, sometimes there are significant differences from the previous versions. This brings in problems such as data loss and compatibility issues if different versions of the software are used by different team members.
2. **Version of project data:** If BIM is to be adopted using an integrated database where each discipline maintains, modifies and updates the data, then technical measures, work procedures and methods need to be put in place to ensure data integrity, allowing different versions of the project data to be managed throughout the project life-cycle.
3. **Version of IFC:** At present the IFC standards are still evolving, and the format has changed significantly in the last five years often making many of the earlier IFC data almost unreadable in the present IFC version. Service providers who maintain IFC data for the clients may have to update the stored data for the clients accordingly. Such updates may not be easy if the changes are significant.

Validation and data integrity: Even though 2D drawings can be generated from intelligent 3D models (Lee et al, 2006), the lack of trust in the completeness and accuracy of the 3D models has remained a major concern for the practitioners involved. As a result, data exchange across the disciplines is limited to 2D drawings in most cases. Development of intelligent model checkers for ensuring integration qualities, which is an important aspect of BIM approach, may be able to address the concern. However, agreed protocols and standard evaluation and validation procedures are needed for acceptable design reviews and approvals using 3D models.

As-built data: Ability to support **facility management** is considered as an important value-added feature for the BIM approach, making a strong business case, as suggested by the FGI participants. The information stored and maintained during the project is useful for later access and retrieval. This database is useful in updating and identifying the information needed for maintaining the building facilities. However, in most construction projects, changes are often made during the construction phase. Hence, the final output may have some variation from the initial design, which will need to be represented and recognised in the BIM. At present, there is no process in place to update the designed model to incorporate the changes made during construction. This is particularly important because it is the actual as-built information which is required for facility management.

As-built drawings may become important for **regulatory** purposes such as sustainability assessment and other performance measures. Once the BIM is updated with the as-built data, it can be used for comparisons between the projected building performance against the actual performance in order to **evaluate design quality**. These types of comparison will allow for more accurate analysis tools by providing more effective and detailed evidence.

The quality of the as-built data is important. When the surveyors provide data for the built

facilities, the building information modeller will need to evaluate and register the quality of the surveyed data. Measures, such as grouping sets of data as sub-models for different parts of the model based on the quality of the survey, can be adopted. These measures are closely related to version and data management.

4.2.2 Technical Issues

Standards: Interoperability issues across different commercial software remained a dominant topic during the FGIs. Shortcomings in IFC certification of commercial software were highlighted. Issues discussed echo the findings reported by (Aranda-Mena and Wakefield, 2006).

Most product libraries that are commercially available target specific commercial applications with a wide market base, for example, Autodesk Revit. This means that such libraries cannot be shared or used by other packages. Besides a standard format for data exchange, there is a greater need for a standard vocabulary for the consistency of data when exporting from one package to another.

Registry of communication and information exchange: Information exchanged between the BIM users through different media is not generally captured in a BIM. During the FGIs, participants suggested that BIM servers should allow message flagging and notifications between team members. Though not explicitly discussed, some of the ideas considered are similar to the concepts of an Enterprise Wiki (Kalny, 2007).

Security: Apprehensions exist about the data security of model servers. These include concerns about Intellectual Property (IP) and protection of copyrights. Concerns related to network security may have technical limitations, but concerns about design protection (IP and copyright issues) can be alleviated by greater awareness and legal measures. IP issues in BIM are legal issues, which are no different to IP issues existing in current practice.

Compatibility of GIS and BIM: Data ex-

change between a Geographic Information System (GIS) model and BIM should be supported, which is missing at present. This is especially important to many large scale civil projects.

4.2.3 Other Issues

Roles and responsibilities: A BIM approach requires changes in the distribution of roles and responsibilities. Some traditional roles, such as draftsmen, may become obsolete, replaced by modellers. New roles, such as BIM managers, have emerged to support greater coordination in developing and maintaining an integrated building information model.

Trainings support: Participants raised concerns about the lack of training and awareness on BIM applications. Improved and up-to-date training modules are required for practitioners as well as students. CAD (Computer-Aided Design) courses taught at architecture and engineering schools do not satisfy the present industry needs. In most architecture schools CAD courses are separated from the design studio, and the design methodology taught in schools often fails to **integrate CAD and BIM in the design phase**. Although some alternative approaches, such as parametric design, have been introduced as a digital means to conceptual design, such cases are still limited. The workshop analysis also indicates the lack of teaching staff with knowledge and experience of modern CAD packages and the reluctance to adopt new technologies and their uses in the curriculum.

Students also need to be trained in applying **computer-supported collaborative tools** in team projects to appreciate the collaborative nature of projects as well as understand and experience the potential benefits. In practice, building professionals work in a team and often coordinate team activities. The adoption of BIM will further increase the level of collaboration. In design and engineering schools although students are in-

involved in limited team projects, the coordination of such team projects is normally manual, face-to-face and within the single design discipline. Students need to be trained to explore state-of-art computer-supported collaborative tools and to collaborate across disciplines.

Apart from the key issues discussed by the FGI participants, the analysis of the data suggests that even though there is a general agreement on the potential benefits of BIM for all AEC/FM disciplines, the actual benefits and usability of the approach is not clear. There is lack of clarity on how BIM can be integrated with current business practice. There is a common misconception that the entire work practice has to be changed for the BIM approach to be adopted. This is primarily because the users fail to realise that a BIM approach can be used for only parts of the project lifecycle to suit different scenarios. That is, industry players often do not realise the flexible scope of BIM in an AEC/FM project.

Different business models will be required to suit varied industry needs (Aranda-Mena et al, 2008). A BIM can be maintained in-house or outsourced to service providers. In the latter case, additional legal measures and agreements will be required to ensure data security and user confidence.

5 CURRENT AND FUTURE RESEARCH

Amongst the main findings as reported above, the FGI data analysis reveals that the AEC/FM industry's overall lack of experience in applying BIM has led to their limited understanding and articulation of needs and technical requirements for BIM. The current and future extension of this research adopts the following two approaches to elicit technical requirements and further obtain industry needs for BIM.

5.1 Approach One: Case Studies - Laboratory Controlled Testing

The first approach is a series of case studies, where leading BIM model servers and applications will be undergoing detailed tests by the research team on real world project data with the following research objectives:

- to test the current functionalities and usability of BIM model servers and applications;
- to identify the limitations of the technologies, especially in a collaborative setting where the integration with other BIM applications such as disciplinary CAD applications, analysis tools and so on is required;
- to identify the gaps and missing functionalities of the technologies, based on the industry inputs from the FGIs;
- to compare the needs and changes in the design and collaboration practice when adopting the BIM approach against the use of other collaboration platforms, such as a DMS (Document Management System), that support traditional work processes and practices, and are more familiar to the industry. Although no specific DMS were discussed during the FGIs, participants' perceptions and expectations of BIM in supporting collaboration are largely influenced by their existing experiences in using current DMS.

5.2 Approach Two: BIM Project Life Cycle Decision Framework

Presently there is limited use and hence limited knowledge of BIM applications and their integration in the AEC/FM industry. The lack of awareness means that direct inputs on technical requirements and industry needs cannot be sufficiently obtained from the industry. Such lack of industry inputs is hindering the advancement and

adoption of BIM related technologies, which are yet to mature. Hence a BIM Project Life Cycle Decision Framework is being proposed in order for the industry players to relate their likely BIM adoption with their familiar experiences on existing collaboration tools from their current practice. The objectives of the framework are:

- to provide a structured approach to willing and potential BIM users to understand and reflect on their work practice and current tool capabilities in order to assess their BIM readiness;
- to create awareness about BIM applications and understand potential usability in different project phases and activities;
- to allow potential BIM users to identify the likely conflicts and risks that would have arisen due to the changes in work practice if they or their project partners adopt BIM;
- to generate a reflective practice among industry players such that the knowledge of available BIM applications allows them to critically evaluate the applications and their impacts on the industry, in order to provide useful feedback for BIM development and integration;
- to facilitate the maturity of BIM applications through the above industry feedback. This in turn will facilitate greater adoption of BIM in practice.

6 CONCLUSION

Based on the key issues and other data analysis presented in the Main Findings section, we summarise the perception and expectation of BIM against the industry's current practice, in terms of the following three main aspects: tools, processes and people.

Tools: Expectations of BIM vary across disciplines. Design disciplines see BIM as an

extension to CAD, while contractors and project managers expect BIM to be a more intelligent DMS (Document Management System) that can quickly take-off data from CAD packages directly. While there are evident overlaps, BIM application vendors seem to be aiming to integrate the two requirements. Our desktop audit suggests that the existing BIM applications are not yet mature for either purpose. Users with CAD backgrounds, such as designers, are expecting BIM servers to support integrated visualisation and navigation that is comparable to the native applications they use. Users with DMS backgrounds, such as contractors and project managers, expect visualisation and navigation to be the important features of BIM servers that are missing in existing DMS solutions. Interestingly, barring a few exceptions, current studies have mostly emphasised BIM as an enhancement to CAD and downplayed the document management aspects. This could possibly be the result of investigations concentrated towards design disciplines. Discussions in the two FGIs also suggest that industry participants are hesitant in discussing new and technical jargons in general.

Processes: BIM adoption would require a change in the existing work practice. An integrated model development needs greater collaboration and communication across disciplines. A different approach to model development is needed in a collaborative setting where multiple parties contribute to a centralised model. Standard processes and agreed protocols are required to assign responsibilities and conduct design reviews and validation. Experience from DBMS (Database Management System) will be useful for data organisation and management, but organisations will need to develop their own data management practices to suit their team structure and project requirements.

Different business models will be required to suit varied industry needs. A BIM can be maintained in-house or outsourced to service providers.

In the latter case, additional legal measures and agreements will be required to ensure data security and user confidence.

People: New roles and relationships within the project teams are emerging. Dedicated roles, such as BIM manager, will be inevitable for large scale projects, as already seem in some real world scenarios. Team members need appropriate training and information in order to be able to contribute and participate in the changing work environment.

In summary, the trends observed from the desktop audit suggest that as BIM matures it is likely to integrate the existing CAD packages and DMS into a single product. The FGI data analysis demonstrates that for BIM to succeed and be accepted widely in the industry all stakeholders have to be informed about the potential benefits to their disciplines. The analysis also shows that (1) the lack of awareness, (2) the over-focus on BIM as advancement of CAD packages only, and (3) the relative downplaying of BIM's document management capabilities have inhibited the interest of non-design disciplines in the AEC/FM industry in BIM adoption. This may be the result of research investigations focusing on BIM and the design community. This chapter reveals that user-centric BIM research has to be more inclusive since the success of BIM adoption lies in collective participation and contribution from all the stakeholders in a building project.

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KEY TERMS AND DEFINITIONS

BIM Applications: Computer-based tools that can directly produce, contribute to or exchange data with a BIM.

BIM Approach: A practice adopts a BIM approach for a building project if the project applies a BIM as the base model for the design and/or construction processes.

BIM Project Lifecycle Decision Framework: A project decision framework developed by the author team to assist the design and implementation of a suitable BIM approach for a building project.

Coding Scheme: A classification of key themes used to categorise the observed data into the expected thematic areas for qualitative data analysis.

Collaboration Platform: A computer-based platform that provides a centralised unit (i.e. a server) for supporting collaborative projects and coordinating team activities.

Database Management Systems (DBMS): A DBMS is a collection of computer-based applications that control the creation, application and maintenance of the database of an organisation and its end users.

Desktop Audit: A common method for testing and reviewing computer-based applications by exploring and comparing their features and usability.

Document Management Systems (DMS): A collaboration platform developed specifically for managing documents shared by multiple parties in a project.

Focus Group Interviews (FGIs): A common qualitative research method that involves interviews and moderated discussions with representatives from selected sample groups, in a collective environment (i.e. a group seminar).

Object-Oriented Modelling: Object-oriented modelling is a programming paradigm that uses objects as data structures to design computer-based applications. In an object-oriented building model, building elements are represented as objects that can contain both geometric and non-geometric information.

Chapter 23

Building Information Modeling in the Australian Architecture Engineering and Construction Industry

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ABSTRACT

Building Information Modeling (BIM) is a modern approach to the design, documentation, delivery, and life cycle management of buildings through the use of project information databases coupled with object-based parametric modeling. BIM has the potential to revolutionize the Architecture, Engineering and Construction (AEC) industry in terms of the positive impact it may have on information flows, working relationships between project participants from different disciplines and the resulting benefits it may achieve through improvements to conventional methods. This chapter reviews the development of BIM, the extent to which BIM has been implemented in Australia, and the factors which have affected the up-take of BIM. More specifically, the objectives of this chapter are to investigate the adoption of BIM in the Australian AEC industry and factors that contribute towards the uptake (or non uptake) of BIM. These objectives are met by a review of the related literature in the first instance, followed by the presentation of the results of a 2007 postal questionnaire survey and telephone interviews of a random sample of professionals in the Australian AEC industry. The responses suggest that less than 25 percent of the sample had been involved in BIM – rather less than might be expected from reading the literature.

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Also, of those who have been involved with BIM, there has been very little interdisciplinary collaboration. The main barriers impeding the implementation of BIM widely across the Australian AEC industry are also identified. These were found to be primarily a lack of BIM expertise, lack of awareness and resistance to change. The benefits experienced as a result of using BIM are also discussed. These include improved design consistency, better coordination, cost savings, higher quality work, greater productivity and increased speed of delivery. In terms of conclusion, some suggestions are made concerning the underlying practical reasons for the slow up-take of BIM and the successes for those early adopters. Prospects for future improvement are discussed and proposals are also made for a large scale world-wide comparative study covering industry-wide participants.

1 INTRODUCTION

Every technological advance brings potential benefits and risk (UNDP 2001). One such technological advance that has the potential to have major impact on the Architecture, Engineering and Construction (AEC) industry is Building Information Modeling (BIM). The concept of BIM is relatively simple yet revolutionary as its success requires a whole new approach to the design and documentation of buildings (Thomson & Miner 2006). Its emergence presents a paradigm change in the industry.

The concept of BIM was first developed in the 1970s with the advent of computer aided drafting (CAD). It has since been the basis for much research. In particular, recent advances in technology have made the realization of the concept possible through more powerful computer hardware and software.

BIM has evolved from the concept of object-based CAD which has the ability to store information for each of the objects in the model. The entity-based CAD that has been widely used throughout the industry, predominantly for drafting purposes, can produce a 3D model through the projection of lines and arcs; but this is where its capabilities end and typically limit the user to drafting purposes. For example, object-based CAD, in which objects such as doors, windows, stairs, walls, etc. which can also be represented in three dimensions, has the ability to store non-graphical information relating to the objects including specifications and design constraints. This information is stored in a logical sense and becomes the basis for the

building information model. Thus, BIM involves the integration of all the building information in a central repository. Each object is described only once and a change of one object is reflected in all views of the model which reduces the associated potential for inconsistent design documentation and the associated difficulties and costs. A Building Information Model is not merely a 3D graphic representation of design intent; rather, it is a comprehensive information management tool based on the simulation of design and construction (Campbell 2007). BIM has its roots in Computer-Aided Design (CAD) development from decades ago, yet it still has no single, widely-accepted definition in the AEC industry.

The objectives of this research are to:

- review the development of BIM;
- assess the extent to which the Australian AEC has already adopted BIM;
- determine whether the benefits achieved by the current users of BIM are consistent with the claims made by the promoters of BIM; and
- identify the factors that have inhibited the uptake of BIM.

2 BIM – A BRIEF LITERATURE REVIEW

There has been a significant increase in the attention academics and industry professionals have directed towards Building Information Modeling

in the last five years. For example, several universities and educational institutions, including the University of Salford and Worcester Polytechnic Institute have been researching BIM solutions. Building Smart Alliance (formerly the National Building Information Model Standard) defined Building Information Modeling (BIM) as “*a digital representation of physical and functional characteristics of a facility...and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition*” (BSA 2009).

The Development of BIM

Early research efforts such as Mokhtar et al. (1998) that ultimately led to the concept and development of the building information model, have focused on the problems created by the fragmented nature of the construction industry. These problems have included poor coordination of the information flows, poor collaboration of the project team and resulting design inconsistencies. This fragmentation of the industry stems from the one-of-a-kind nature of construction projects and the effective and efficient delivery of a construction project being dependent upon the successful coordination of the knowledge skills and resources of many firms and professionals. Such fragmentation of the industry presents many problems associated with the information flows between the participants of a project which has been the basis for much research. BIM is a useful tool to integrate the fragmented industry by eliminating inefficiencies and redundancies, improving collaboration and communication, and enhancing overall productivity (Campbell 2007).

Over the past few years there has been rapid development in ideas relating to how building information could be managed. Mokhtar et al. (1998) developed an information model intended to replace drawings as the main repository of design information and principal communica-

tion media. Their research identified that having several sources for the same element of data, i.e. a collection of many drawings drafted independently, was a significant cause of inconsistency in design documentation. Essentially they proposed a central database containing all the building information detailed sufficiently to produce technical construction documents suitable for the erection of the building.

The research of Mokhtar et al. (1998) was built upon by Hegazy (2001) and Zanelidin (2001) who developed the information model further, and proposed that it would be more successful if used in a collaborative environment. The important conclusion being that technology alone is not sufficient for success and that the relationships between people must also evolve with technology in order to produce the right conditions for success. This can be seen through the adoption of the ‘design-build’ procurement technique which has created a more collaborative environment in which successful outcomes have been achieved. This change in the relationships between project participants is important for adopting BIM and, it is believed by the proponents of BIM, that BIM will be a tool useful in further fostering collaborative environments which promote seamless information flows between project participants.

There is a history of interest in managing information, and information flows, to minimize design inconsistencies which has been promoted as one of the advantages of BIM by software producers. Tse et al. (2005) discovered that the reduction of design inconsistency was one of the most common reasons why architects used BIM. The literature indicates that the concept of BIM is not necessarily new, but rather that new technology is making the concept more viable than in the past.

Suter et al. (2007) developed an approach and prototype system to reconstruct the building model based on “sensed object location information”. Their tag-based building representation is very easy to convert to boundary-based building

representations using solid modeling routines and spatial queries. Borrmann & Rank (2009) reported the potential to implement directional operators in a three dimensional spatial query language to interpret the attribute-driven geometric information that is implicitly contained in building information models.

Succar (2009) proposed a BIM framework which aims to provide a research and delivery foundation so that industry practitioners can have a better understanding of underlying knowledge structures and from this are able to negotiate implementation requirements. This is a tri-axial model involving BIM stages, BIM lenses and BIM fields. The model also defined the interactions between policy, technology and process is imperative for the implementation of BIM in the AEC industry.

In recent years the BIM concept has been developed to include more information relating to building objects; for example, the creation of 4D models in which time has been incorporated for the purpose of modeling the sequencing of the building construction. Further efforts have been made to expand the capabilities of BIM's applications in which costs and other aspects are considered in the model. BIM research and development for the architecture, engineering and construction industry in general focuses on the provision of parametric 3D modeling software and on achieving interoperability between various applications (Kaner et al. 2008).

Construction Client's Group (2008) reported the practice in New Zealand which moves BIM to the programme (4D) and the cost plan (5D). These additional dimensions enable the project team to track the project 'virtually' forwards and backwards in time, play out 'what if' scenarios and get to grips with complex logistics and buildability issues (Construction Client's Group 2008). The first 6 months of the project have seen a number of benefits delivered by BIM, such as greater certainty, coordination and innovative practice.

Schlueter & Thesseling (2009) extend the application area to energy performance assessment.

They developed a prototypical tool where energy and exergy calculations are directly integrated into the building information modeling editor. This tool has proved to enable fast estimation of energy and exergy performance of the specific design, facilitating necessary parameter input by using non-expert decision criteria. It is crucial to adopt BIM in the early stages of design to the full scale benefits of BIM.

BSA (2009) highlighted several limitations of current BIM practice and development: (1) it is incompatible with energy simulation software; (2) quantity take-off needs to be seamlessly linked to the central BIM. They also reported that a number of completed buildings in the UK have used BIM, including the extension to the Sanger Institute in Cambridge and the Roche HQ in Welwyn. In Norway, every Statsbygg (the property services agency) project will have to be designed and built using BIM from 2010. Also, since 2003 the General Services Administration (GSA), a very large client in the US, has been exploring aspects of BIM such as energy simulation, materials quantity analysis, and construction scheduling on pilot projects (Gonchar 2007 p 84). The GSA has enjoyed their experiences with BIM and has said that all their projects commencing after 2007 will involve BIM. The GSA predicts that teams using BIM for spatial management are unlikely to return to the old technology (Gonchar 2007 p 84).

Success Factors

To achieve its full potential BIM requires a collaborative environment (Plume & Mitchell 2007). A move to which has been in operation for some time. The use of procurement techniques that foster a more collaborative environment demonstrate this. Although BIM requires a collaborative environment to achieve its full potential, it is also considered to be an effective tool to help foster the collaborative environment. Adoption of BIM demands a team who are enthusiastic about the tool and realise its potential (Construction Client's Group 2008).

In addition, the success of the implementation of BIM depends on the changes of work practices, human resources, skills, relationships with clients and contractual arrangements (Kaner et al. 2008).

It would seem that many of the benefits of BIM for a client are experienced later in the project lifecycle and that the client, if the owner occupier or end-user, is likely to enjoy the greatest benefits of BIM as this is where the initial set-up costs can be offset through the decreased operation costs achieved through better design. Since the building occupation and facilities management phase of the building lifecycle are the longest, typically 50 to 75 years, it is likely that the true benefits of BIM will be realized during this phase of the building lifecycle (Gonchar 2007 p 87).

After interviewing a number of international experts, Howard & Björk (2008) suggested that the benefits derived from BIMs (e.g. greater efficiency and increased profits) depend upon the procurement methods used. Their study found that fixed price contracts using BIM benefited the contractor more than the design and build contracts.

Benefits of BIM

Isikdag et al. (2008) pointed out that there are two definitive characteristics of BIMs, namely enabling interoperability and facilitating data sharing and exchange between software applications. BIM plays a crucial role in the field of construction information integration and interoperability (Fu et al. 2006). BIM can be used for: design visualization, design assistance and constructability review, site planning and site utilization, 4D scheduling and sequencing, 5D cost estimating, integration of subcontractor and supplier models, systems coordination, layout and fieldwork, prefabrication, operations and maintenance (Campbell 2007). The literature suggests that using the BIM approach provides benefits to both the individuals involved and the industry as a whole. Model Solutions (AEC) Limited (2004)

reported in the CAD User AEC Magazine that: "Major clients already recognize the benefits and are beginning to insist on [using BIM]."

Autodesk (2003), a major software publisher of BIM software tools, suggested that the benefits of BIM include: increased speed of delivery, better coordination, decreased costs, greater productivity, high quality work and new revenue and business opportunities.

Mokbel (2003)'s study revealed that 35% of the scope changes on a specific project were primarily due to poor coordination and that the use of 3D parametric building models had a significant impact on productivity and on improving the coordination of the design process. This research identified the significance of inconsistent design documentation with respect to contract variations and how this could be substantially reduced by the use of a BIM approach. Tse et al. (2005) also discovered that the reduction of design inconsistency was one of the most common reasons why architects used BIM.

Ku et al. (2008) pointed out that the design team (i.e. architect and engineers) can gain streamlined inner design team communication and collaboration with the shift from 2D paper-based representations to 3D geometric representations in BIM. The study of two complex shaped buildings revealed that architects tend to adopt collaboration strategies from a geometry standpoint with the construction team during the design development. This contradicts the popular vision where BIM is viewed as a real-time central data repository.

A 3D CAD model can be used to generate construction planning (de Vries & Harink 2007). Zhou et al.'s (2009) research pushes this direction a step further by promoting collaborative 4D construction planning. They argued that the compatibility of BIM and 4D models support the multidisciplinary collaborative construction planning and social interaction (see also Allen & Smallwood 2008).

BIM plays a key role in the collaborative design of mechanical, electrical and plumbing systems, particularly in healthcare projects. Based

on a case study of a \$96.9 million healthcare project, Khanzode et al. (2008) confirmed that the implementation of BIM, coupled with virtual design and construction, can bring both qualitative and quantitative benefits. These benefits include: labor savings for subcontractors, improved safety performance, less rework, zero conflicts in the field installation of the systems, and time and cost savings for the whole project.

BIM facilitates the development of detailed information and analysis in the very early stage of the building process which in turn improves the decision making and reduces downstream changes (Manning & Messner 2008; Klotz and Horman 2007). It also enables the creation of new approaches to the whole life cycle process within the built and human environment for the 21st century (Arayici 2008). A BIM-based approach improves construction metrics compared to construction without BIM (Suermann & Issa 2007).

Isikdag et al. (2008) discovered that BIM provides sufficient information for a seamless automation of data management tasks in the geospatial environment for site selection and fire response management. Their study indicates that the high level of geometric and semantic information acquired from BIM can be transferred into the geospatial environment.

A case study of the Royal Hospital London, a 912-bed facility designed by a global architectural firm, HOK, for completion in 2012 also demonstrates that, through the use of BIM, costly potential hazards and maintenance issues could be identified prior to construction thereby reducing contract variations and disputes in the construction phase (Gonchar 2007 p 86).

Goldberg (2005) suggests that the major advantage to architects and engineers is the increased productivity in creating design and construction documentation, rather than the insertion of information in the model which is likely to benefit other project participants. Presently, productivity improvements appear to be experienced through using BIM, as he claims in *Cadalyst*, a magazine

which provides essential information about information technologies in the key market segments of AEC. "...some companies claim a 30-40% increase in productivity compared to standard 2D CAD"

Moreover, Fu et al. (2006) suggest that another benefit to the industry as a whole would be the standardization of building information formats to suit the requirements, format of interfaces, databases, file and data exchange in computer applications which would naturally flow from the adoption of BIM. This would improve the ability to re-use the information throughout the project lifecycle; something which is presently very difficult because of the fragmented nature of the information in the different phases of the building project (Isikdag et al. 2008). Fu et al. (2006) suggested that BIM would consolidate the project information in a standardized format and overcome the issues presently associated with the fragmentation of information.

Arayici (2008) studied a refurbishment building in East Manchester and concluded the benefits associated with the adoption of BMI as enabling: "... automated and fast data capture and modeling for not only in design and planning, building refurbishment, effective heritage documentation and VR modeling but also disaster management, environmental analysis, assessment and monitoring, GIS implementation, sophisticated simulation environments for different purposes such as climate change, regeneration simulation for complexity and uncertainty."

BIM enables data to be organized and used/reused during the facility lifecycle to document transactions, identify data requirements specific to disciplines and inform business decisions to improve value (Kaner et al. 2008). Furthermore, BIM provides mechanisms to generate building information automatically and to facilitate the maintenance of the designs (Vanlande et al. 2008).

The Uptake of BIM

Despite the potential benefits of BIM its uptake has been slow. The implementation of BIM has received an increasing attention. This is evidenced by a number of papers published in past few years; for instance, the Journal of Information Technology in Construction (ITCon) published a special issue on “Case studies of BIM use” in 2008. However, the majority of what has been published is still presented in a hypothetical sense as BIM is still considered in its infancy albeit it is developing rapidly (Fortner 2008). It is fair to say that the theory of BIM has been advanced to a large extent however there is a long road for the widely adoption of BIM in the industry.

According to the American Institute of Architects’ 2006 survey, entitled *The Business of Architecture*, about 16 per cent of firms have acquired BIM tools, and roughly 10 per cent are using them for billable work (AIA 2006). However, among large firms consisting of 50 or more employees, just over 60 per cent have acquired BIM software, and just over half are using it on billable projects (Gonchar 2007 p 84). Gonchar highlights that adoption is now likely to be considerably more widespread since the data, collected in the Spring of 2006, is already considered too old in the context of a rapidly evolving technology.

In 2004 an article from the CAD User AEC Magazine suggested that: “A number of large clients and construction projects are claiming to have successfully implemented a BIM... In reality this is not being fully realized.” (Model Solutions (AEC) Limited, 2004). Tse et al. (2005) in their survey of registered architects in Hong Kong identified that more than half of the respondents (54%) had never heard of BIM. According to their study, the overall uptake of BIM in architecture firms is still noticeably low.

Pazlar & Turk (2008) pointed out that “Currently there is no widely used Building Information Model (BIM) in the Architecture, Engineering, Construction and Facility Management sector.”

They explained that the fragmentation nature of the sector and the unique products are responsible for the slow uptake of BIM. In addition, most of applications of BIM are large property owners and healthcare projects (Howard & Björk 2008; Manning & Messner 2008; Khanzode et al. 2008).

Kaner et al. (2008) investigated the adoption of BIM for precast concrete design in four buildings. Their conclusion was that “Progress in adopting BIM is slow but certain.” Their case studies showed that the improved engineering productivity and improved quality of design and documentation are the major drivers for structural engineers move to BIM.

Despite what appears to be a slow uptake, Jay Batt, Senior Vice President of Autodesk AEC Solutions, believes that the uptake of BIM has nearly reached “tipping point”. Batt’s encouraging outlook may be biased because of his interest in promoting the uptake of BIM, but Mike Kenig of Holder Constructions also believes the adoption of BIM is “close to tipping point” (Speed 2007, p T11). Holder Constructions have learned how to create intelligent 3D models because they can improve service delivery and are currently using partial models on the majority of their projects (Speed 2007, p T5). However, there appears to be little collaboration with other project participants in the actual creation of the BIM. In fact, “Instances of implementation from the start to the end of a project are still rare ... Although BIM users constantly refer to the model, in actual practice, a multidisciplinary model project team is rarely, if ever, served by a single seamless database. Instead teams rely on a series of models usually organized by discipline and are often dependent on different software platforms. The models are generally updated and coordinated at regular intervals, often via a project extranet.” (Gonchar 2007, p 86). Gonchar (2007) supports this observation with a case study of an individual architect who uses several digital tools to create different aspects of the model depending on which tool is best suited to the task. This approach tends

to be common practice and there is rarely an all encompassing single model created, but rather a series of models used to simulate different aspects of the project.

Plume & Mitchell (2007)'s research found that the object model CAD, commonly referred to as BIM, has been used by a substantial proportion of architects. However, these models are built and optimized for the primary purpose of drawings output and are "shared" as traditional 2D layered drawings.

The United States is the leading country in BIM development and applications. A recent market survey shows that 48% of the architectural offices in the US already use building information modeling (AIA 2007, cited in Schlueter & Thesseling 2009). In an Australian context, CRC for Construction Innovation launched a research project, called "National BIM Guidelines and Case Studies" in 2007. Their interim report shows that "at the present stage of development in Australia the predominant form of available BIM software is model-based CAD systems and the predominant BIM user is the project architect." The project also identified the need to train current staff and the lack of available trained recruits as the largest obstacles to the adoption of BIM by the Australian AEC industry (CRC CI 2008).

Based on an action research approach, Baldwin et al. (2009) pointed out that the adoption of BIM, coupled with virtual prototyping will fundamentally change the procedures relating to procurement and the roles of the participants. There will be an increasing requirement to involve specialist subcontractors and key suppliers from a very early stage in the design process. Vanlande et al. (2008) proposed a building lifecycle management system by taking various project phases and participating parties into account during the development of BIM. A semantic indexation method was adopted in their study to extend the BIM boundary towards the facility management phase.

Donath & Thurow (2007) designed a prototype system to record and adjust building surveying

data and to integrate this with the architectural surveying and planning process. They claimed this system will bring benefits, such as: increased planning security, improved cost effectiveness and improved quality of building measures.

Baldwin et al. (2008) investigated the design information modeling to evaluate the options to reduce construction waste in high rise residential buildings, i.e. prefabrication and pre-cast. They concluded that BIM represents a good platform for developing the analysis of construction waste and the implications of design decisions. In addition, BIM provides a design team with a tool to evaluate the impact of the design decisions on the overall construction process with the assistance of Virtual Prototyping (Baldwin et al. 2007; Baldwin et al. 2009).

Implementation Barriers

Past research and industry publications have also identified and discussed barriers impeding the implementation of BIM. For example, Tse et al. (2005) identified barriers including:

- the split between architecture, design and drafting;
- inadequate objects and object customisation capability;
- a complicated and time-consuming modeling process;
- a lack of training and technical support;
- a lack of clear requirements from clients;
- extra file acquisition costs; and
- the unavailability of free trial software.

Tse et al (2005)'s research identified the most salient obstacle to the widespread use of BIM and the future of n-dimensional modeling to be the separation of architecture design and drafting. In addition, Bernstein & Pittman (2005) suggested that the barriers impeding the uptake of BIM also included: convincing the project participants to use it, and ultimately, the client to pay for it as well as

the uncertainty that results from the contractual risks and responsibility changes that come with the new technology. Thomson & Miner (2006) also raised questions in respect of the contractual risks and implications that BIM brings to the project, thereby emphasizing the importance of clarifying the contractual issues in order to ensure that the adoption of BIM is a success for all concerned.

In addition to the barriers above there are also the technical issues associated with BIM. Although specifying parametric building object behavior for a building information modeling system is theoretically possible in practice it is very complex and tedious, as identified by Lee et al. (2005). Similarly, the technical aspects of model management, such as the systematic and automatic updating of the information contained in the model, are possible, but there is still scope for further improvements. This issue of maintaining the semantic integrity of the model is a key component of BIM as discussed by Plume and Mitchell (2007) who also stated that almost every author in the field had drawn attention to this issue. As a simple example of this problem, Plume & Mitchell explain that when values obtained through analysis applications are uploaded to the model the architect changes the design and this results in the values no longer applying. Therefore there is a need to keep track of information in the model and be aware of when it becomes redundant or incorrect.

Contrary to the technical issues above, Goldberg (2005) argued that the main problems lie not with the capability of the new BIM software, but with the need to train professionals in how to use these programs. Further to this, is the fact that many computer savvy professionals who may be capable of using the software are new to the industry and lack the experience to understand good construction practices and good design.

Interoperability (initial limitations of the technology, particularly cross platform compatibility between the different programmes), liability (ownership and the legal standing of the model),

upfront investment and fee structure, and the industry's culture to resist changes are responsible for the slow uptake of BIM in the New Zealand construction industry even with identified advantages (Construction Client's Group 2008).

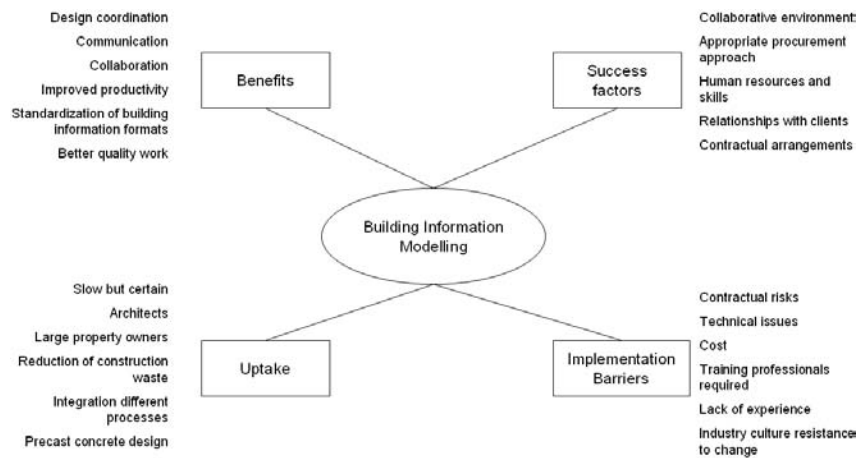
Manning & Messner (2008) adopted a case study approach to investigate the implementation of BIM in the programming phase of two health-care projects. The primary challenges found were (1) information transfer bottlenecks, (2) current lack of parametric content for significant project vendor products, (3) unfamiliarity of BIM's breadth of ability and associated experience of application in programming, and (4) a lack of understanding of interoperability limitations and abilities. The utilization of BIM usually requires organizational changes which presents a hurdle in opposition to the successful utilization of BIM tools (Ashcraft 2006).

Howard & Björk (2008) interviewed a number of international experts and concluded that there are some issues associated with the current state of BIM: (1) too complex so may need to be used first in specific areas; (2) too many standards relevant to BIM; (3) a long timeline to gain benefit from the adoption of BIM; (4) the distribution of benefits depends on the chosen procurement approach; (5) needs a special information manager role of and needs special education; (6) most applications of BIM are by large property owners in the public sector; and (7) some clients with successful experiences of using BIM may not wish to share their knowledge.

Isikdag et al. (2008) identify the cost associated with the usage of BIM as including; the direct costs of BIM work stations, training, setup of piece and connection libraries, management of the adoption phase and lost productivity during adoption.

Implementation of BIM is complex matter as it involves the redefinition of design roles and responsibilities that are embedded in traditional design processes and rational boundaries (Ku et al. 2008). Both the design team and construction team need to understand the changing practices

Figure 1. BIM Framework



derived from BIM. According to Schlueter & Thesseling (2009), the biggest obstacle for architects in adopting the BIM approach is the tentative use of BIM by other industry partners such as engineering firms. According to Kaner et al. (2008), the lack of BIM hardware, software and experience with the client is a barrier to the adoption of BIM in a project.

Figure 1 summarizes the benefits, uptake and implementation of BIM in the AEC industry.

3 RESEARCH METHODOLOGY

The methodology used in conducting this research consisted of the following stages:

- Survey of AEC professionals; and
- Follow-up telephone interviews with selected survey respondents.

The primary instrument for data collection was a survey questionnaire similar to the questionnaire survey conducted by Tse, et al. (2005) which addressed the usage of BIM by Architects in Hong Kong. The second was follow-up telephone interviews with several of the questionnaire respondents who provided their contact details.

The questionnaire survey used in this research

project was sent to a sample of 104 professionals in the Australian AEC industry. A response rate of 33% was achieved which is considered good for mailed surveys. The telephone interviews were conducted following the survey questionnaire to clarify responses and delve deeper with more complex questioning that could not be achieved through the questionnaire survey.

Responses to the questionnaire survey were tabulated in a spreadsheet in which the data could be manipulated to identify patterns and trends. These findings were then related back to the findings of the literature review. The questionnaire survey was followed by an in-depth interview with selected industry practitioners who answered the questionnaire.

Sample Design

The holders of the necessary information were identified as participants in the AEC Industry. For the purpose of this research it was decided that Architects, Engineers and Contractors would adequately reflect the industry. Thus the population for this research project was Australian Architecture, Engineering and Construction industry professionals. Given the objectives of this research project, a very large sample frame would have been ideal. However, due to limited

resources, the sample size was limited to 104 and this consisted of:

- 36 Architects
- 36 Engineers
- 32 Contractors

It was believed that the extent to which BIM is used in the Australian AEC Industry is low. For this reason the sample selection criteria was intentionally designed to increase the potential number of responses from BIM users to provide a greater volume of data from BIM users. This was achieved by using the yellow pages of three Australian States; New South Wales (NSW), Victoria (VIC), and South Australia (SA) as a sampling frame for the consultants. Following the suggestion of the research supervisor every third consultant with a listed website was selected from the sample frame as it was thought that these consultants would be more computer savvy and more likely to be involved in BIM. This selection was reduced further by randomly removing several listings to achieve the desired sample size.

The sampling frame for the Contractors involved contractors who had been accredited under the Australian Government Building and Construction Occupational Health and Safety (OHS) Accreditation Scheme. It was felt that they were more likely

to be involved in BIM as they were typically larger, and more likely to have the resources to adopt BIM. The contractors specializing in road construction were removed from the sample frame and then every fourth contractor was removed to reduce the sample further to achieve the desired sample size.

This sampling method possibly created a bias which may overstate the extent to which BIM is used in the industry as a whole by potentially inflating the volume of responses from BIM users and it is important to consider this when analyzing the data. However, this approach was considered justified by the budget constraints of this research and the need to obtain sufficient responses from BIM users in order to provide a meaningful representation of their perspectives.

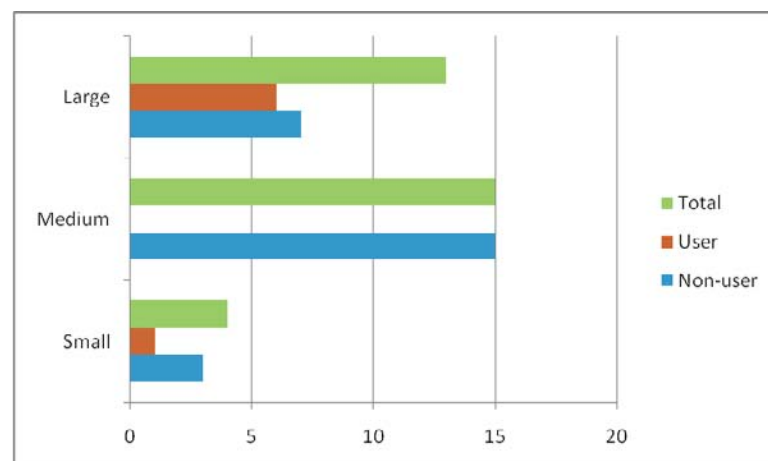
4 DATA ANALYSIS

Descriptive Analysis

As shown in Figure 2, the majority of firms that already used BIM were large firms. Interestingly, no medium size firms (as respondents) used BIM in their practice.

Figure 3 shows that the current usage of BIM in the industry is fairly low. It indicates that the majority of the projects on which BIM is being

Figure 2. Usage of BIM by size of firms



used to some extent exceed a construction cost of \$20 million. In addition, it was found that all respondents who have been involved with BIM had positive experiences with BIM and would continue to use BIM in the future.

Main Reasons for using BIM

Figure 4 shows that quality improvements and time savings are perceived as the major reasons for using BIM in projects.

Figure 3. BIM usage by the construction contract value

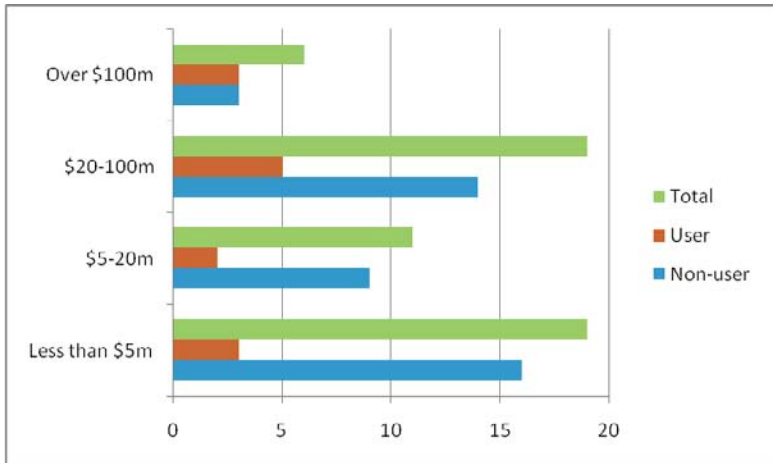
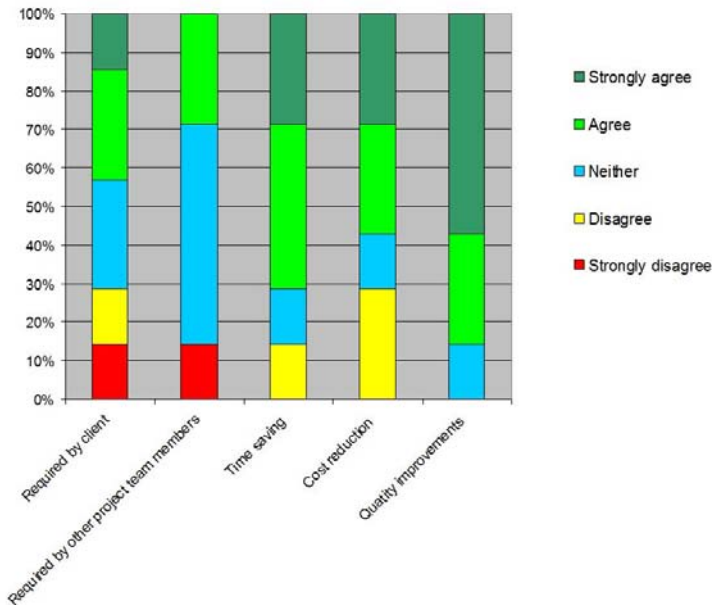


Figure 4. Main reasons for using BIM



Advantages

The majority of respondents perceived the main advantages of using BIM in projects were as detailed in Figure 5:

- Better coordination of documentation
- High quality work
- Greater productivity
- Increased speed of delivery
- New revenue and business opportunity

Perceived Barriers

The respondents perceived the major barriers to BIM in order of significance as below (see Figure 6):

- Lack of BIM knowledge and expertise
- Complete lack of awareness of BIM
- Resistance to change
- Inadequate technology and interoperability issues

- Legal issues concerning the ownership of the model and its contents, the responsibility for updating and coordinating the model and ensuring consistency between multiple models which define various aspects of the same project.

“Currently, legal decisions for the AEC industry are based on a 100-year-old court decision

Figure 6. Existing barriers to adopting BIM in AEC projects

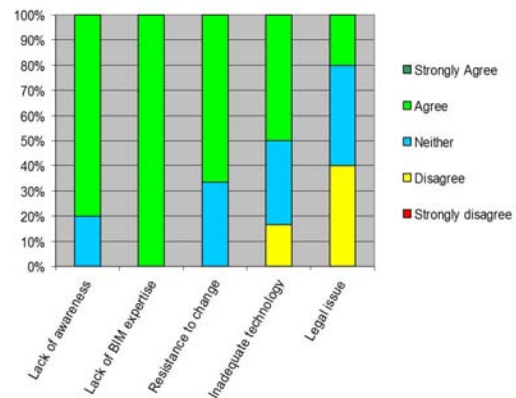
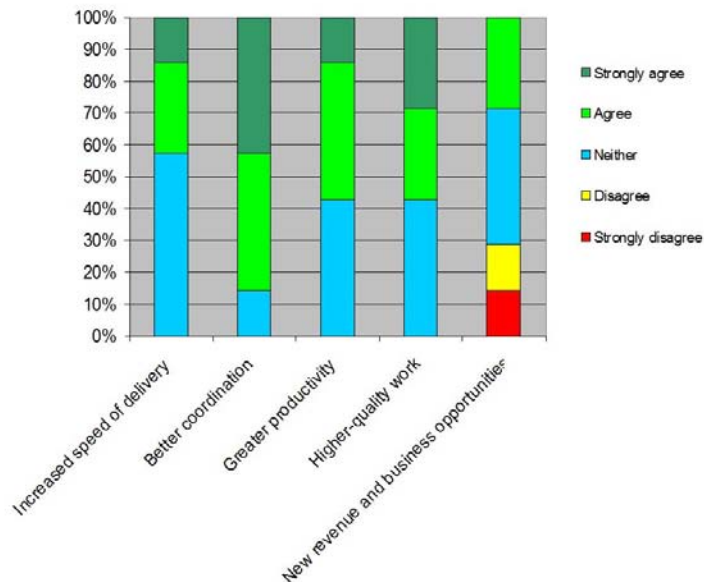


Figure 5. Advantages of adopting BIM usage in AEC projects



that focused on the warranty of the rights of the individual stakeholders of a project and did not focus on a collaborative assessment.” (Post 2007 p 12). BIM depends upon a collaborative environment; however, the current legal framework for transferring risk is inappropriate. It has been commonly recognized that new laws will have to be created to help in the paradigm shift to collaborative BIM.

Further to the findings illustrated above respondents also suggested the following problems were commonly encountered when adopting and using BIM:

- “Skills development has had to increase to keep pace with technology.”
- “Set up costs, setup time, interoperability, training.”
- “Training, component creation, technique developments.”
- “Generally issues related to taking up new systems:
 - software limitations;
 - staff resistance; and
 - confidence and leadership.”

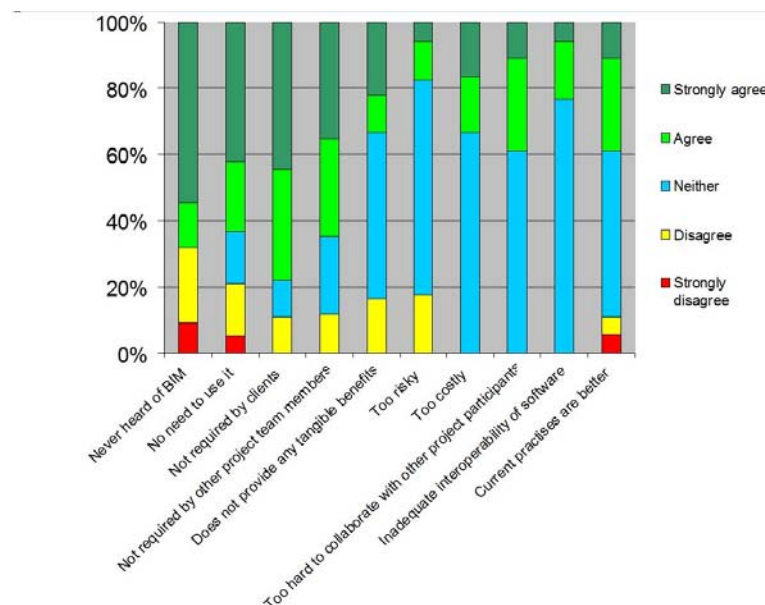
Figure 7 indicates that the main reasons why respondents had not been using BIM are:

- They had never heard of BIM
- BIM is not required by their clients or by other project team members
- They believed there was simply no need to or benefit in using BIM

The respondents indicated that the industry can be motivated to adopt BIM by means of: (see Figure 8):

- Client demand
- Proven success on trial research projects
- The need to remain competitive with other competitors using BIM
- Greater awareness and understanding of the BIM approach
- Demand from other project team members
- Government incentives
- Cheaper software
- More BIM trained and savvy professionals
- Better interoperability of software
- Support from professional bodies

Figure 7. Reasons for not using BIM



Interviews

Interviews were conducted with five questionnaire respondents to delve into their personal experiences with BIM and provide insight into their firms' involvement with BIM. Across the interviewees there was a general consensus that BIM saved considerable time later in the project. It was recognized that initially more time was required to be invested up-front to create the BIM; however, this initial time investment was more than off-set by substantial time savings achieved later in the project.

It was also evident from the interviews that very few project teams share a BIM. Instead each discipline builds their own BIM to suit their own purposes. Interviewee D in particular emphasized that this would perhaps be different if there was a greater interest from clients to invest in building the BIM such that it may be used by all disciplines for downstream-applications without requiring a BIM to be built by each discipline to suit their purposes.

The majority of interviewees pointed out that BIM has been used in conjunction with other project participants. It is common for both architects and engineers to be involved together. It is interesting to note that no interviewee mentioned that any other project participants, such as cost consultants and building certifiers were involved even though respondents were given the option to list other project participants who were involved in the BIM. Typically BIM is used for internal purposes. There is very little sharing of the model across disciplines.

Interviewee A, an Engineer, described how they would typically still receive 2D drawings from the architect and from the architect's drawings they would create their own BIM for their own purposes, such as for structural and heat load analysis. There were primarily two reasons for this. Firstly they had found that once the model was created the speed with which they could conduct the analyses was greatly improved. Furthermore, if minor changes were made to the design the model could be updated and a recalculation could

Figure 8. Motivations for using BIM

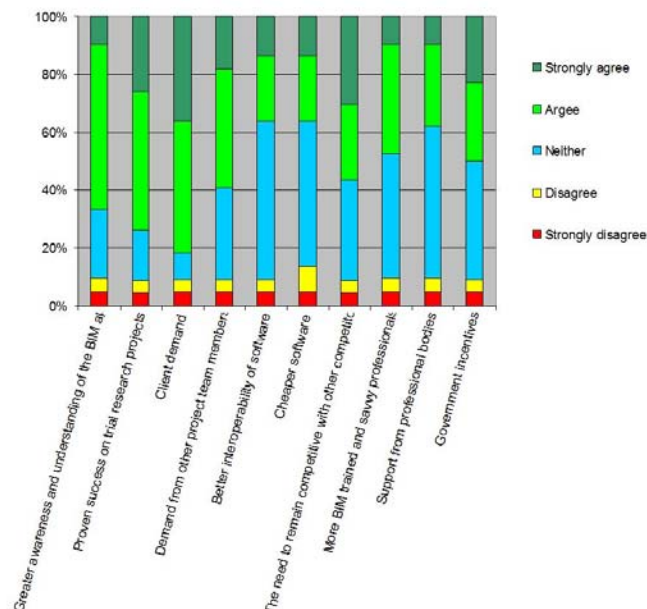


Table 1. Summary of Respondents' Profile and Involvement with BIM

Interviewee	Role	Firm size	Operating sectors	Value of projects	BIM experience
Interviewee A	Engineer	Large	most sectors of the industry including: residential, commercial, industrial, health care, educational, and defence in all States and Territories of Australia except Tasmania	\$5 million to over \$100 million	In the last two years, the firm used BIM on less than 25 per cent of the projects undertaken by his business. However, interviewee A had been aware of BIM and its advances for several years before that.
Interviewee B	Contractor	Large	most sectors of the industry including: residential, commercial, industrial, health care, educational, and civil engineering in the states of ACT, NSW, QLD, SA, and VIC	\$20 million to \$100 million	In the last two years, the firm used BIM on less than 25 per cent of the projects undertaken by his business.
Interviewee C	Contractor	Large	operating in NSW in most sectors of industry including: residential, commercial, industrial, health care, educational, church, and entertainment	\$20 million to \$100 million	Very limited use of BIM
Interviewee D	Architect	Large	most sectors of the industry including: residential, commercial, industrial, educational, public and hospitality in NSW, QLD and VIC	\$20 million to \$100 million	In the last two years, the firm used BIM on approximately 75% of the projects undertaken by his business
Interviewee E	Contractor	Medium	commercial sector in SA and WA	\$5 million to \$20 million	Very limited use of BIM

be conducted with minimal effort saving time in re-conducting analyses and providing almost instantaneous advice to the client. The second reason, which Interviewee A suggested was also one of biggest issues hindering the adoption of BIM was that architects building the initial model still did not know how to build it so that other project team members could use it effectively for down-stream applications, such as for conducting a heat load analysis. In many cases Interviewee A had received a model from an architect that did not enable other members to connect to it thereby rendering the model useless for any analysis and leaving the engineer no choice but to create their own model. It was rare for engineers in his business to collaborate with other members of the project team in creating the BIM. The only other members of the project team who had been involved in the past were architects.

From the contractors' side, Interviewee B stated that on projects where Interviewee B has been engaged early in the design phase to provide construction advice, the BIM has been found to be useful enabling changes to be made promptly and the development of the design to proceed quickly. To date Interviewee B has used the model mostly for 3D visualisations to give a better understanding of the components of the building and how it could be built. It has also been useful for communicating the design to the clients in 3D which was often found to be much easier for them to interpret than a set of 2D drawings. From Interviewee B's perspective the greatest advantage of BIM over conventional drafting methods was that it "improves the confidence that the design will be less likely to be contaminated with errors" when a change is made and all views of the model are changed iteratively.

Interviewee C had not heard of BIM at the time the questionnaire was administered and could not provide responses to many of the survey questions. However, in the last few months his company had been trialing a software package which would link a BIM and a construction schedule to simulate the construction. At that point he was still unsure whether they would adopt the new technology, but was curious to see what could be done with it. From his experience he was not aware of any architects or engineers using BIM on any of the projects he'd been involved with and so his interest in BIM was low. However, he suggested that if there was a rapid swing towards BIM in the industry then it was likely that his company would be using BIM in the next three years, subject to the findings of their internal trials. He described his company as dynamic and eager to keep abreast of competitors, thus remaining competitive would be their strongest reason for adopting BIM. On the other hand Interviewee C saw little merit in using BIM to simulate construction programs and methods.

Interviewee D discussed how there has been very little demand from their clients to use BIM. As their use of BIM had not been driven by the client, Interviewee D's business used BIM mostly for internal purposes and rarely collaborated or shared the model with other project participants. This has meant that they have not experienced any legal issues as they did not share their models with other project participants, nor did the models form any part of the contract documents. From his experience he had not seen other cases where single models were created and contributed to by several project participants from different disciplines nor was he aware of any cases where a BIM had become part of the contract documents. In most cases where more than one project participant was involved in BIM, each participant would still have their own model for their own tasks. For example an engineer may create a structural model based on architectural drawings which they use for analysis purposes. It is the engineer's responsibility to

ensure their model matches the architect's drawings. Much of his business' reason for using BIM had been to create consistent 2D drawings which had become the contract documents and used to produce 3D visualizations to better conceptualize the form and space of the building. They had also experienced advantages arising from much faster, more consistent design documentation and ultimately much higher quality output.

Interviewee E had very little involvement with BIM. His company was trialing various software packages for computer assisted quantity take-offs and 3D modeling for conflict detection, but was by no means using BIM to its full potential and nor were any of the architects or engineers with whom Interviewee E worked. In respect of their in-house 3D modeling for fabrication purposes, they would build the models themselves from scratch which took a lot of time. However, "any time lost at the front end was picked up at the back end, and more." Thus, time and cost savings were being achieved, and Interviewee E could relate this to BIM. He felt that although extra time might be required for creating the BIM, the potential time savings later in the project could be substantial.

The interviewees who had a reasonable degree of involvement with BIM had positive outlooks for the future of BIM. Interviewee D claimed that following their positive experiences with BIM they would not be returning to their previous conventional practices. He also believed "without a doubt, this is the future of the industry."

Interviewee B had also observed that the uptake of BIM was steadily increasing amongst consultants and for larger projects the use of BIM, in one form or another, was becoming the norm in the design phase of a project. In his opinion, BIM was definitely the way of the future for the construction industry and there was very little that "can stop it once the inertia builds up".

5 DISCUSSION AND IMPLICATIONS

The literature findings showed that the concept of BIM is developing rapidly and that although there is not yet a universally accepted definition of BIM, the concept is well established in the minds of some academics and software developers.

The literature review also provided a background of the up-take of BIM in other parts of the world and identified several factors which affect the up-take of BIM. These included the benefits BIM is expected to bring to the industry, and the extent to which some of these benefits are already being experienced by early adopters. Such benefits include: improved design consistency, greater productivity, standardization of building information formats, better quality work and increased profits. The literature review also identified several barriers to the implementation of BIM including the upfront cost, contractual risks, technical difficulties such as the complexity of specifying parametric building object behavior in a BIM system, and interoperability issues, as well as cultural issues such as a lack of awareness and resistance to change. According to previous studies, Building Information Modeling has achieved significant development from theoretical perspective, however it is still too early to claim that it has been widely accepted and adopted in practice in the AEC industry.

The questionnaire survey assessed the up-take of BIM in Australia and explored the factors affecting this up-take. One of the major findings of this survey was that it has revealed that only 25% of the respondents were involved in BIM and only half of all respondents had even heard of BIM. This finding is very similar to the finding by Tse in 2005 where 54% of respondents were unaware of BIM. However, it is difficult to make statistical comparisons between these surveys because they were undertaken at different times and in different countries. Other factors, such as sample selection methodology, sample size, the

newness of BIM, and the rate of development of BIM, make it difficult to compare the results of the two surveys.

The survey demonstrated that the vast majority of the respondents involved in BIM were architects and engineers from large sized firms who were using BIM software mostly for drafting and 3-D visualisations. Several engineers were also using BIM for structural, and heat load analysis. These findings were consistent with the findings of the literature review. Telephone interviews clarified that most respondents' involvements in BIM were primarily for internal purposes and there was rarely a single model to which several project team members from different disciplines contributed simultaneously. However, there was broad agreement from the respondents involved in BIM that their businesses were experiencing advantages claimed by BIM proponents, including; better coordination, higher quality work, greater productivity, and increased speed of delivery. It was verified in the telephone interviews that these advantages were achieved through BIM and these advantages produced cost savings which more than off-set the initial costs and extra time required for creating the model.

At this point the results of the survey suggest that there is general disagreement that BIM is creating new revenue and business opportunities; perhaps because the client demand is insufficient and this in turn may be due to the client's lack of awareness of BIM. It is obviously very difficult to quantify these benefits and ultimately it will most likely be the experience and the market place rather than research that determines whether the benefits of BIM outweigh its costs. Similarly, the costs are difficult to quantify as they do not just include the cost of new software, but also changing business transaction models and working relationships which make it very difficult to assess the true cost of implementation. Despite not being able to quantify the financial benefits accurately, all respondents using BIM had had

positive experiences with BIM and will continue to use it. Also in the telephone interviews several respondents believed BIM was inevitably the way of the future for the industry.

Interestingly, of the 75% of respondents in this survey who were not involved with BIM, more than two thirds either strongly agreed or agreed that they were not using it because they had never heard of BIM. This lack of awareness is clearly a significant reason why the up-take of BIM is slow. Of those using BIM, 80% agreed that lack of awareness of BIM was a significant barrier to implementation. This is also consistent with the findings of the literature review, but once again it is very difficult to draw direct comparisons due to the time differences, and sampling methodology. It was also discovered that client demand would be the strongest motivator for non-users to become involved in BIM which would suggest that non-users are not yet aware of the benefits users are experiencing and their motivation to use BIM would come from a need to use it not a want to use it. However, if few consultants are aware of BIM, there may not be many clients that are aware of BIM either.

The survey also verified that other implementation barriers identified in the literature review were still an issue. These included: lack of BIM expertise, lack of awareness, and resistance to change. An overwhelming majority of BIM users agreed these were all still significant issues.

6 FUTURE RESEARCH

BIM is a relatively new concept in the AEC industry and at the centre of a rapidly evolving field of knowledge. This research touched on a few broad issues relating to the up-take of BIM and the factors affecting that up-take. There are many other avenues of research within this field that could be studied in more detail, but to expand this research further there is clear scope to:

- monitor the uptake of BIM;
- assess the experience of those who have used BIM; and
- explore the issues that may arise as a consequence of introducing BIM.

Monitoring the up-take of BIM is important because the current up-take of the new technology and the rate of up-take are useful to anyone who is interested in adopting the new technology, but is unsure of the right time to do so. BIM is like the use of fax machines. Faxes can only be sent between fax machines. One is required at either end of the line of communication for it to work. Similarly, BIM can only be used successfully as a communication tool when both parties are BIM capable. Thus, the true benefits of BIM in a collaborative context are unlikely to be realized until the majority of professionals are BIM capable. Perceptions of respondents in the telephone interviews suggested that there would be a turning point in the up-take of BIM at which time enough businesses would be involved to enjoy the true collaborative benefits of BIM and it would be difficult for non-users to compete in the industry. Being aware of the up-take may be useful in assessing the right time for each business to become involved and predicting when the up-take will reach this critical turning point.

A more detailed study of both the positive and negative experiences of BIM users would also be useful to those considering adopting BIM. A balanced argument is essential in providing sound knowledge in this field and it would not be sensible to focus on just the benefits or just the disadvantages. For this type of research, interviews are a more suitable research tool. They provide the opportunity to clarify questions and answers to ensure both the interviewer and interviewee understand the questions and responses. It was also found that interviews can allow for more freedom in altering questions and initiating open discussion that could not happen in a questionnaire survey. Indeed, very few respondents to

the questionnaire survey took the time to write answers to the open-ended questions.

Case studies both for projects using BIM and projects developed specifically for experimenting with adopting BIM to its full potential, would be ideal for testing the true benefits and efficiencies of this new approach to design and documentation. Such case studies could also explore the issues that arise from the adoption of BIM, such as: the nature of relationships between the participants in a project and the legal ramifications of BIM. Many of the survey respondents agreed that positive findings from trial research projects would motivate them to use BIM. Given the economic necessity to improve efficiency in the construction industries around the world as identified in past research such as the Egan Report, and the need to reduce unnecessary costs which trickle through to many other sectors of the economy, there are grounds for the government to provide funding or subsidize owners who experiment with BIM and publish their experiences as a means of accelerating the knowledge in this field and subsequently the adoption of what appears to be a better solution for the industry and the economy as a whole. Similarly, a large scale world-wide comparative study covering industry-wide participants will help to understand the BIM practice in different contexts. The lessons learnt can then be applied in order to improve the current practice.

Future research opportunities also exist to investigate the legal issues associated with the adoption of Building Information Modeling (BIM) in the Architecture, Engineering and Construction (AEC) industry.

7 CONCLUSION

During the period of economic downturn, it is paramount to improve the efficiency and effectiveness of the design and construction processes. BIM seems a useful tool to achieve this goal. It is imperative for participants in the AEC industry

to: 1) learn what BIM is; 2) learn how it may affect their business; and 3) to develop strategies to adopt BIM in their practice.

This research reviewed the development of BIM, the extent to which BIM has been implemented in the Australian AEC industry, and the factors which have affected the up-take of BIM. The questionnaire survey and interviews showed that there are a number of benefits of adopting BIM in AEC projects. These benefits include: better coordination, high quality work, greater productivity, increased speed of delivery, and new revenue and business opportunity.

The results also indicate that the up-take of BIM appears to be relatively slow and implementation, in terms of multiple project participants being involved in the BIM seems rare despite the benefits. The slow rate of adoption could be accounted for by the lack of awareness of the BIM concept, and the lack of BIM capable professionals. Other implementation barriers were identified to include: interoperability of software, high costs, and the complexity and tediousness of specifying parametric building object behavior necessary for BIM.

In order to overcome these barriers, several measures could be taken to motivate the industry practitioners to move forward with the adoption of BIM in their practice. As a starting point these could include: stimulating client's demand for BIM, successful adoption of BIM on trial research projects, the generation of a greater awareness and understanding of the BIM approach, provision of government incentives, and a reduction in software and other costs associated with the adoption of BIM.

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KEY TERMS AND DEFINITIONS

Building Information Modeling (BIM): “a digital representation of physical and functional characteristics of a facility...and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” (BSA 2009). It is a philosophy and useful tool to coordinate various inputs to design which also contributes towards the construction.

Architecture, Engineering and Construction (AEC) Industry: The sector of the construction industry that provides the services on the architectural design, engineering design and

construction services. It is a sector which is very active in the adoption of Information, Communication and Technology. This is also a sector which is very active in the international arena.

Object-Based CAD: One type of CAD (Computer-Aided Design). Objects such as doors, windows, stairs and walls can be represented in three dimensions. It has the ability to store non-graphical information relating to the objects including specifications and design constraints.

Entity-Based CAD: Another type of CAD (Computer-Aided Design). It has been widely used throughout the industry, predominantly for drafting purposes. It can produce a 3D model through the projection of lines and arcs.

Interoperability: A term to be used to describe the ability of various individuals or organizations to interact and work together so that a common goal can be (better) achieved. Under the technology context, it can be defined as the degree to which diverse systems or components are able

to exchange information and make most of the exchanged information. This concept has been promoted by a number of organizations such as Institute of Electrical and Electronics Engineers (IEEE).

Constructability: Used to measure the degree to which the design solution can be achieved during the construction stage. It promotes the involvement of the construction team from very early stage of the project. As a result, the construction knowledge and experience can be adopted to optimize the design solution.

Life Cycle Management: An approach which looks at various stages of a project (i.e. from conception to completion and commissioning) as a system rather than focusing on a single stage. It recognizes the impacts of both the upfront cost and ongoing cost. In construction context, this approach has been used to measure the cost performance (lifecycle costing) and sustainability performance (footprint).

Section 8

Education and Training

Chapter 24

Removing Barriers to BIM Adoption: Clients and Code Checking to Drive Changes

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ABSTRACT

Building information modelling (BIM) is not only an authoring tool for architects and engineers, but also for all stakeholders in the building programme procurement process. Analysis tools like code checking of building regulations and environmental simulations that can report on heating loads, daylighting and carbon use will push the adoption of intelligent modelling faster and further than previously thought. The benefits for clients should not be underestimated either and some are already reaping them where project certainty is to the fore. However, the professional language that architects and engineers espouse is a latent force that can run counter to fostering collaboration. An emerging professional, the Architectural Technologist, can bridge that divide and adopt the adjunct role of manager in the integrated project delivery.

1 INTRODUCTION

Building Information Modelling (BIM) has been around a number of years now but its unilateral adoption has been slow. There are a number of issues here and one is the entrenchment of the different professionals and their methodologies. While it is absolutely right for an architect to control aesthetics and space, nobody questions that it is equally

right for the engineer to control the structure and/or services. What is questionable is their mindset and language, if there is to be the real possibility of shared data, and genuine cross-discipline collaboration.

Sharing data and collaboration does not sit well with the disciplines' involved in the building industry. Cicmil and Marshall (2005) elaborate and elucidate a scenario of pseudo collaboration, where a two-stage tender is hopelessly inadequate due to

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the intransience of the quantity surveyor (QS) in their perceived role of advisor to the client. There is no mechanism in place to allow the QS to enter into a collaborative state with the main contractor and no desire to either. Cartlidge (2002) probably summed it up best with "...quantity surveyors must get inside the head of their clients".

There are many forces at work to discourage collaboration (Porter 2007) including the treat of new entrants, the buying power of both suppliers and buyers, rivalry among existing firms and the fear of substitutes. These strong entrenched attitudes (Walker 2002) in the design construction divide were addressed in the procurement of Heathrow's Terminal Five (T5), delivered on time and to budget (Haste 2002), where such an environment was nurtured and encouraged (Ferroussat 2005). It was based on the principles specified in the Constructing the Team (Latham, 1994) and Rethinking Construction (Egan, 1998). Had BAA followed a traditional approach T5 would have ended up opening 2 years late, costing 40% over budget with 6 fatalities (Riley, 2005); this was not an option for BAA (Potts 2002). Carefully defining responsibility, accountability and liability, the focus was on delivery. Remuneration was based on reimbursable costs plus profit with a reward package for successful completion. This incentive plan encouraged exceptional performance with the focus on the issues of value and time. Value performance occurred primarily in the design phases and was measured by the value of the reward fund for each Delivery Team and calculated as the sum of the relevant Delivery Team Budget less the total cost of the work of that Delivery Team.

The time reward applied only during the construction stages. Here, worthwhile reward payments were available to be earned for completing critical construction milestones early or on time. If the work is done on time, a third went to the contractor, a third went back to BAA and a third went into the project-wide pot that would only be paid at the end (Douglas, 2005). There was a no blame culture meaning that if work had to be

redone the fault was not apportioned to anybody but the rewards would either be reduced or not awarded at all. This had the effect of applying a kind of peer pressure where it was in the interest of all parties not to fail, which created a place where the vertical silos of expertise were traded for viaducts of collaborative techniques. BAA took out a single premium insurance policy for all suppliers, providing one insurance plan for the main risk. The policy covered construction and Professional Indemnity (Potts, 2002).

Sadly, while T5 was collaborative it was not a virtually modelled project and when the first satellite building was recently commissioned this method was abandoned for a traditional method of procurement. Questions must be asked as to how much sway the various disciplines and the entrenched methods had in this change of mind. Or was the management chain of command too onerous. The team structure had a hierarchy of several layers of management; the development team, the project management team, delivery teams and task teams. There was no common model to reference and the level of comfort of the construction manager may not have been too cosy. Construction managers have the lowest level of comfort, working with other professionals (under 20%), while owners, architects and engineers have nearly twice that level (Eckblad, Rubel and Bedrick, 2007), meaning that while the traditional demarcations have a good *bonhomie*, issues arise if the industry can afford this luxury anymore.

2. BACKGROUND

2.1 The Professional Architectural Technologist

Developments are underfoot to establish the technologist as a professional body with the ability to sign off work. The following is generally a synopsis and distillation of the relevant points in the new syllabi and proposals for content for

Figure 1. Heathrow Terminal 5 © James Harty 2008



a new course being tabled by the Dublin Institute of Technology (DIT).

To address the educational needs of the professional architectural technologist, the Dublin School of Architecture is intending to replace its three-year Level 7 Ordinary Bachelor's Degree with a Bachelor of Science (Hons.) in Architectural Technology (Level 8) together with a Postgraduate Certificate in Applied Architectural Technology (Level 9). The Postgraduate Certificate in Applied Architectural Technology is intended to lead to the award of a Master's Degree.

"New methods of design and procurement have led to changing roles within the design and construction teams, with Architectural Technologists frequently playing a key role as technical designers, and in doing so emerging as professional partners to architects, engineers and surveyors in the building design process.

...The RIAI welcomes the emergence of honours degrees in architectural technology ... and seeks to work with the educational institutions in developing a context for professional accreditation of the new degree programmes.

... Whether or not Registration is introduced, professional membership and accreditation systems will have to make provision for these developments one way or another" - Royal Institute of Architects in Ireland, President James Pike, November 2006

The vast majority of Irish Architectural Technology Graduate Network (IATGN) members have expressed a strong interest in obtaining further qualifications at undergraduate and postgraduate levels, where among other things the technologist should maintain proficiency in emerging computer application software in information technology in general and building information modelling in particular. The technologist should play a leading role in information management and quality assurance processes (*Part A - Self Study*, 2009).

The issues raised are many and varied. They include title, competences (limits and overlaps relative to the competences of an architect), function (responsibilities arising from competences as employee and in self employment), recognition of experience in place of formal qualification, authority to sign documentation, variable education standards, professional support for

self employed technicians, and the implications of Building Control Act, especially the technical assessment process.

The impact of European Union policies and regulations on the building industry over the last decade has been considerable. Legislation in the areas of Building Control, Planning and Health & Safety, alongside the ongoing development of EU standards and other codes of practice, continue to inform and control an ever more complex legislative environment.

The EU Energy Performance of Buildings Directive (EPBD) requires the development of energy calculation methodologies and EPBD certificates of energy performance. Building Energy Rating (BER) and Dwelling Energy Assessment Procedure (DEAP) energy performance assessment have been developed in response to this, while Building Regulations have been revised to include for higher energy performance of buildings and renovations. All these developments require additional technical training.

The Bologna Declaration (1999) recognises that European higher education systems face common internal and external challenges related to the growth and diversification of higher education. Its goal is to create, by 2010, a European space for higher education in order to enhance the employability and mobility of citizens, and to increase the international competitiveness of European higher education.

Its objectives are the adoption of a common framework of readable and comparable degrees and the introduction of undergraduate and post-graduate levels in all countries, with first degrees no shorter than 3 years with ECTS-compatible credit systems

With the changing nature of building procurement and construction systems in recent years, some graduates have established architectural technology consultancy practices which offer technical consultancy services to architects in areas ranging from fire engineering and energy design to technical design and information pack-

ages. Opportunities exist for the development of technical design consultancies with the proposed new academic programmes aiming to address this need.

As a result of this, the intended outcomes are to:

- Engage critically and collaboratively with the architect in the building design process, using knowledge and understanding of historical and contemporary developments in architecture and architectural technology, with an understanding of the architectural design process.
- Engage critically with structural, mechanical, electrical, fire, acoustic and other engineering disciplines, applying knowledge and understanding of engineering design in the management and coordination of consultant design input in the building design process (ibid).
- Engage critically with cost control consultants, applying knowledge and understanding of cost measurement, quantification and control, and the role of the QS in monitoring the cost impact of technical design decisions in the building design process (ibid).
- Engage critically with domestic and nominated specialist design sub contractors, using an understanding of design and construction procurement processes and contracts in the management and coordination of contractor design input at post tender and construction stages of the building design process (ibid).
- Engage critically with the building contractor in the building design and construction process, using understanding of site practice and procedures and of building contracts (ibid). No other institution is offering this degree of critical engagement at the moment in an official capacity, while many are seeking to address this new

development soon. Also it should be noted that only within the technologist field is there the wherewithal or the ability to dovetail all the above mentioned collaborations in a meaningful way. Sure enough a hierarchical management structure can supervise the process but having this intricate interaction with the other disciplines is the technologist's domain.

2.2 BIM at DIT

The application of these aims is then further developed into modules for the delivery of the course content. The course modules are intended to run over the latter three years of the four year undergraduate programme. There is a progressive and comprehensive build-up to the graduate's education, which structures the exposure and presupposes achievable outcomes so that the levels are realised in tandem with the student's studio work.

Module 1 aims to develop the learners understanding of the role of the architectural technologist on the design team, using the building model to explore the collaborative roles of the architect, technologist, structural engineer, mechanical & electrical engineer and QS in the building design process.

The learning outcomes are that the digital model is used to develop the architectural design in collaboration with the architect/architectural student, that it is used to coordinate engineering design input in collaboration with the structural and mechanical & electrical engineer/engineering student, and that it is used to coordinate cost control input in collaboration with the QS/QS student.

The design process is to compare and contrast the roles of the architectural technologist, architect, engineer, quantity surveyor on the design team, and to participate in design team meetings playing a technical design development and coordination role

Module 2 aims to develop the learners understanding of the role of the architectural technologist in the construction process, using the building model to explore the input of the specialist design sub contractor / fabricator and construction manager in the building design and construction process.

The learning outcomes are to demonstrate an understanding of interoperability, to use the digital model to coordinate sub contractor design input and to use the digital model to extract and elaborate construction detail in collaboration with the construction manager/construction management student.

The construction process is to compare and contrast the design roles of the design team and the roles of the domestic, nominated, specialist and design subcontractor and building contractor, to describe the sequence of principal events in the design and construction of a building, to compare and contrast traditional subcontractor drawing development coordination systems with BIM, and to participate in construction team meetings playing a technical design coordination role

Module 3 aims to develop the learners understanding of the use of BIM on facilities management, post-construction measurement and geomatic data integration using a variety of related software applications. The learning outcomes are that on completion of this module, the learner will be able to use BIM for building energy performance analysis, to compare and contrast the roles of the architectural technologist and the geomatics surveyor, and to participate in construction team meetings playing a technical design coordination role (*Part A - Self Study*, 2009).

2.3 PG Cert Applied Architectural Technology

The PG Cert aims to develop and deepen the learner's sense of professionalism, building on their undergraduate learning and their experience in practice, and provide the opportunity to plan

career development and prepare for further study in areas of architectural technology specialism.

The aim of the Construction Legislation module is to develop and deepen the learner's understanding of construction legislation, regulations, codes and standards, building on their undergraduate learning and their experience of construction legislation in practice.

The aim of the Regulations in Practice module is to develop and deepen the learner's understanding of the building regulations in general, and the areas of fire safety, universal design, and sustainable design in particular, building on their undergraduate learning and their experience of building legislation in practice.

The aim of the Procurement and Contracts module is to develop and deepen the learner's understanding of the building procurement process and the use and application of building contracts, building on their undergraduate learning and their experience of construction legislation in practice.

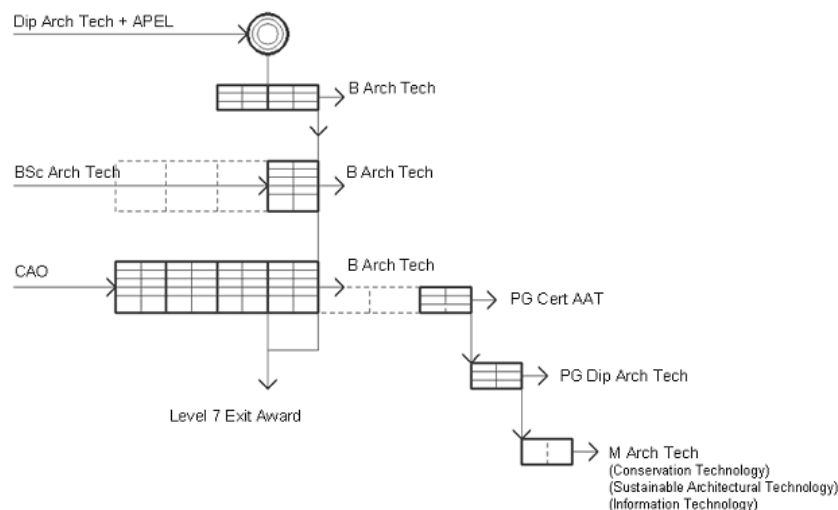
The aim of the Management & Quality module is to develop and deepen the learner's understanding of the various management processes involved in the practice of architectural technol-

ogy, building on their undergraduate learning and their experience of construction legislation in practice (Postgraduate Certificate in Applied Architectural Technology, Part B - Dublin School of Architecture January 2009).

Generally it can be seen that the modules mimic and duplicate the Professional Practical (Part III) exam for architects. A new post has been advertised and filled for a senior lecturer to run both courses with what seems to be identical content. The only difference is that the architect will complete this after a minimum of three (bachelor) plus two (currently a diploma) with one year practical training and two years professional practice (i.e. 8 years), whereas the technologist will require an extra year in total (9)".

These are significant changes and developments in the course structure. Likewise it also shows a definite tendency to position the technologist in a more professional light. In Spain the *arquitecto* and the *tecnico* sign construction contracts jointly. In The Netherlands certain master's courses allow technologists to become registered architects. Many countries have technologists that go on to complete an architectural qualification but many IATGN members see this

Figure 2. Department of Architectural Technology (DIT): Planned programmes.



as a damning compromise and a general disservice to technologists.

The course content also reflects the growing importance of BIM as a procurement tool.

2.4 Design and Procurement

Requests for information arise because of inadequate documentation and drawings in the first place. Christopher Alexander (Notes on the Synthesis of Form, 1964) describes three scenarios of designing content and form. The first being in unselfconscious societies where the building process has not changed through many generations and the content relates directly to the form, since the person building it lives in it where the community has established workable solutions. The second happens when artisans or craftsmen emerge to do specific tasks within the community. It is not their house so repairs and chances for mistakes become possible.

This is not due to any lack of quality in the work but because of an increase in the magnitude and complexity of the work. This is a semi-conscious state and the way the work is done with an image of the content required together with an image of the form delivered. The last scenario is a formalisation of this process where the images are formalised (a formal image of content and a formal image of form) so that they can be better recognised and controlled. This is a fully conscious state and the building industry essentially endorses this method with formal procedures for checking and controlling the work that procures a house or whatever.

This can be seen with the various parties working together to produce a building. Previously light tables would be used to correlate the various tasks, or overlays of digital drawings could provide a method for formalising the process being undertaken. But the light table does not even feature in the cartoon industry today and like the balls of twine that QS's used to take off measurement are long consigned to the trash can. More common is

the emergence of technical meetings now occurring on site, often in parallel with the architect's site visit, but chaired and run by technologists. These usually comprise of the subcontractor and the technologist who puts work into context, as well as the sequence and first/second fixes required to complete the work.

This avoids witnessing such situations of a bracing member finishing up one meter inside an external wall because nobody told anybody what to do, where it was done knowing full well that there would be extras to rectify the error. Also complete facade panels being delivered on site and mounted where the openable lights clashed with the position of the stepped back columns, meaning they were unopenable. These meetings avoid the need for rework and try to keep everything up to speed and on time, if there is a critical time path. But this happens on site and increasingly the model can resolve these situations earlier in the studio. This situation also highlights the demise of the architect/clerk of works relationship.

The paradigm in modelling came when an acceptable method was found for sharing or distributing data. It allowed ownership or more importantly intellectual rights to be retained by the various design team members' work, while allowing them to remain stakeholders in the project. This cannot be underestimated. Its motto is to do the work in one place and only once, no more checking, cross checking, and red-lining other consultants' drawings in the traditional method but rather having an open source know-how which is not compromised with fears of one expert being undermined by another or lumbered with finding component collisions later in the procurement process, on site for instance.

This has now moved the debate further in that the stake-holdings (of ownership) in the model have a requirement for overall co-ordination. There is a need for the management of the sharing, integration and tracking as well as maintaining the datasets which Jonassen (2005) sees as a rather awesome endeavour. The situation is

poised for the introduction of the BIM manager. There will be a need for overall management and leadership but where it will come from is now the major issue for all concerned. If the model is to be hawked from one discipline to the other then where is the co-ordination? Who ensures that it is kept functional, or merely operational, for want of a better word?

Under traditional project procurement, other disciplines in the design team could be reluctant to get involved above and beyond basic and initial observations before the architect had substantially formed the building. This was so for many reasons, primarily because it would be abortive work if the architect made a litany of changes, which was often the perceived case. Generally the other team members were there at this stage to ensure that space was allocated for when they got involved at a less turbulent stage. Typically, this would mean a structural engineer staking a need for a certain size ceiling void for the placement of structural members together with a service engineer who would place all ducting and pipework in the same void. This was seen as an appropriate level of involvement at this time and was seen as adequate cover for their involvement later. There is a professional language and protocol at work. Traditionally too this led to exactly where problems occurred on site when there had not been thorough cross checking of the various disciplines' work to avoid such errors. The effect of this initial approach meant that it could occupy much of the remaining (project) time being resolved.

To alleviate this problem the various disciplines often shared their drawing files so that overlays and references could be checked and rechecked by the differing parties. However, the problem with this was that only those areas which had been drawn could be checked. If a difficult part of the building had not been fully drawn then it could not be fully assessed or resolved until it came to light, often on site, leading to additional instructions, delays and counter claims.

This applies equally to more straightforward

parts where the fault was not so obvious. Generally the experienced practitioner learnt this through hard won knowledge from previous projects; it was a 'learn-as-you-go' scenario that came at a price the industry has been happy to pay to date. Also it could only be tolerated on projects following a similar vein. New ground heralded a new battle field, with all that entailed.

Young, Jones and Bernstein (2008) see the value in BIM being the integration of the tools and the process. The AGC BIM Forum (*BIMForum.org - home*) sees this as a dichotomy where the individual users are identified as 'lonely BIM' as opposed to the IPD practitioners which it calls 'social BIM'.

BIM has intelligent objects and distributing them makes sense. Authoring tools allows design to be embedded, construction to be sequenced, and scheduling to be broken down into elemental works; while a costing model can be implemented, fabrication can soon replace traditional shop drawings and ultimately an operational model can be handed over to the client. While Young et al (2008) see architects rejuvenating themselves as the main drivers of BIM with 40%, contract managers and general contractors come in at second on 18% with a combination of both at 14%. Owners are next at 13%. However, this is the current situation. It remains to be seen if architects can remain at the controls.

2.5 Project Certainty

On a project in Hong Kong (Fong, 2007), the developer saw things differently. The project is Swire Tower at One Island East and here the technology has both aided the building process, while acting and giving feedback, as the lower floors have risen above the busy city streets.

"The design and procurement methods being used on the job represent a full integration of information into a single 3D Building Information Model. This 3D database is being used simulta-

neously to coordinate architectural, structural and mechanical design information. As well as producing detailed project specifications for cost estimation and construction scheduling... (it discovered) ...close to 2000 clashes leading to a cost saving of close to \$13 million. The contractor is updating the virtual model as the building is being constructed, so that the model can be used for operations and maintenance once the construction is completed”.

For the developers it was about project “certainty”, knowing what was going to be built and at what cost. While this certainty gave control back to the architect, it was the client who is instrumental in the procurement method (Fong 2007). Aouad (2004) noted many trends against BIM adoption in Hong Kong and they are worth naming as they surmise the general thinking at the time. They included that there was no perceived need to produce BIM, existing CAD systems were adequate, BIM would not reduce draughting time as it was not flexible enough, it was not required by clients, and finally it was not required by other team members. (*Papers: The utilisation of building information ... [paper 2005/8], 2005*).

Comparing this to the McGraw-Hill Smart Market Report on Interoperability (‘Young, ‘Jones, & ‘Bernstein, 2007) a mere three years later there are stark differences. Under factors influencing BIM, 68% believe that there is less draughting, 49% cite client demand, 47% improved communication and out of nowhere comes code checking at 25%. There are many others but the remainder of this chapter will focus on code checking and its implications. This will also impact on client demands and hopefully make the case for the new technology.

There are many causes for this and prime among them was the American Institutes of Architects (AIA) national convention in Las Vegas in September 2005 where Thom Mayne (Strong, 2005) said the immortal words: *“If you want to survive, you’re going to change; if you don’t, you’re*

going to perish. It’s as simple as that”. The AIA championed Integrated Practice, Interoperability and Integrated Project Delivery, which are all variants of the same thing; collaboration. The other significant fact was that when Autodesk acquired Revit which Chuck Eastman claims had the same effect as legitimising BIM.

3 MAIN FOCUS

An allegorical tale is of a student, returning from practical training, at a young practice that had recently won a provincial town competition for a new public building in the town square. Essentially it had no right angles and the municipality made it a priority that there was complete disabled access in the winning scheme. In the first instance it was modelled in Sketch-Up to satisfy the architects that the new situation met with their design criteria. This demonstrated a good knowledge of the relevant building regulations and their application. Then it was modelled in ADT in order to demonstrate to the structural engineers that their A4 key junctions worked precisely where they had been chosen but failed when the section line was moved a mere meter up or down.

Close collaboration with the engineer ensured a pin jointed solution could be employed resolving key parts of the building in the studio and not on site had the errors not been highlighted when they were. This was one of the reasons for the school’s change to a modelling basis soon afterwards, in an attempt to minimise the number of programmes students’ needed to master. It is also an example of the technologist understanding both discipline’s modes of working and responding appropriately to both. Finally, it illustrated client requirements being assimilated and the solution being fittingly presented, by the technologist (student).

Another factor, parallel to this legitimisation process, was that computers were providing a means of building previously unbuildable works for architects like Frank Gehry (*DIGITAL PROJ-*

ECT-frank gehry.). He set up Gehry Technologies (GT) to realise his unique forms.

Two consecutive projects are the Walt Disney Concert Hall in Los Angeles and the Guggenheim Museum in Bilbao. With regard to the concert hall, Gehry found himself beset with cost overruns and the project was shelved for a period due to lack of funding. It finally cost an estimated \$274 m. which is more than five times the \$50 m. budget at the start of the job.

In this situation Gehry has said that his position went from having the parental role at the start of the project where he was in control, to an infantile one when cost overruns threatened to scupper it. He says: *"...then the construction people say just that: we know what to do - straighten out a few things - we'll get it on budget. Of course the owner finds himself very confused about this..."*, and the focus moves from the architect to the contractor. The architect has lost face in the eyes of the owner and the contractor is now seen as the saviour, if the building is to be realised. He goes on to cite that: *"in our time you have the Sydney Opera House where poor Jørn Utzon gets clobbered. It's a horrible story. It practically destroyed the man's life"*.

Conversely, when tendering came about for the Guggenheim Museum in Bilbao, GT sent a member of staff over to Bilbao to train the bidders in the software prior to tender, to show them how to extract the quantities of this complex building where not one piece of steel is the same. This was pretty unique in 2004. The result was that *"...they came in 18% under budget on just the steel alone. There were six bidders and the spread between them was 1%. Now that is knockout, rare, you don't ever get that"* said Gehry seeing more than a fifth being knocked of the budgeted estimate.

In the Walt Disney instance, not having the model and being forced to overlay 2D drawings to collaborate contributes to massive cost overruns. In the Guggenheim instance, making the data available removes error and the need for

contingencies because of the complexity of the building. This heralded a new dawn for Gehry where he now uses selective tendering, and to qualify he insists on their software being used and bidders learning how to use it and the virtual model to extract quantities. This has put him back in charge, restored him to the parental role in his dealings with clients, now that he can more precisely control the process. The intelligent model (BIM) has done this for him.

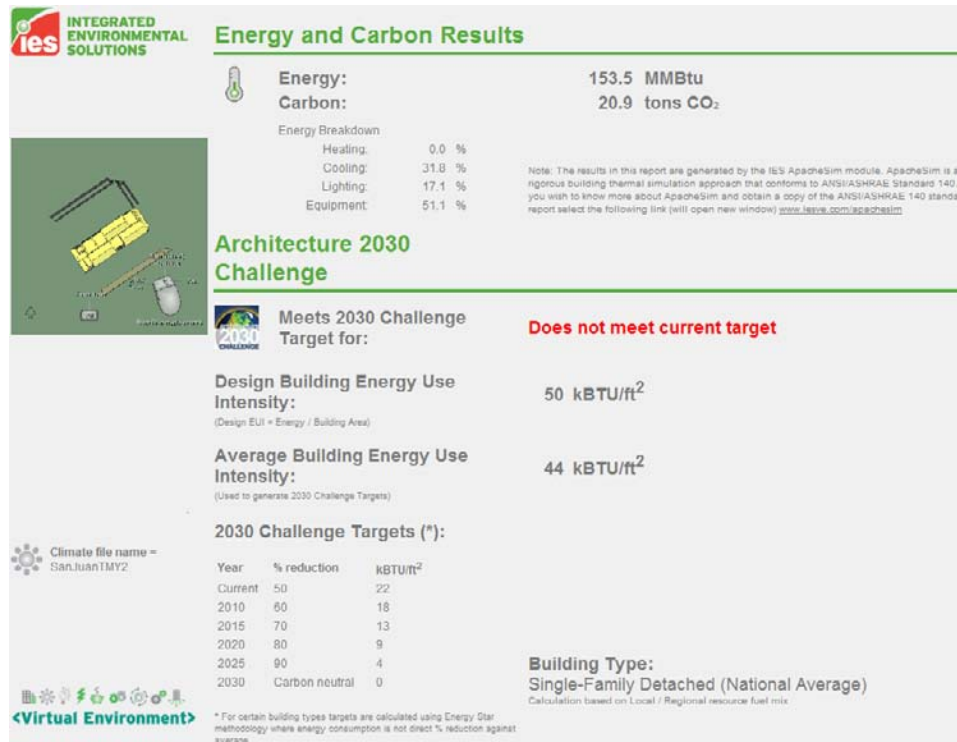
From the evangelistic viewpoint this is the clarion call, but from the practical position there are many other issues. Primarily there is ownership. Who will own the model, who will manage the model, and who will co-ordinate the model's passage through its turbulent growth. In the Gehry case it is a star architect and in such lofty situations those choosing or succeeding to work with him have identified this type of work and accept its challenge.

In a more standard situation there is also the temperament of the disciplines concerning when they want to get involved. Many firms have broached this new technology inhouse and are reaping the rewards inhouse. There is still a reluctance to share the model. That said the output is often shared but this is in the form of overlays not inner access to the crown jewels. This also manifests where there is no common software base. The Industry Foundation Classes (IFC's) were developed to eliminate cross platform translations but simple tests of translating the most elementary model objects show that this is far from satisfactory.

Sustainability

Recent publications from the EU have made it clear that concerted efforts to cut carbon emissions are crucial to the future of economic and social sustainability of the region. While there is broad agreement in principle, practice is entirely another matter. The sheer amount of data and the

Figure 3. Quantative Result of whether an ongoing design meets criteria or not during design proposals (does not meet current target- red text). Generated report by IES -ve software



shear spread of influence is enough to scare even the sincerest practitioner. Thankfully a rack of solutions are making this task a little easier.

In initiatives like 2030 Challenge and 2010 Imperative, the scientists have set goals and the politicians deadlines which make the problem more manageable. Categories and weightings have been established (including energy, water, surface water, materials, waste, pollution, well being, management and site ecology) in which ratings can be drawn. These then give an indication of how successful the exercise has been, carbon-neutral being the highest of six results.

These nine categories are broken down to credits (energy is 36.4%), and 90 out of the 100 achieves the highest score. So far so good, except that researchers are falling over themselves to provide toolkits to calculate these categories and the waters are becoming muddied again. However, of the list one British Research Establishment

Environmental Assessment Method (BREEAM in the UK) stands out.

Analysis software that produces BREEAM reports can use the building information model to give quantifiable results. This has significant appeal. The Netherlands are now considering adopting BREEAM and Denmark is also seriously looking at the situation. This means that the model can provide information about compliance, and also provide a place where experimentation with values (insulation for example) can quickly render results. Changes to the model are reflected in the reports and there is a seamless interface were the toolkits plug directly into the modelling programme.

This is code checking in practice. The University of Applied Science in Berlin is using modelling and analysis software in the studio to inform the process of the design in an ongoing, way while interrogating the model with 'what-if'

scenarios and achieving sustainable solutions with scientific results.

David Conover describes buildingSMART as a concept which is the opposite of building dumb (Conover, n.d.a; Conover, n.d.b). He looks at automated code compliance looking at model codes, standards, and federal, state and local regulations that are based on those documents, working towards;

“...seamless communication between public and private sectors through building smart using smart codes,

“...the delivery of better and more efficient public services and enhanced public safety,

“...more timely and accurate approval and validation of design, construction and continued use”

“...who wouldn't like to get a building permit in a day or approval?”

Checking then involves testing each piece of code with the instance. Three results are possible; first is that it is not applicable, second that it is exempt, and lastly that it is required and so passes (Conover, n.d.a; Conover, n.d.b).

A confidential memorandum between an international well known architect and their local enablers (a large well established national firm) notes *“that the best way to exchange information for co-ordination is as ‘dumb’ geometry”* and that ‘X’ and ‘Y’ *“will experiment with exchange of files with differing file formats to determine the best method of exchange”*. This high level low level solution is akin to the slide rule analogy of computers by Chuck Eastman, who said *“... it (BIM) is a big a leap forward from convention CAD as a computer is from a slide rule.*

4 FUTURE TRENDS

So if the pressure is not coming from within then what will drive the changes? Clients were instrumental in the DWG format being adopted as deliverables more than twenty years ago, and they appear in the factors influencing BIM as having 49% influence. Code checking's appearance at 25% in the McGraw-Hill Report on Interoperability is significant in that there was not widespread checking then, so it must be determined as a ‘wish-list’ item (‘Young et al., 2007).

Pazlar & Turk (2008) found that moving a simple wall in and out several programmes led to data being dropped. Typically, a field would have no corresponding field in the new format and if not critical would be dropped. On passing back that field would be voided. Even using IFCs evidence was shown that all export functions were not supported. It could be as innocent as the wall hatch or pattern being lost in a vertical section, but even so it meant that the operator had to be vigilant *“not blindly trusting the mapping process”*.

Alan Baikie of Graphisoft argues in Building Design's 2008 World Architecture 100, an annual survey of the top architectural firms in the world, that larger firms are slower to invest heavily in terms of money, time and effort in their migration into the 3D realm, leaving the door open for nimbler firms (Littlefield 2008).

5 CONCLUSION

Many would say faced with this evidence that it is unbelievable that it has not been adopted in greater numbers. However, there are questions of ownership which latently must be having an effect. IPD outlines that the collaborative process demands full commitment from all parties but there is a certain amount of entrenchment from the professional disciplines towards engagement. Before each stakeholder in the supply chain makes

their contribution, there can be a stand-off, with the misconceived view of avoiding abortive work.

It is seen as a baton passing exercise where there are sign-offs at each work stage so that there is a finite body of work to be tackled by the remaining team members. It harks back to traditional methods and without a custodian or manager it is stagnating. Confidence has not been established and more showcase projects are needed. With a defined role of adjunct manager the situation can be reversed.

This coupled with the work that educational institutes are doing to produce technologists, leads me to believe that they will be the custodians of this new idea. This can be seen already with Frank Gehry who has established Gehry Technologies, an independent holding company that provides an indispensable service for him but who also act on their own as can be seen with Swire properties in Hong Kong.

Project certainty was an issue for the Swire Tower. GT became the BIM process consultant for this project and used their expertise to create the model prior to construction. The contractor updated the model as the building was constructed, so that the model could be used for operations and maintenance when the building was completed.

Finally, sustainability with its need for indicators is fostering a code checking environment to deem compatibility in the carbon neutral race. Coupled with code checking of building regulations and all related laws which can be codified or enumerated, this is leading to a beach head where clients will demand the today building permit over the typical three month turn-a-round often experienced by the conventional method. Clients like certainty and will drive this cause. The latent uptake by the professionals can be alleviated by the adjunct manager, a role which can be fulfilled by the technologist, who has the unique ability to understand the professional languages of all or most of the stakeholders, together with the know-how gleaned from an intimate knowledge of the model. They are trained to know what each

profession does and they are trained to know what each project needs from the other professionals.

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KEY TERMS AND DEFINITIONS

BIM: Building Information Modelling is a method of procuring a construction project through the use of a common model, or a visualised database.

IPD: Integrated Project Delivery is the collaboration of all stake holders in a project working together as a team and sharing data so as to minimise duplication in its reuse and to facilitate exchange

Technologist: The (Architectural) Technologist is a new profession growing out of the technician's role but with wider skills and deeper knowledge of building procurement, construction management and collaborative methods

Code Checking: Code checking is a digital method that can interrogate the model's database and using analysis tools can robustly establish model compliance with statutory legislation, local planning and building regulations as well as

sustainable targets. It requires writing all rules and regulations into machine readable code which is then applied to the digital model. A report is generated or non-compliance highlighted for remedial attention

Sustainability: Sustainability is a performance demand for environmentally friendly buildings. There is a target requirement of achieving carbon neutral buildings in the very near future with quantifiable data

Model Management: Model management is the ability of sharing and integrating data while tracking and maintaining the data flow across many disciplines and from inception of the project to decommissioning of the building

Authoring Tools: Authoring tools are the means used to build the information model.

Analysis Tools: Analysis tools are the means used to interrogate the virtual model to check for compliance and highlight areas for remedial action

Chapter 25

Design and Evaluation of an Integrated Design Practice Course in the Curriculum of Architecture

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ABSTRACT

The architecture, engineering and construction (AEC) domain is moving to a new kind of practice. Professionals are leaving the traditional way of design - engineering projects delivery and moving to a more integrated one. The implications of this initiative have started to appear in the curriculum of construction and architecture schools as well. This chapter presents the design and evaluation of an elective undergraduate course which aims to convey both the theoretical and practical principles of integrated design. This course has been designed for the curriculum of architecture to replace the Computer Aided Design and Drafting course, in which traditional 2-dimensional drafting used to be taught. In this new course, students tried to deliver a design project collaboratively by exchanging data between selected applications. Although some technical problems have occurred, the case studies have proved that integrated design is possible using the latest improvements in the Information and Communication Technologies (ICT) domain. The evaluation of the course has also revealed various barriers related to implementing integrated design principles at educational programs.

1 INTRODUCTION

Information and communication technologies (ICT) have been affecting the way we conduct business. Many industries have redefined their processes within the last couple of decades as a result of this. The construction industry and its related businesses

are also under the pressure of using new digital mediums more efficiently. Design and construction projects now have the opportunity to be delivered in a more integrated manner as the new ICT tools begin to proliferate within the industry. Clients and owners are pressurizing the project participants to deliver a more integrated practice. It has become evident that integration promises to make the design,

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construction and operation of buildings much more streamlined and efficient.

In spite of these rapid changes, training related issues are considered to be one of the important barriers that impede the delivery of projects in a more integrated manner. Eastman et al. (2008, p.300) and Sacks and Barack (2009) explained that the current lack of trained personnel remains a barrier to achieve a more integrated practice within the construction industry. In a more detailed survey, Kunz and Gilligan (2007) tried to measure the benefits of Building Information Modeling (BIM) use and factors that contribute to its success. The results indicate that management support, training and the availability of staff are the biggest value-adders. It has been found out that lack of training, staff and software are among the main impediments of creating a more collaborative project delivery platform. Hartman and Fischer (2008) conducted a similar survey and identified that there is a lack of knowledgeable practitioners who could move the industry into the new age. They have concluded that AEC industry and companies need to establish far reaching education and training programs.

In order to adapt to this new situation, the educational institutions need to make the necessary changes in their curriculum and teach the up-to-date information. The professional life now demands university graduates to be more capable in using the latest ICT tools more than ever in order to deliver more effective projects in terms of time, cost, quality and satisfaction. Some of the schools have now included courses in related topics in order to promote the idea of the Integrated Project Delivery. As Cheng (2005) states there is an urgent and immediate need for architectural education to prepare future practitioners who will catalyze this change.

In the last couple of years, there have been a number of research projects that aimed to demonstrate that the concept of integration is working (Kam et al., 2003; Kam and Fischer, 2004; Plume and Mitchell, 2005; Tanyer and Aouad, 2005;

Plume and Mitchell, 2007; Mitchell et al., 2007). Moreover, as Sacks and Barack (2009) state the benefits of integrated project models have been researched and measured in architectural practice (Birx, 2005), in structural engineering (Sacks and Barak 2008), in construction (Khanzode et al., 2005) and in fabrication detailing (Sacks et al., 2005). In these projects, researchers have tested the capacity of the international data standards with case studies and recorded the strengths and weaknesses of the technical issues along the process. Although many efforts record the technical and practical effects of integrated practice, very few research efforts are available to record the requirements and consequences of the integrated design practice from the curriculum perspective of educational institutions.

This chapter presents some of the major challenges and opportunities that 'integrated design practice' presents in architectural educational settings. The need and evaluation of an undergraduate elective course has been presented in this context. The chapter starts with a short history of computing in the architecture curricula. Next, integrated design practice is defined and main approaches to integration are explained. The last section explains the development and evaluation of an undergraduate elective course in which the theoretical and practical aspects of integrated design has been taught.

2 COMPUTING IN THE ARCHITECTURE CURRICULA

Computers have entered the architectural schools more than a couple of decades now. In the first introductory years, a number of schools were experimenting with computers and there was not a systematic teaching framework (Pittman, 2005). During the last couple of decades modern *ICT tools* and *digital media* have been fully adopted by the discipline and profession of architecture (QaQish and Hanna; 1997). As a result of this, virtually

all architectural schools introduced computing classes. Today computers are an integral part of the studio education and students are using several software applications in order to solve the design problem in hand.

As a response to the advances in the ICT domain, universities have preferred different approaches to the employment of CAD in the curriculum. Some preferred to include the CAD education as an integral part of the studio education whereas the majority prefers separate classes that teach CAD concepts. To evaluate computer utilization by architecture schools with regard to the curriculum structure, several researchers have done assessments regarding the aspects of computers involvement and integration. For example QaQish and Hanna (1997) have explored the integration of computer aided design and drafting (CAD) classes into architecture schools by examining its utilization across the curriculum of architecture in seven countries. This study has found out that around 92% of the schools have integrated CAD into their curriculum. Similar studies have been conducted by Penttilä (2002), Penttilä (2003) and El Shafie and Abd-Allah (2006). These studies have also demonstrated that the architecture schools are technically quite well equipped in the deployment of the ICT tools.

In spite of the high usage of the ICT tools within the profession and universities, the last couple of decades have seen enormous changes in the employment of the new technologies in the architecture education. Penttilä (2006) emphasized this transition and stressed that the profession of architecture has faced remarkable and thorough changes during the last few decades. Penttilä examines this transition in three main eras: i) Early 1980s, ii) Mid 1990s and iii) Early 2000s. 1980s are the last days of hand-drawing; namely the era before CAD. 1990s are the expansion of architectural CAD – the era of the digital drawing appearance. Finally, the 2000s are the era for integrated and pervasive web-supported digital design and the advent of Building Information Modeling.

There have been many research efforts examining the first two periods in the curriculum of architecture. Some researchers (e.g. Taşlı-Pektaş and Erkip, 2006; Çil and Pakdil, 2007) have evaluated the attitudes of students and design instructors to computerization. Also the use of new mediums in design studio classes has been researched by many (e.g. Çağdaş et al., 2000; Çolakoğlu and Yazar, 2007). In the last couple of years, researchers have been examining the implications of new ICTs (Sökmenoğlu and Çağdaş, 2006) and integrated work practices on architectural education as well. The movement from CAD to a more integrated work practice creates several challenges and opportunities for the architects, the profession of architecture and the education of architecture (Denzer and Hedges, 2008).

3 INTEGRATED DESIGN PRACTICE

The previous section has indicated that the introduction of digital design and Building Information Modeling has started a new era in order to manage the construction information more efficiently. This is closely related to the inefficiencies and waste in the construction industry which has been demonstrated by various reports in different countries. For example Teicholz (2004) stated that the labor productivity for the U.S construction industry has fallen 20% since 1964. On the other hand the productivity of non-farm industries has risen by 125%. Some financial figures have also been published by recent studies: According to a research carried out by the National Institute of Standards and Technology (NIST) in 2002, the lack of interoperability between various software applications costs the US construction industry \$15.8 billion annually (Gallaher et al., 2004). If this figure is compared with the 2002 annual expenditure of the US construction industry, which was \$374 billion, it is understood that around 4.2% of the project cost is wasted annually because of the interoperability problems between project

participants. According to another study titled *SmartMarket Report*, which was conducted by McGraw-Hill Construction Analytics (2007), interoperability costs add 3.1% to a typical project budget.

An effective integration between project team members is necessary in order to deliver projects more streamlined and efficiently. For this, project parties need to adapt themselves into a more collaborative way of working. A more integrated project delivery team could bring solutions to the long listed problems available within the construction industry. With recent advances in IT, many regard that substantial solutions could be found to transfer the industry to a more productive level.

3.1 Definition of “Integration”

Researchers have used many definitions to describe the term integration: Aouad (2000) gave the definition of *integration* as the ability to share information between different actors/disciplines using a common model developed within a sound and reliable framework. Vincent (1995) stated that the word *integration* became widely used to describe the desirable concept of freely exchanging information between different participants in the construction process. Sanvido and Medeiros (1990) described *integration* as a better use of electronic computers to integrate the management, planning, design, construction and operation of constructed facilities. According to Thorpe (1995), the ability to achieve wide-scale *integration* of construction information and data need to be established for more productive work. Björk (1999) explained that integration of different computing applications is used in the life cycle of a building. Designing with an integrated approach means, to exchange knowledge and work in collaboration with a multi-disciplinary team, from the consultant or specialist to the client or final occupant, working together aiming at developing a design that reaches mutual goals (Cadima, 2007).

More recently, the American Institute of Architects (AIA) has published several reports in order to promote the principles of *Integrated Project Delivery*. According to AIA (2007), integrated project delivery (IPD) is defined as follows:

A project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.

According to this definition, IPD is a new project delivery system, which requires a highly collaborative approach between project team members at a very early stage. IPD depends heavily on latest technologies, international data standards and interoperability between parties. While not necessary, Building Information Modeling (BIM) is a very important tool that can facilitate the integration between project parties.

3.2 Approaches to Integration

The first efforts of integration tried to integrate various off-the-shelf software applications, such as CAD, estimating and construction planning systems, in order to create seamless information flow between different parties. This method works quite well if there are limited number of software applications to be connected. However, as the number of software packages increases, the number of wrappers that has to be created also increases (Underwood and Alshaw, 1997).

The latest and biggest effort in achieving the integrated design medium is the *product modeling approach*. In this approach, the integration of computer applications is achieved through a *single data model*, where information is stored centrally and is accessible from all the parties. An integrated *data model* is a central repository system used for the storage of data and processes

required by various disciplines during the life cycle of a project. Ideally, each item of information should be entered by users and stored only once in a shared model. The client, designers, suppliers, contractors and external bodies should all have access to the same model. This approach, if implemented effectively, can have significant potentials in improving the overall design and construction processes.

Several research efforts have been carried out in order to achieve the “ultimate” data model that can capture the information related to the whole project life cycle stages. These efforts have well been reviewed by İlal (2007). As pointed out by İlal (2007), the need for an integrated design has been around for a couple of decades. But the computational environment to support this important process has been materialized only recently. Today the largest effort in the building industry is the standard data model created by the multinational organization called *buildingSMART International* (formerly International Alliance for Interoperability, IAI). This data model is called *Industry Foundation Classes (IFC)*. IFC cover the whole life cycle of project information and provide a mechanism to exchange data between various software applications available in the project life cycle. Most of the latest CAD packages support interoperability standards; therefore it is possible to exchange data freely between project participants.

3.3 Building Information Modeling (BIM)

An important aspect of the culture-change in the architecture - engineering - construction and facilities management (AEC-FM) industry is the *Building Information Modeling (BIM)* approach. BIM represents the process of generating and managing data throughout the life cycle of a building (Lee et al., 2006). In BIM, architects produce the 3D model of the product; the model is a database that exists in one file, unlike 2D

computer drafting, which will have one file per drawing, or more (Sacks et al., 2004). BIM is fundamentally different to computer-aided drawing in that it enables modeling of the form, function and behavior of building systems and components (Sacks et al., 2004).

BIM is considered as a new way of work by many. In order to adapt to this new work practice, many organizations are defining new processes. Statsbygg, acting on behalf of the Norwegian government as property manager and advisor in construction and property affairs, has recently announced that the participants of the new museum facility competition near Oslo must produce simple digital 3D-models/BIM (Statsbygg, 2009). The US and the Singapore Governments have developed automated code compliance checking mechanisms which allow architects to submit BIM based project models to the necessary approval bodies (Corenet, 2006; ICC, 2009). The BIM based project models could be evaluated online according to predefined regulations for buildings (e.g. fire escape, structural safety, etc.). The American Institute of Architects (AIA) has defined new contract types for integrated project delivery. US organization General Services Administration (GSA) announced that it would require all schematic design submittals to be in BIM format starting in 2006. The GSA has mandated the use of BIM not only for its immediate benefits of meeting schedules and controlling construction costs, but also for the long-term benefits of controlling building operating costs and limiting energy use (Khemlani, 2007). The Associated General Contractors of America has announced that a new BIM education program has just been released on April 6th, 2009 (AGC, 2009).

3.4 Integrated Design Principles at Educational Institutions

In order to meet the demands and challenges of professional life, the educational institutions must make the necessary adaptations. In fact, several

educational institutions have been guiding the research in the area of computer integration. As a result of these efforts, integrated practice has been incorporated into their curricula. This issue has become an important topic not only for the discipline of architecture but also for the disciplines of civil engineering, construction management and architectural technology.

Salazar et al. (2006) explained that at Worcester Polytechnic Institute, the concepts of BIM have been presented to the civil engineering students by two main courses. Sah and Cory (2008) explained the design of a new undergraduate course where a transition from the traditional 2D CAD to Building Information Modeling has been achieved. The results show that eighty-seven percent of the students felt confident using BIM for visualization. Ninety-four percent of students were appreciative of the fact that the coursework reflected the current practices. Mulva and Tisdell (2007) recorded the teaching experiences of BIM in the School of Architecture at the University of Kansas (Lawrence). The tool was also used effectively to teach planning, scheduling, and productivity concepts in other courses in the curriculum. They concluded that BIM is indeed a new frontier for construction education (Mulva and Tisdell, 2007). At Auburn University, currently two information technology skills courses are taught in the curriculum with the intention to expose students early in their academic careers to a variety of the technologies used in building construction (Liu and Hein, 2007). Auburn University introduced BIM by way of a one-week tutorial, followed by a semester-long introductory course (Taylor et al., 2008). The New Jersey Institute of Technology introduced BIM in various upper-level studio classes and use it as the main tool in a design studio (Rudesill, 2007).

In spite of these special cases, the extent of the education programs in this field is not very widespread throughout the world. In order to understand the extent of this new practice in schools' curricula Sabongi (2008) mailed a survey to all members of

the Associated Schools of Construction (construction management, construction science, building science or construction engineering) which offer four-year undergraduate programs. According to the results of this study, BIM is currently being addressed in only about 10% of undergraduate programs. Less than 1% responded that BIM is taught as a stand-alone course, while 9% said BIM is addressed as part of existing courses. Another study carried out by the BuildingSMART Alliance (BIMWiki, 2009) presents a survey of educational institutions that are involved in BIM research and teaching activities. The list contains 64 universities most of which are from the USA. The list may not be complete; however, it shows that there is a growing interest to the practice of integration.

The situation in the architecture schools is not very much different. Some universities are now teaching the principles of BIM in separate classes or as part of the design studio. Students can export their object-based CAD models to a wide variety of analysis software tools to conduct daylight, shading and thermal analyses. Plume and Mitchell (2005, 2007) report on such kind of a multi-disciplinary building design studio where a shared IFC (Industry Foundation Classes) building model was employed to support a collaborative design process in a studio-teaching environment. In similar projects, students from architecture, interior design, landscape architecture, mechanical engineering, environmental engineering, construction management and computer aided design departments worked together to provide optimum solution to a design problem. One of the main results of these studies was the interoperability problems among various software applications. Teams concluded that the data flow among the various required software are promising, yet still not mature enough.

4 DEVELOPING A NEW COURSE FOR INTEGRATED DESIGN PRACTICE

4.1 Course Content

As a response to the developments explained above, a new course has been designed at the Spring 2009 semester at Middle East Technical University (METU), Department of Architecture. The course currently serves as a technical elective with the title of “Computer Literacy in Architecture”. The main aim of the course is to introduce students the technical and practical issues related to the *integrated practice*. By the end of this course, students are expected to:

- Understand what integrated practice is
- Understand the techniques and technologies to achieve integrated practice
- Understand the concept of Building Information Modeling (BIM)
- Study and learn to use several BIM based software platforms
- Carry out a limited integrated design practice exercise

The course was not carried out like a design studio. On the other hand, there were several lectures, class and homework exercises for the students. Ten students, all of whom are from the third year level, have been registered for this twelve weeks course for the 2008 – 2009 Spring Semester. Throughout the semester, the students are required to produce object based CAD applications of a project (selected by them) as part of the class and homework exercises. As a result of this, each student has gained enough knowledge to use several BIM based packages.

The course included 3 main modules. These modules are summarized as follows:

4.1.1 Module 1: Vision of Integrated Practice

The course started with the introduction of the problems of data and information sharing in the architecture – engineering – construction – facilities management (AEC-FM) industry. In the first part, typical life cycle stages of a construction process and the data exchange problems between these stages have been explained, and then studies explaining the cost of inadequate interoperability were discussed. After the demonstration of the current situation, ICT visions created by different organizations have been mentioned. Among these visions, the one created by Construct IT (Sarshar et al., 2002) have been explained in detail. This vision explains an integrated design and construction approach (model-driven project delivery) for the life cycle of construction projects. This module covers a 2 weeks period out of 12 weeks.

4.1.2 Module 2: Introduction to BIM Concepts

This module included lectures about integrated design practice and the concept of Building Information Modeling (BIM). The module started with the explanation of the differences between the CAD and the BIM approaches. Next, object-based modeling, object-instance-attribute concepts were explained to the students shortly. The module continued with the history of the product modeling concept and the data exchange standards such as Industry Foundation Classes (IFC). In the final part of the module, BIM case study projects have been demonstrated and some technical and cultural barriers of using the BIM approach have been explained to the students. This module covers a 2 weeks period out of 12 weeks.

4.1.3 Module 3: BIM Training

In the third module, the students are demonstrated some of the BIM packages available for content

creation. Each student has studied one of the software applications in detail and demonstrated the main functionalities to the rest of the class. Before this module, the students were not familiar with the demonstrated BIM applications extensively. This module covers a 5 weeks period out of 12 weeks. The module is divided into 3 sub packages.

CAD Packages Module

Today, some of the CAD packages are supporting the integrated design process through international data standards. Students can access the academic versions of these packages free of charge. These packages can produce 3-dimensional object based CAD data and therefore support the creation of the geometry part of the BIM data. Throughout the course, three students have explained BIM based CAD programs in detail. At the end of each session, there was a main homework such as producing one of their previous projects in these CAD programs. This module covers a 3 weeks period out of 12 weeks.

Energy Applications Module

This module introduced one of the mostly used energy analysis applications. By the help of this program it would be possible to carry out complex simulations in day lighting, acoustics, thermal and energy analysis, etc. By the help of this tool, the performance assessment of buildings could be carried out during the design process. In this module, 2 students have explained the day lighting and thermal comfort analyses to the rest of the class. This module covers a 2 weeks period out of 12 weeks.

4.2 Final Project: An Integrated Design Initiative

The last 3 weeks of the course was devoted to the final project of the course. For this, three groups were created out of the ten students and each group was assigned to carry out an integrated design initiative among the members. Each group has

selected one of their architectural design projects that they have created during their educational life. As the size of the groups were very small and as the groups were composed of only architecture students, the scope of the effort was kept very limited. As a result of this, each group was assigned the following tasks to complete using the BIM approach. In this process, the data between the group members were exchanged by the IFC format.

- Prepare the design using CAD-BIM package 1
- Model editing using CAD-BIM package 2
- Prepare the bill of quantities (BOQ) using CAD-BIM package 3
- Prepare the thermal simulation

The groups did not undertake these tasks extensively as this was an introductory course. For example, the thermal simulations were conducted for a single space instead of the whole building. The students monitored the process, recorded the advantages and disadvantages and provided their comments about how successful the results were.

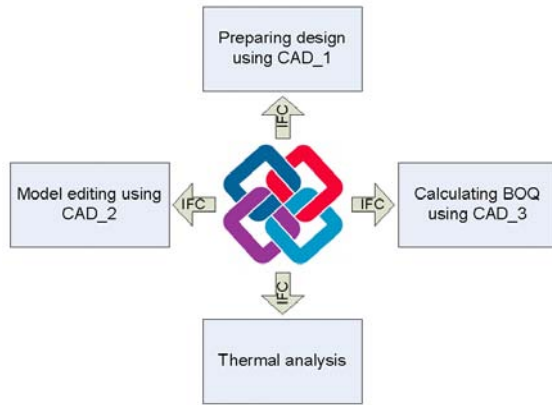
4.3 The Evaluation of the Course

A questionnaire has been prepared to evaluate the proposed course. After carrying out the integrated practice exercise, students were asked to fill in this questionnaire by which they have provided their opinions about the initiative. 10 students, who have been registered for the course, filled in the questionnaire. Later, a discussion has been carried out in order to explore the selected choices.

The questionnaire included topics in the following areas:

- evaluation of the curriculum,
- barriers to adapt “integrated practice” in the undergraduate education,

Figure 1. Content for the case studies



- evaluation of the technology,
- the future of the “integrated practice”,

4.3.1 Evaluation of the Curriculum

First, the students were asked about the support of the university curriculum in integrated practice. 9 out of 10 students believe that the curriculum of the department is not sufficient in supporting the integrated design practice (see Figure 2). Students have expressed the lack of courses in this area. The deficiency in the curriculum appears to be a major barrier in promoting this new way of project delivery (see Section 4.3.2).

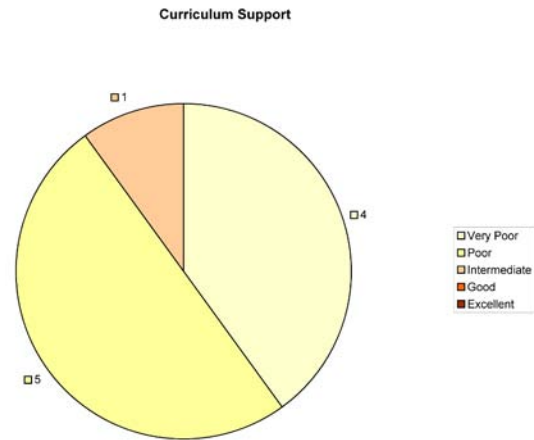
4.3.2 Barriers to Adapt “Integrated Practice” in the Undergraduate Education

In order to explore the issue further, students were asked about the factors that impede the implementation of integrated practice in the curriculum of architecture. The results are given in Figure 3 and explained under 2 main headings: i) issues related to the awareness of the topic, ii) issues related to the curriculum.

Issues Related to the Awareness of the Topic

9 out of 10 students agreed or strongly agreed that they have not been informed well enough about

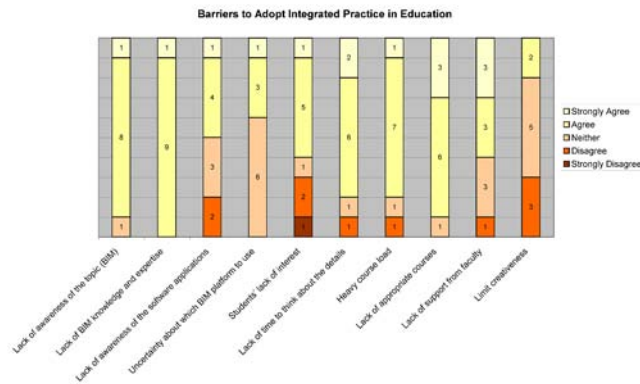
Figure 2. Curriculum support for integrated practice



the recent developments to conduct integrated design practice. As a result of this, students believe that they lack the necessary BIM knowledge and expertise. To illustrate, the students have explained that prior to this course they were not aware of what integrated practice is, why it was needed and what the concept of Building Information Modeling is. Students have heard about some of the software platforms (e.g. object based CAD platforms). However, they did not know that these applications, in fact, serve to the concept of integrated design practice. 4 out of 10 students have explained that there was an uncertainty among the students about choosing the most appropriate object based CAD platform at the beginning of the course. Finally, half of them stated that they did not know the software applications other than the BIM based CAD platforms. These issues prove that there is a lack of appropriate training programs in the Department which explains how best students can benefit from the integration.

In order to understand the platforms the students use in presenting the design ideas, the students were asked further questions (see Figure 4). The questionnaire demonstrated that all students, who have taken this course, feel very comfortable with 2D CAD applications. 8 out of

Figure 3. Barriers to adopt integrated practice at educational institutions



10 students also prefer to produce 3 dimensional CAD models from these 2D CAD drawings. 4 out of 10 students are using 3 dimensional visualization mediums (e.g. rendering programs) for presentation purposes. Finally, 7 students sometimes prefer to use object based CAD platforms for several courses (e.g. design studio, structural design and analysis courses, etc.).

Issues Related to the Curriculum

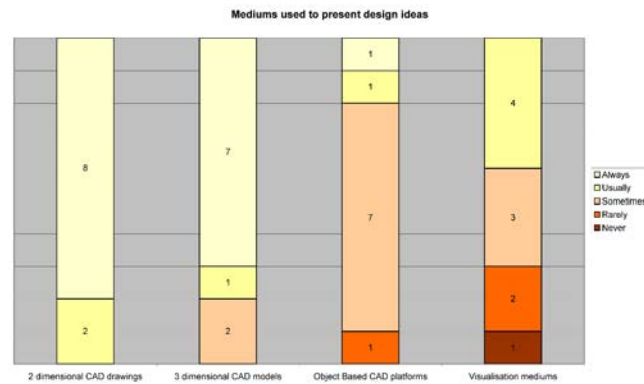
Next, curriculum related factors that impede the students to adopt integrated design practice were evaluated. Students have stated that (8 out of 10 students agreed or strongly agreed) they find it very difficult to think about the technical details that are required by integration during the studio education. At METU, the studio education includes term projects which take a maximum duration of 3 months. This duration may be reduced to 2 months if there is a warm-up exercise at the beginning of the term. In such a short period of time, students are mostly busy with deciding the new form and arranging some of the environmental issues such as the relationship of the project with the urban environment. Some of the issues (e.g. the structural integrity) are taught as an integral part of the design process. However, usually there are no detailed investigations or analyses about the structural integrity or the building performance

issues. Other than a few pioneering professional practice and construction courses, recent innovations in architectural education have largely focused on formal skills needed to succeed in design (Cheng, 2005).

Students believe that (8 out of 10 students agreed or strongly agreed) their course load provides a barrier in adopting an integrated practice approach in their educational system. As already mentioned in *Section 4.3.1 - Evaluation of the Curriculum*, the availability of an appropriate course that promotes integration is also important. 8 out of 10 students agreed or strongly agreed that the support from the faculty members is essential for learning the integrated design practice.

The new way of integrated work practice necessitates changes in the curriculum of institutions; but the exact nature of the shift is unclear (Cheng, 2005). There are arguments and counter-arguments that BIM could limit the creativeness of architecture students. For example, Cheng (2006) stated that in order to work collaboratively with a BIM application, the operator must have an understanding of the tool, knowledge of materials and construction methods, and appreciation for professional practice. Cheng (2005) points out that if BIM is introduced in the curriculum without respecting its considerable liabilities, design thinking will not survive. Seletsky (2006),

Figure 4. Computational mediums to present design ideas



on the other hand, states that BIM promotes more sophisticated ‘design thinking’ because it allows students simulate their decisions in validating—and not just positing—what they’re proposing, thus acting intuitively and analytically. According to the evaluation of the course, half of our students were neutral about the effect of BIM on creativeness. This might be because they haven’t used BIM based CAD platforms starting from the early stages of the design problem. Some stated that BIM based CAD tools would be more appropriate for the later stages of design where some design decisions such as form and materials have been materialized. In this context one comment is interesting (Balkanay, 2009):

I think the “integrated practice approach” does not limit creativeness or what you want to do during the design process. This practice gives architects the chance to try out various alternatives of the same design. For example, in previous semester, I tried to produce ‘the shadow diagram’ of the site for the studio project. I really studied hard for these calculations. On the other hand, if I had known this concept and the appropriate program that we used in this course, I would have eased my process.

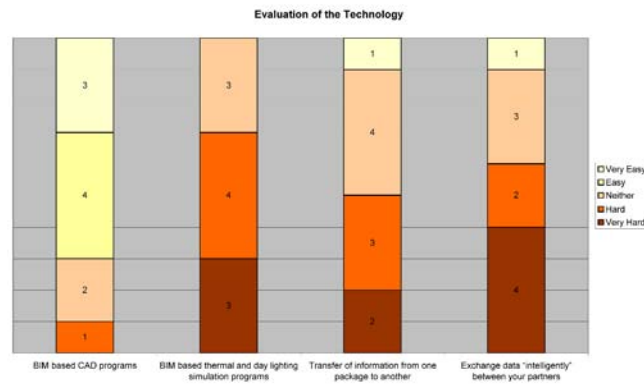
The views of our student are in line with the argument of Seletsky (2006). The integrated design approach supported by the BIM concept could have helped this student simulate her design decisions. There is a need for more detailed research that examines the capabilities of BIM programs and whether the inabilities that might be available in programs have any effect in the design process.

4.3.3 Evaluation of the Technology

The advantages and especially the problems of IFC based data exchange have been reviewed well by many researchers (Fischer and Kam, 2002; Kam et al., 2003; Kam and Fischer, 2004; Pazlar and Turk, 2008; Jeong et al., 2009). Contrary to these examples, this research did not aim to record each and every technical problem occurred during the evaluations process. On the other hand, it was aimed to capture the evaluations of the students about the new work practice.

In this part of the questionnaire, students were asked i) how easy it was to use the BIM based programs and ii) How easy it was to transfer data from one package to another. The results are depicted in Figure 5.

Figure 5. Evaluation of the technology



Ease of the Use of the BIM Based CAD Software

Due to their previous CAD knowledge, 7 out of 10 students have found that the use of the BIM based CAD programs is very easy or easy. Some authors (e.g. Eastman et al., 2008, p300; Sacks and Barack, 2009) explained that students can grasp BIM concepts and become more productive using BIM tools more quickly than they were with CAD tools. In our study, it has been observed that the CAD background of the students contributed in understanding the concepts of the BIM based CAD tools. Although the educational settings are different, this result is conflicting with Sacks and Barack's (2009) who stated that the civil engineering undergraduate students who had 2D CAD experience found it more difficult initially to learn the BIM tool than their counterparts who had never used CAD.

On the other hand, students have had difficulty in understanding the concepts available in the BIM based thermal and day lighting simulation program. In the second year, these students have taken a course titled "Environmental Design". However, the students have indicated that they have had difficulty in transferring the theoretical knowledge that they have taken in that class while using the analysis tool. Moreover, students have not used this kind of analysis tool before. As a

result of these, 4 out of 10 students have faced difficulties in using the analysis tools. This difficulty is closely related with how successfully the studio education is integrated with the courses in which structure and building performance related issues are taught.

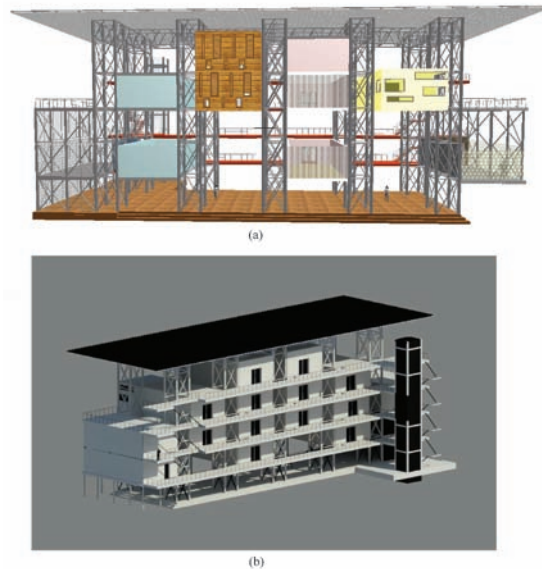
Ease of Data Exchange between Parties

All three groups stated that they have faced problems while they were transferring data between various packages. This section demonstrates some of these problems shortly.

Experiences of Group I. The project that Group I (Apak et al., 2009) presented was designed by Emine Kirman, Selim Niels Güner and Burcu Günay. The project is an art center located in Mersin. The building consists of open public space on the ground floor, exhibition area, official units, café, restaurant, library, lecture room, workshops, studios and audiovisual room.

Throughout the process, Group I observed that the size of the IFC file gets larger while the project file has been transferred between different BIM programs. This problem provided a barrier in carrying out thermal simulations effectively. On the other hand, Group I observed that the data exchange between different CAD packages is promising (see Figure 6-a and b). However, in order to have a better visualization, the group

Figure 6. Project models in two different BIM platforms



members have searched alternative IFC viewers in which they can view the project in its original material color.

The group members expressed that the import process have resulted many warnings and errors which they do not understand (see Figure 7-a and b). They have explained that they couldn't decide whether they need to fix these or not. Also they do not have any idea why these have happened.

Group I carried out the thermal simulation by exchanging the CAD data via the IFC approach. The Group carried out simulations related to the thermal gains and losses of the exhibition hall. As expected the thermal loss is higher in winter. However, direct solar gain could be increased if the direction of the building is changed (see Figure 8-a and b).

During the thermal simulation process, some problems, which are related to the usability of the simulation program, were noted by the students. The students stated that one can either import all the building elements or the spaces (zones) into the program. Importing all the building elements complicates the data management. In this case, it

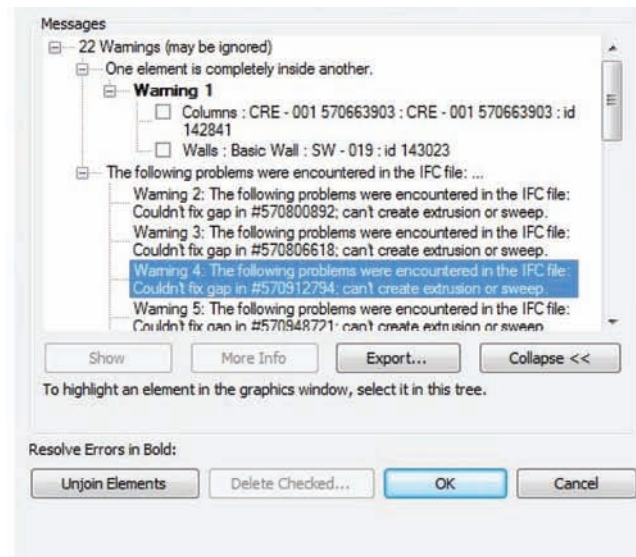
would be very difficult to identify specific zones. On the other hand, importing only the spaces provides much simple option. However, in this case, some necessary elements (e.g. doors and windows) are missing from the scene. Therefore, one needs to create these elements again.

Experiences of Group II. The project that was presented by Group II (Atıcı et al., 2009) was designed by Melike Atıcı as the first project of the fourth semester. The project was designed for the Prosteel Student Competition and consists of a library, conference hall and café (see Figure 9-a and b).

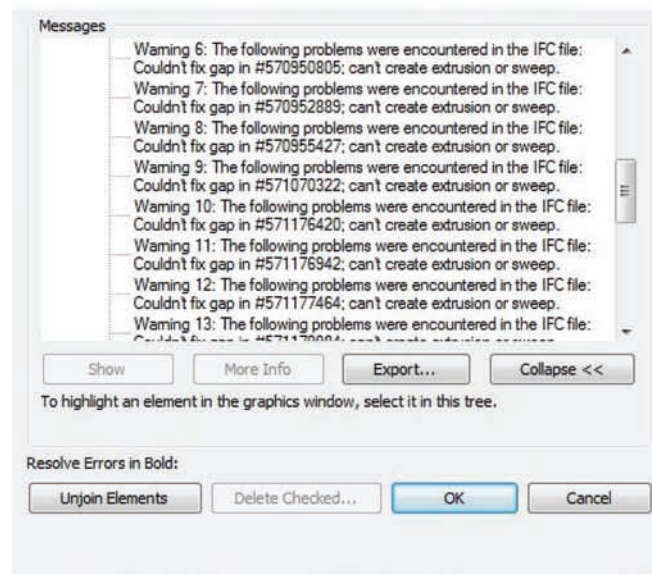
Group II faced problems in converting the IFC file between the CAD packages. Some of the elements (e.g. windows and the doors) are missing after the data exchange. Similar to Group I, Group II have stated that the import process produced many warnings and errors, which they do not understand (see Figure 7-a and b).

Group II carried out the thermal simulation by transferring the CAD data to an analysis program using the BIM approach. During the thermal comfort analysis, the group members used two different

Figure 7. Warnings and errors during the import



(a)



(b)

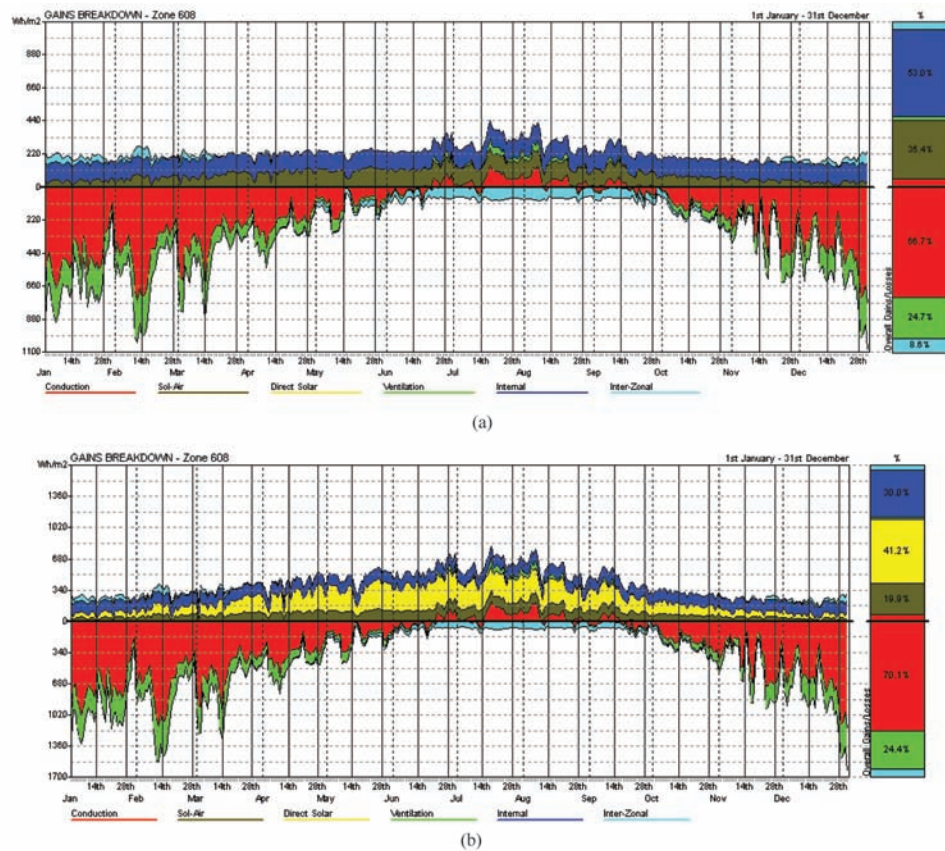
building materials to see the effects in one of the zones (see Figure 10-a and b). As expected, using a higher insulated material resulted a more stable temperature inside the analyzed zone.

Experiences of Group III. The project that Group III (Çelebi et al., 2009) presented was designed by Sertan Demirdağ as an apartment block which contains sixteen dwellings and

four souvenir shops. The Project is located in Istanbul and it was designed as a studio work (see Figure 11).

Group III stated that they could work collaboratively as a group using the concept of BIM. The main problem of the group was the misinterpretation of data in different CAD packages (see Figure 12-a and b).

Figure 8. Thermal gain/loss as calculated by the simulation program



Group III members tried to analyze the thermal comfort of one of the corner rooms facing north. They have analyzed the conditions using two different materials (see Figure 13-a and b). The analyzed zone provides a slightly better thermal result with Material A for January 1st.

Summary of Technical Evaluation

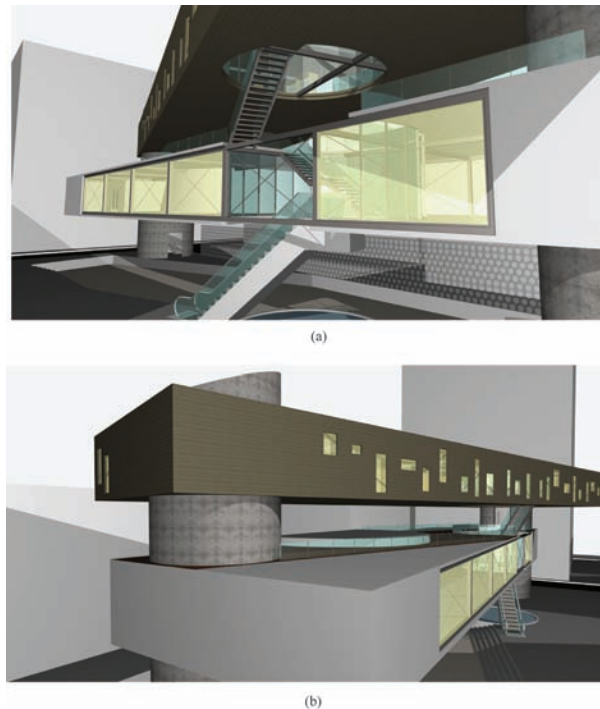
The inspection of all groups' feedback has revealed the technical problems and whether the effort was successful enough to carry out an integrated practice. In summary, the group members have observed the following technical problems:

- Large IFC file size prevented effective simulations

- Several warnings and mistakes occurred during the IFC import
- Missing objects after the data exchange
- Mistakes in interpreting the geometry data in different CAD packages
- Visualization problems after the data exchange due to material loss or rendering
- Difficulty to manage objects in the thermal analysis tool

In spite of these technical problems, all three groups stated that the BIM approach facilitates the collaborative design practice between different parties. They could exchange data 'intelligently' between the group members. None of the groups have faced problems with calculating the bill of

Figure 9. Project model as designed by the architect



quantities. The intelligent data exchange helped the group members carry out simulations at the early stages of the design. Although, some technical problems occurred, the final project has proved that the technology is promising and proved that the integrated design practice is possible. The scope of the effort was kept very limited due to the smallness of the groups. Future practices need to carry out similar projects with different project members and with wider scope.

4.3.4 Future of the “Integrated Practice”

The majority of the students (8 out of 10 students) agreed or strongly agreed that the application of “integrated project delivery” will continue to increase in the educational life as well as in the professional life (see Figure 14). The only disagreeing student stated that in spite of its many advantages, it is possible that integrated design practice will face up high resistance from the Government and

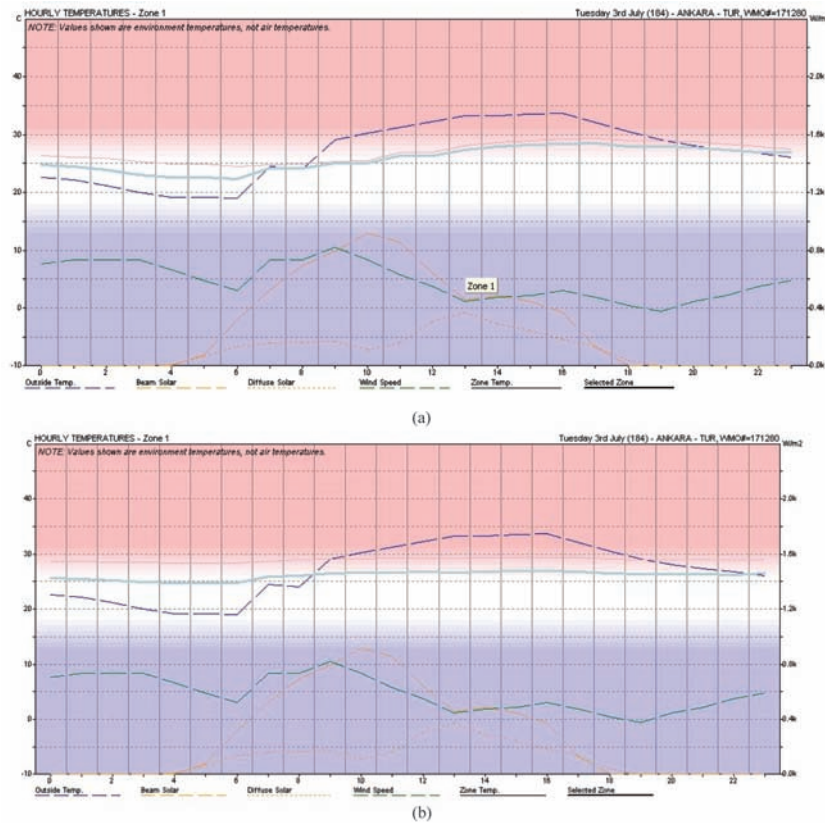
the professional bodies as this practice will create many ‘redundant’ employees.

Finally, it has been asked to the students what would be the best way to incorporate integrated design practice into the curriculum of architecture. Majority of the students think that this could be accomplished via a separate design studio course in which they could explore the concepts, software applications and the practice more extensively (see Figure 15). The creation of new design studios in this topic will educate students who will be the professionals of the future. 3 out of 10 students think that the course could include students from other disciplines such as civil engineering and mechanical engineering apart from architecture.

4.4 Discussion

The previous section presented some of the major challenges and opportunities that integrated design practice presents in architectural education

Figure 10. Thermal comfort analysis with material A^1 and material B^2



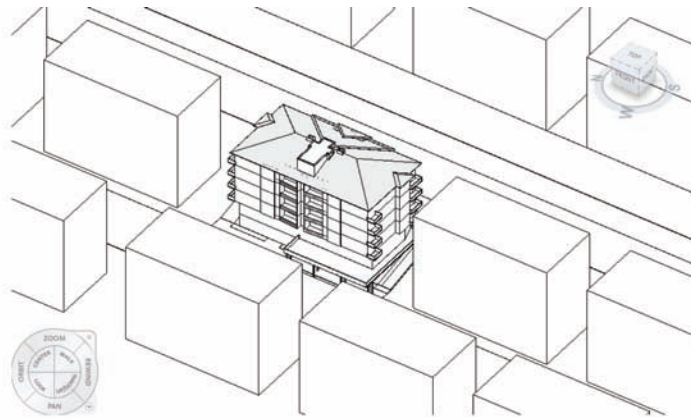
settings. The wide-scale implementation and proliferation of the integrated practice within the construction industry requires a close collaboration of several organizations. Government, professional bodies, industry and the educational institutions need to collaborate for a wider implementation of Integrated Project Delivery.

First, schools need to develop educational strategies in order to teach the principles of integrated practice. New programs, teaching methods, infrastructure and human resources will be needed to deliver this new way of work practice in educational settings. Some schools have already started transforming their curricula by introducing new courses on this subject. A short introduction has been given in Section 3.4. It seems that if integrated design principles are not considered as part of the studio education, it would be very

difficult to promote this new way of project delivery in the curriculum of architecture. As Cadima (2007) states, many schools of architecture still contribute to the dissociation between technical issues and design, where most of the subjects, including environmental issues, are taught separately from studio work and design studies and are left as an option to the design process. If this disintegration continues, there will not be a good chance of implementing integrated practice in the educational system of architecture.

Lack of awareness has been found to be an important barrier for implementation. There should be knowledge transfer mechanisms (lectures, workshops, studio work, etc.) in order to inform students and faculty staff about the latest technical and conceptual advances that promote integration. This could provide a faculty-wide

Figure 11. Project model as designed by the architect



(a)



(b)

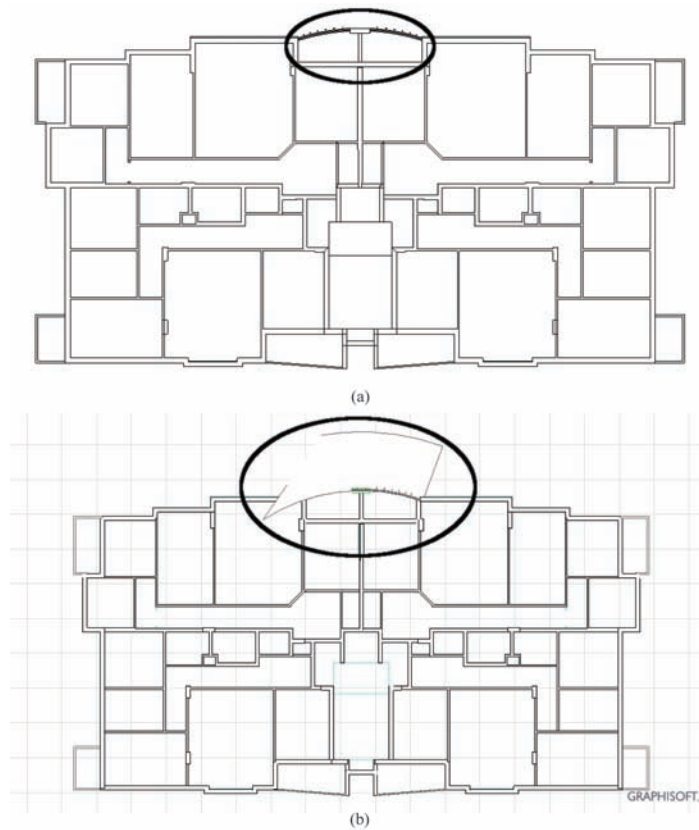
interest in delivering projects in a more integrated manner.

Secondly, professional bodies and government agencies need to be aware of the technology and the concept of Integrated Project Delivery. As stated in the literature review section, some governments have started to prepare their construction industry for the future by implementing product model based project delivery mechanisms. This may not be an easy task for many. As one of our students thinks (Balkanay, 2009) it would be hard for the professional bodies and governments to accept integrated design principles and technologies

immediately. It is possible that lack of knowledge and resistance to new technologies and practices may prevent the introduction of this new project delivery method.

Finally, the new project delivery mechanisms introduced by the government and professional bodies are forcing the construction industry to adapt to this new way of practice. However, the lack of awareness on the demand side may create another barrier. Clients need to be brave enough to enforce the project parties to implement Integrated Project Delivery mechanisms.

Figure 12. An example of geometry misinterpretation after the data exchange



5 CONCLUSION

Recent advances in information and communication technologies (ICT) are affecting the way we conduct business. Within the last couple of decades many industries have redefined their processes and moved to a more productive level. The construction industry and its related businesses are also under the pressure of using new digital mediums more efficiently. Design and construction projects now have the opportunity to be delivered in a more integrated manner as the new ICT tools begin to proliferate within the industry. Clients and owners are pressurizing the project participants to deliver more integrated practices. It has become evident that integration promises to make the design, construction and operation of buildings much more streamlined and efficient.

The implications of this new project delivery method have begun to appear in the business and educational existence of some countries. The educational institutions serving the AEC-FM sector are trying to update their present curricula and introduce the Integrated Project Delivery to the students, who will be the professionals in near future.

This research has explored the implications of integrated design practice at an architecture school. An integrated design practice course has been designed and delivered at the 2008-2009 Spring Semester. Ten students from the third year class have been registered to this course and carried out an integrated design initiative in groups consisting of 3 or 4 members. During the process, students have faced some technical problems (e.g. missing elements, large data files, etc.) in

Figure 13. Thermal comfort analysis with material A^3 and material B^4

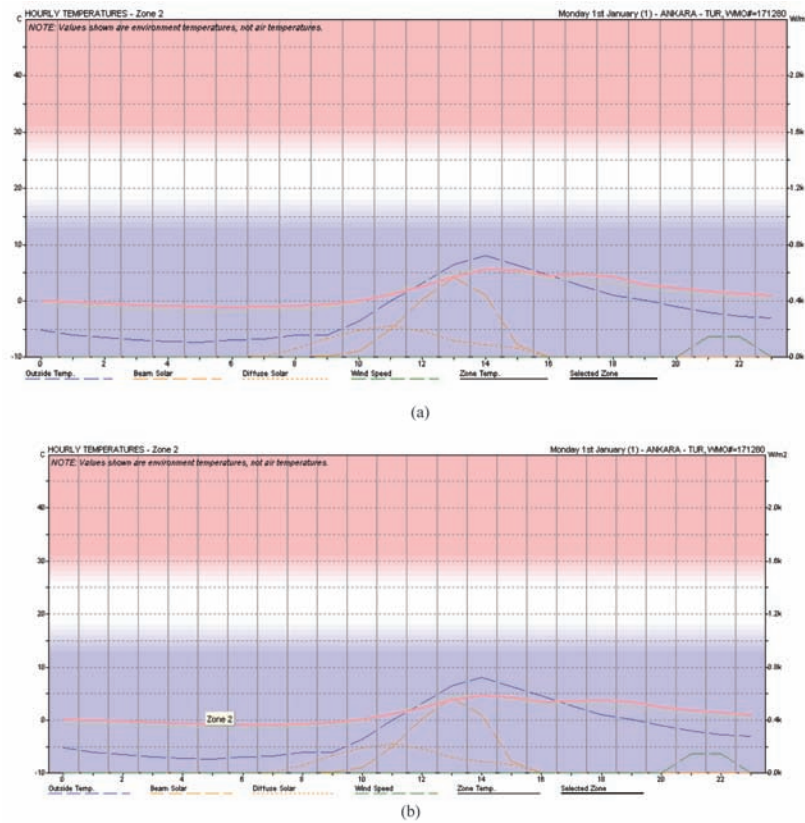
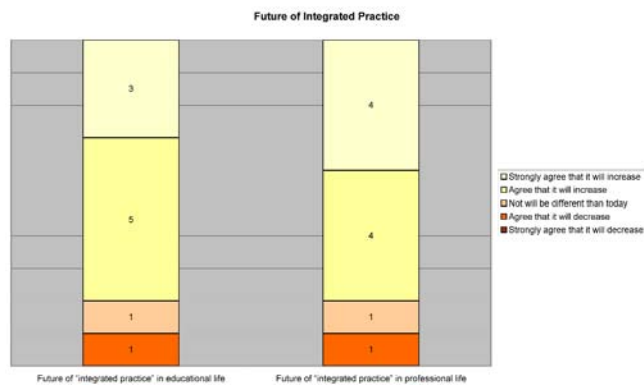


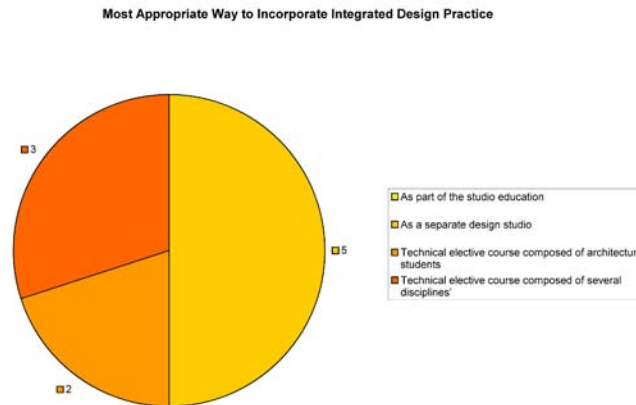
Figure 14. Future of integrated practice



the data exchange. However, the case evaluations proved that the technology is promising and therefore this practice could be applicable. The evaluation of the course has also demonstrated the

barriers to implementing an integrated practice in educational settings. Awareness and curriculum related issues have been identified as the major barriers that prevent a wider introduction of the

Figure 15. Most appropriate way to incorporate integrated design practice



topic within the educational institutions. There is an urgent need to setup new courses in this field and create knowledge transfer mechanisms within educational institutions.

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KEY TERMS AND DEFINITIONS

Building Information Modeling: Building Information Modeling is the model based storage and exchange of building related data

Curriculum of Architecture: Courses offered as part of the architectural education

Data Model: An abstract model that describes how data are presented, organized and related to.

Integrated Data Model: A central repository system used for the storage of data and processes required by various disciplines during the life cycle of a project

Integrated Project Delivery: A new project delivery approach that integrates project parties and their practices based on a reliable framework

Integration: Ability to exchange data/information between different project members and life cycle stages

Interoperability: Ability to exchange data/information between two or more systems

ENDNOTES

- ¹ Brick timber frame: 110mm external brick plus, 75mm timber frame with 10mm plasterboard inside
- ² Reverse brick veneer-R20: Timber external cladding with R2.0 (75mm) insulation and brick internal
- ³ Brick timber frame: 110mm external brick plus, 75mm timber frame with 10mm plasterboard inside.
- ⁴ Concrete block plaster: 110mm concrete block with 10mm plaster either side.

Section 9

Case Studies

Chapter 26

The Role of BIM in the Architectural Design Process: Learning from Practitioners' Stories

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ABSTRACT

The objective of this chapter is to identify the role of BIMs in the architectural design process from the practitioners' point of view. The chapter investigates the main factors affecting the practitioners' use of BIM, and how BIM impacts their work and interactions. The chapter presents a holistic research approach as well as the findings from its application in four real-life projects. In these projects, much of the practitioners' focus was on upgrading skills and improving technology. Nevertheless, a number of their challenges were linked to the nature of the architectural design process, particularly to its "hard-to-grasp" iterative and intuitive features. A conclusion of this research indicates that the role of BIM is affected by the many interdependencies, relations and interfaces embedded in the highly complex and partly unpredictable real world practice. A future challenge would be to understand, master and balance these relationships - upstream and downstream across multiple levels, processes and activities. The presented holistic research approach and the related findings contributed to research which aimed to embrace the complexity of real-life problems and gain a more comprehensive understanding of what is happening in practice.

1 INTRODUCTION

"The architect must be able to do two things; i.e., understand what people need and build houses."

By asking architects about what they see as their main responsibility and contribution to the design process, it is likely that they especially mention two points: first, creating good architecture, and second complying with the contract conditions and requirements of the clients, users and building authorities. The first point is related to the product,

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the second is related to the processes leading to production of that product.

Architects traditionally play distinct and important roles in the architectural design process (Gray and Hughes, 2001). Their highly complex, sophisticated and in part tacit skills (Lawson, 2006) make them suitable for several tasks and roles – from being design specialists, translating the many project constraints and information into physical form, to being involved in management tasks where they lead, coordinate and administrate the design process. Architects are, however, not alone in their efforts to create successful buildings and real estate. Cuff (1991) describes design as ;

“A social construction, where buildings are collectively conceived”.

Behind both the seemingly simple quotations above is a highly complex universe where predictable and unpredictable interactions, interrelations and interdependencies between actors and processes create our physical environment.

The Practice of Architectural Design meets the Digital World

More than thirty years ago the architects and other practitioners involved in the architectural design process faced an entirely new situation due to the new and rapidly expanding Information and Communication Technology (ICT) industry. They have, however, been slow to adapt the new technologies in their work and interaction. Compared to other industries, the Architecture-Engineering-Construction (AEC) industry is lagging behind when it comes to the successful implementation and use of ICTs (Gann, 2000; Wikforss, 2003a). Despite the high expectations on the potential of the new technologies in enhancing growth and improving processes, the productivity status of the AEC industry described in the Latham Report (Latham, 1994) is still an issue of concern in many countries.

With the new millennium and the growing awareness within the industry about the potential of the new technologies, more and more powerful industry stakeholders have participated in research and development (R&D) projects to encourage and promote the integration of ICT into the practice. In recent years an array of international and national joint efforts and alliances have been introduced (Bazjanac and Kiviniemi, 2007) i.e in Denmark, Finland, Norway and the USA. These initiatives support 3D object-based modeling and Building Information Modeling. The integration of these technologies is expected to lead the AEC industry into a new era, characterized by better communication and exchange of architectural design information between project actors involved in all phases of the building's life cycle. There is thus an increasing pressure on practitioners for adopting new technologies in their work and interactions. Furthermore the implementation of these technologies is expected to impact both working methods and role definitions in their projects (Berg von Linde, 2003; Sundell, 2003; Wikforss, 2003a, 2003b). Crucial questions arising out of observations of trends and movements within the current industry and research are;

“How the adoption of new technologies will affect the development of good architectural design solutions and real estate? What happens with the complex universe of interactions and interdependencies between processes, roles, and actions which are an integral part of the architects' and other practitioners' daily work?”

Research dealing with ICT in the AEC industry has been dominated by a focus on the development and improvement of new software and hardware systems, and on technology related to issues of implementing these in practice (Wikforss and Löfgren, 2007). More research is needed on the impact of non-technological and human factors - an issue which has increasingly gained the attention of researchers (Amor et al.,

2007; Rezgui and Zarli, 2006; Saridakis and Dentsoras, 2008).

The Objective and Focus of the Chapter

The objective of this chapter is to identify the role of Building Information Models (BIMs) in the architectural design process from the practitioners' point of view. A holistic research approach is presented and applied to explorations of practitioners' experiences from using technologies supporting 3D object-oriented modeling or BIM in four real-life projects. The chapter is based on the findings of a PhD project conducted in the period of 2004-2008 with the title;

"Exploring relations between the architectural design process and ICT – Learning from practitioners' stories" (Moum, 2008).

The main objective of this PhD project was to contribute more knowledge on the current situation in practice by investigating relations between the architectural design process and ICT in real-life projects. An important issue was to gain knowledge about practice by unlocking the knowledge that is embedded in practice. In the research, two research questions were addressed:

1. What are the factors affecting the implementation and use of ICT in the practice of architectural design?
2. How does the implementation and use of ICT impact the work and interactions of practitioners involved in the architectural design process?

The chapter focuses on the implementation and use of technologies supporting 3D object-based modeling or BIM (this comprises for instance; 3D modeling tools, IFC (or other standards for information sharing), applications such as viewers and clash detectors). In this chapter, the term "BIM"

also comprises the 3D object-based models and 3D product models. The term "Implementation of technologies" denotes activities putting the use of these into effect. The term "use" relates to how the actors involved in the architectural design process practice ICT in their work and interactions; individually and within a discipline, and collectively and across the disciplines. The expression "practice of architectural design" is used to emphasize that this chapter deals with the architectural design process related to practice and to situations in real-life projects. From an overarching view, here practitioners are the actors involved in the AEC industry. The main focus is, however, architects and their interactions with other actors involved in the architectural design process.

The chapter is structured as follows. Following a review of the field and related literature and research, the holistic approach and the cases are presented. In the main part of the chapter, the key findings are described in perspective of this specific chapter. Furthermore, some future trends are discussed. Finally, some concluding remarks are rounding up the chapter.

2 BACKGROUND

This section clarifies the underlying understanding of the architectural design process and the current status within BIM development.

The Architectural Design Process

"The synthesis of design solutions is characterized by uncertainty, unpredictability, the joy of discovery, and the frustration of fruitless explorations. It has fascinated baffled and challenged designers, researchers and philosophers for at least 2,500 years." (Kalay, 2004, pp.199).

The practice of architectural design and the roles and tasks of the actors involved has evolved over decades and centuries. Societal, political, economic and technological development and movements have formed the AEC industry we know today and the practice of architectural design. The quotation above indicates that this evolution has been followed by countless attempts to tackle the challenge of understanding, mastering and explaining the processes behind our built environment.

The first generation of design methodologists' focus on the design process as something sequential and linear in the 1960s, has long been challenged (Lundequist, 1992). The understanding of the architectural design process as a complex universe of predictable and unpredictable interactions, interrelations and interdependencies between actors and their actions, relates to observations of the practice of architectural design made by researchers such as Kalay (2004), Lawson (2006) and Schön (1991). Kalay (2004, p.13) refers to design as a cyclical relationship between two paradigms; i) design as problem solving, where the designer attempts to produce solutions to ill-defined problems, and ii) design as puzzle making, where design is seen as a process of discovery where given parts are synthesized into a new and unique whole. Lawson (2006, p. 49) describes the design process as "a negotiation between the problem and solution through the three activities of analysis, synthesis and evaluation," and challenges the comprehension of the design process as a sequence of activities. Schön (1991) characterizes the design practice as a reflective dialogue between the designer and the design situation.

Different trends in the society, as for instance globalization and the increasing concerns about sustainability and environmental issues are among several which are increasing the complexity of the design process even more. The focus on integrated practice and collaboration, where specialized participants with different backgrounds, preferences

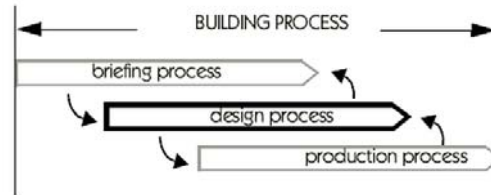
and experiences try to achieve a common goal, is growing within both research and practice (Elvin, 2007; Haymaker et al. 2006; Matsushima, 2003). Barrow (2000, pp. 272-273) introduces the term Cybernetic Architecture in his thesis as below:

"... cybernetic architecture is a return to the pre-Renaissance comprehensive integrative vision of architecture as design and building (...) the emerging architecture process is a 'collective' body of knowledge and specialty skills found in many individuals".

The entire building process and the interactions between actors and processes, can be presumed to rely on the generation, interpretation, distribution, coordination, management, and storage of information (Emmitt and Gorse, 2003; Gray and Hughes, 2001). The expectations to the use of BIM are closely related to the potential for processing and storing a vast amount of information, for instance about the geometry, and the attributes and properties (of the objects) of the physical building. Whereas information can be explained relatively simple, the related term knowledge is a far more complex subject, particularly the so called tacit knowledge. Griffith et al (2003) describe three types of knowledge:

1. Explicit knowledge can be articulated, and is thus accessible to others (for instance objective knowledge based on facts).
2. Implicit knowledge is knowledge which is hard to grasp, but which can be "transformed" into something which can be articulated.
3. Tacit or "silent" knowledge cannot be put into words and plays an essential role in the work and interactions of the actors involved in the practice of architectural design. Tacit knowledge can be described as a kind of "feeling of" (Schön 1991) and can be expressed, for instance, by experience-based, intuitive and unconscious habits and actions. This knowledge embodied by the practitioners

Figure 1. The building process and its three main phases – which are again divided into an array of sub-phases (based on an illustration in “Samspillet i Byggeprosessen” (Haugen & Hansen, 2000, pp. 10)).



involved in architectural design is crucial, but hard to grasp and unlock, for computer systems and also for researchers.

These features of the architectural design process are closely related to cognitive processes and design thinking. Some features of the architectural design process are, however, also given by regulating external factors. The practitioner must deliver design information and project material to the client, the building authorities and the contractors. The process is regulated in phases, each presenting a higher level of detail and information depth, and each to be approved by the stakeholders before moving on to the next phase i.e. the outline design phase, the scheme design phase and the consultants' detailed design phase (Gray and Hughes, 2001). Furthermore, the time and performance related definitions of these phases are mostly specified in the project contracts. These might also be regulated by guidelines or regulatory demands on the national level. The architectural design process is positioned between the statement of the brief (more or less defined) and the start of the building production. However, in practice, one project phase does not follow the other in a pure sequential process. Limited time resources, tough project budgets and the contractual models call for an overlap of the phases (Fig. 1).

The metaphors of “baking bread” and “playing jazz” can be used to highlight and simplify the different character of these features of the

architectural design process. Baking bread could be seen as a linear, predictable, explicit and measurable process - based on for instance repetition and routine. This can be related to the activities described above, which are central in order to drive the processes forward due to the agreed time and cost. Playing jazz is on the contrary a rather improvised, intuitive and tacit process leading to a unique performance, based on “the feeling of”, on talent, practice and experiences. This process might be compared with the hard-to-grasp elements of the architectural design practice described in the beginning of this section. This “something” going on in the head of the designers, is also a magical “something” resulting in the unique and great architectural solutions and buildings. The “baking bread” and “playing jazz” metaphors are representing co-existent processes in the architectural design practice. The interplay and balance between these are crucial for -what actually gets built-. The practitioners involved in the architectural design process must thus deal with the interplay between highly iterative, unpredictable and non-linear activities on one hand, and regulated and linear activities on the other.

What is BIM and BuildingSMART?

The term “BIM” stands for Building Information Model or Building Information Modeling. However, although BIM has its roots in computer-aided design research from decades ago - the term BIM

has no single, widely-accepted definition (Eastman et al., 2008). According to Laiserin (2007), one of the “Godfathers” of the term, the answer (i.e. definition) depends on the end purpose of the person defining it. Software developers might define BIM in terms of what their respective software offers, whereas many academic researchers might see BIM as a theoretical ideal not necessarily (ready) to be implemented in the real world.

The BIM-handbook authored by Chuck Eastman and his colleagues (Eastman et al., 2008), describe BIM as “a modeling technology and associated sets of processes to produce, communicate and analyze building models”. In a report funded by Erabuild initiative (Kiviniemi et al., 2007), researchers and practitioners from the Nordic Countries use the term “BuildingSMART technology” and describe Building Information Modeling as;

“A methodology for building design and documentation – by creation and use of, coordinated, internally consistent computable information about a building project in design and construction”.

In the report they introduce the term integrated BIM as;

“A Building Information Model whose information needs to be shared and thus warrants open international standards for information sharing”.

To be able to exchange information freely – the BuildingSMART concept is based on three open international standards for (as pillars of) information sharing. Based on the definitions given in the Erabuild report (2007), these are described very briefly here: IFC (Industry Foundation Classes) is an exchange format, defining HOW to share information. IDM (Information Delivery Manual) are information requirements, defining WHICH information to share, and WHEN. Finally, IFD (International Framework of Dictionaries), is a

reference library, defining WHAT information to share. The “Building Information Circle” (Fig. 2) illustrates the idea of BuildingSMART; a consistent and smooth flow of information across all involved actors and throughout the entire life cycle of a building based on these three pillars. The figure has been referred to on many occasions in conferences and seminars organized by the International Alliance for Interoperability (IAI) and BuildingSMART through the last years.

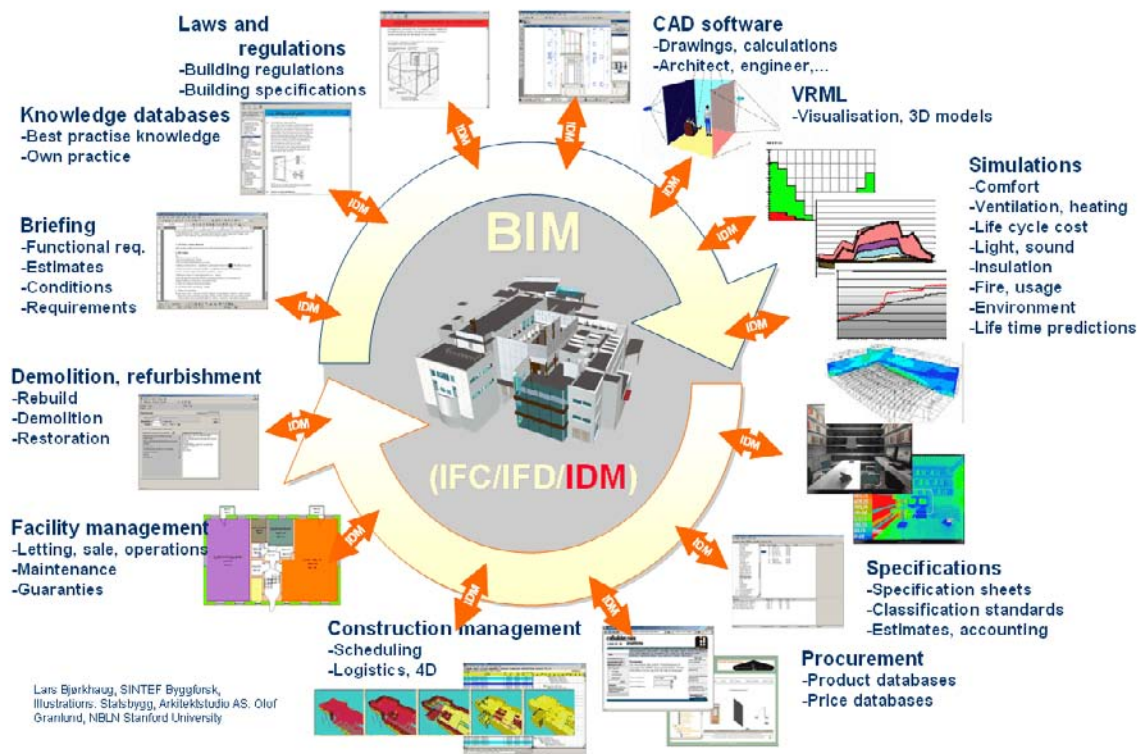
The open standards (IFC, IDM and IFD) have until yet only been partly implemented in, the practice of architectural design and the real life projects referred in this chapter.

Historical Milestones and a Shift in focus from Technology Development to Implementation

According to Howard and Björk (2007), the first research dealing with product modeling took place as early as the 1970s. However, a first “push” behind the development of this technology came with the start of the ISO STEP (Standard for the Exchange of Product Data) standardization project in 1985 and with several European and German research projects into the mid-1990s (Junge and Liebich, 1997) i.e. COMBI (1993-1995), (a EU-sponsored project). The knowledge gained from these projects served as the basis for the industry consortium IAI, which in the mid-1990s took over product modeling standardization for the AEC industry. The IAI is the prime mover behind the development of the Industry Foundation Classes (IFC). From the end of the 1990s, Finnish research activities, for example the VERA program (VERA, 2006), were important catalysts in the IAI’s efforts to develop the IFC. Today, the IAI is a worldwide consortium comprising a wide array of research and development efforts.

In the first years of the new millennium, the limited adoption of these technologies in practice, the rising concern about productivity in the AEC industry, and industry stakeholders’ increasing

Figure 2. The “Holy Grail” of the BuildingSMART community (Illustration made by Lars Bjørkhaug, SINTEF Building and Infrastructure, with illustrations from Olof Granlund, Statsbygg, Arkitektstudio AS and LBNL Stanford University). Downloaded from: <http://buildingsmart.byggforsk.no/blog/index.php/2008/02/29/a-building-information-circle-from-us-to-you>



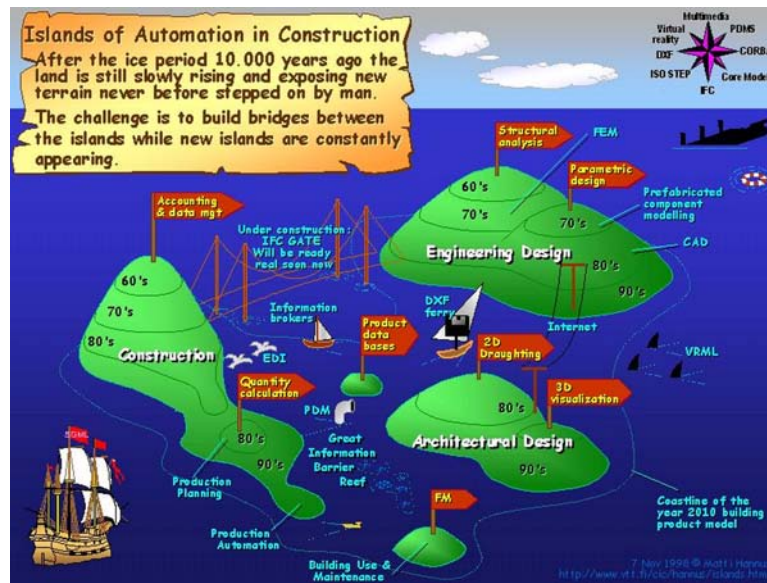
awareness of the new technologies’ potential triggered a shift in focus from technological development to the implementation. The Finnish ProIT (Product Data in the Construction Process) program initiated in 2002 (ProIT, 2006), and the Danish ‘Digital Construction’ launched in 2003 (EBST, 2005), are both examples of R&D programs on the national level, where powerful actors in both industry and research have combined forces to stimulate the integration of the new tools, and efforts such as the ROADCON project, initiated in 2002, are examples of European research initiatives which attempted to develop a strategy for implementing ICT in the AEC industry (Rezgui & Zarli, 2006). At the same time, the program for

the international IAI conferences focused more and more on stakeholders perceived to have the power and ability to implement the developed standards and technologies. In June 2005, the IAI introduced the brand “BuildingSMART”, as the label for the growing efforts in several countries (such as Norway), to integrate technologies supporting 3D object-based modeling and BIM in their AEC industries.

Visions of a New Era in the AEC Industry

At an international information seminar on the IFC and the International Alliance of Interoperability

Figure 3. Islands of Automation in Construction (Hannus et al. 1987).



(IAI) in Oslo on June 15 2004, it was suggested that the implementation of IFC-based BIM will, in practice, trigger a paradigm shift in information handling and communication across actors and phases throughout the whole life cycle of a building (The seminar was organized by the IAI Forum Norway in co-operation with Foreningen Næringseiendom (FNE) and the Norwegian Society for Facilities Management (NBEF)).

Many visions, aims and expectations connected to the development and implementation of technologies supporting 3D object-based modeling and BIM started to manifest decades ago. In the famous “Islands of Automation in Construction” (Fig. 3), a group of Nordic researchers illustrated the vision of a “land-raising”, where the new technologies will connect the islands of automation into one big island, without the borders between planning phases and roles which today are a source of communication friction, delays and misunderstandings (Hannus et al., 1987).

In a presentation of the Norwegian BuildingSMART project (Sjøgren, 2006) the technologies

supporting 3D object-based modeling and BIM are expected to “reduce uncertainty and improve decision making in the building life-cycle” to solve the “Babylonian confusion in the AEC industry”. The presentation claimed that 25-30% of the construction costs in the current AEC industry are incurred due to communication errors and loss of information as a result of the need to re-enter and re-create the same information several times in different systems and software before the building is handed over to its owner.

Another expected effect of implementing these technologies is the “front-loading” of design efforts, enabled by the potential of the technologies to support earlier concretization of design solutions and decisions making. Typically, the peak of design efforts is placed in the detailed design phase, where design changes result in increased costs. By front-loading these peak and design efforts into an earlier phase in the building process, the design solutions can be changed without the same negative effects on costs.

The Implementation of BIM in the Architectural Design Practice

“BIM will lead to less errors, less delays in the building process – and cheaper and better buildings.”

This was stated by Øivind Christoffersen, the general director in Statsbygg, the major public client in Norway in a press release April 2008 (BuildingSMART, 2008). The visions and expectations related to the technologies supporting 3D object-based modeling and BIM have caught the attention of an increasing number of stakeholders in various countries. The quotation above is giving an impression of the increasing focus and expectations among stakeholders on BIM and related activities in Norway. Similar focus and expectations as expressed by this quotation can also be found in USA, Finland, Denmark and Germany. In Denmark, a regulatory client directive was issued from January 1 2007, requiring the use of 3D object models in, public building projects with building costs exceeding 20 million Danish kroner (approx. 2,65 million Euro). In May 2007, one of the Norwegian public clients, “Statsbygg” (the Directorate of Public Construction and Property Management), announced their intention to require the implementation and use of IFC compliant BIM in all their projects starting from 2010 (BuildingSMART, 2007).

In USA, TAP (Technology In Practice), which is hosted by AIA (the American Institute of Architects), monitors the development of computer technology and its impact on, architecture practice and the entire building life cycle, including design, construction, facility management, and retirement or reuse (TAP, 2008). Each year a “BIM reward” is given building projects which are regarded as front runners in the use of BIM. AIA has also published a series of reports on integrated practice, where various researchers and practitioners are reflecting on the development of architectural practice due to the impact of technology (AIA,

2006). These are only some out of many examples of activities related to the implementation of BIM in practice.

Visions meet Reality

“After ten years of IFC development, its adoption and use in the construction industry is still marginal. The ambitious approach of the IAI may have focused too much on the model-based world instead of the real one, leaving IFC as a theoretical model specification or an academic exercise rather than a useful industry standard for professionals in practice.” (Wikforss and Löfgren, 2007, pp.337-338)

In the quotation above, the authors refer to the former Nordic chairman of the IAI and his keynote lecture on the CIB W78 conference in Montreal, “Ten years of IFC development - Why are we not yet there?”

They, together with several other researchers (e.g. Amor et al., 2007), point on the slow adaptation of BIM and open standards in practice and call for research looking beyond the purely technology-oriented issues (which until recently have been the main focus of BIM related R&D). Laiserin (2007a, 2007b) in some of his rather critical articles emphasized the necessity “to separate hype from reality” in the current discussions on BIM.

The CAD director in a major international company, explains that the description of BIM as something superior and different from 2D CAD has resulted in unreasonable expectations, and ultimately frustration.

“I find myself bucking a certain amount of misguided attitude about ‘having to model everything in 3D’ and answering questions like, ‘Why hasn’t BIM taken off?’” (Guttman, 2005).

In an interview conducted by the author in spring 2007, he explained that the major theoretic-

cal problems and visions addressed by the many R&D efforts are eventually turned into smaller and more practical problems in their building projects. According to Guttman, the basic problem architects and other practitioners face is how to deal with new digital tools within a project where there is much work to be done and drawings to be produced. Although his company is a key actor in an international industry consortium for integrating Building Information Modeling in the AEC industry, and they are very enthusiastic about implementing new technology, the practitioners involved are constantly running into practical problems that make it easy to fall back into traditional ways of working.

Big Bangs, Challenging Gaps, Square Pegs and Horseless Carriages

This story from practice indicates several challenges arising out of what Wikforss (2003) calls a big bang between the traditional AEC industry and the rapidly developing ICT industry. Some of these challenges are related to the above-mentioned practical issues. Others are related to the complex nature of -still not fully understood- architectural design process. Chastain et al. (2002) describe two paradigms of problems related to the encounter between the practice of architectural design and the digital world. They call the first paradigm trying to put “a square peg in a round hole”, which describes the problem of adapting new technology to current practice, indicating a mismatch between the designers’ tasks (holes) and the tools applied (pegs). This mismatch or gap might be caused by a failure to understand the designers’ tasks, or by the replacement of traditional tools with new ones that have the wrong affordance (a potential for action, the perceived capacity of an object to enable the assertive will of the actor (Chastain et al., 2002, p.238). They call the second paradigm “the horseless carriage”, which characterizes “the shifting perception of a practice as it transforms in relationship to a new technology” and where

“the task of transportation is described through the lens of a previous technology – even though the practice of travel had changed” (Chastain et al., 2002, p.239). The tools used by the architects are changing with the development of new technologies, but without reflection on how this affects the practice of architectural design.

The story relates in a wider context to an observation made by several researchers (for instance Gibbons et al., 1994; Schön 1991); there is a gap between the professional knowledge established in research and academia and the actual demands of real-world practice. Heylighen et al. (2005, 2007) question the traditional one-way flow of knowledge from research and academia to practice. They call for more focus within academia on ‘unlocking’ and using knowledge embodied by architectural design practice. Schön’s (1991) famous description of how studio master Quist supervises and reviews the work of one of his architectural students is one example which illustrates that by studying real-life situations, more understanding can be achieved; in this case about what he calls a reflective conversation within architectural design.

Current Research on the Implementation and use of BIM in the Architectural Design Process

Alongside the increasing focus within the AEC industry on implementation of ICT through the establishment of R&D efforts at national and international level, there is a growing interest among several research communities in the experiences gained from applying new technologies to practice. The international CIB W78 conference, held in Maribor, July 2007, was entitled; “Bringing ITC knowledge to work”. Several papers dealing with industry experiences and challenges were presented and discussed in one of its workshops (for instance Samuelson 2007, Simondetti 2007). There is an increasing amount of journal article on the issues. Howard and Björk

(2008) are reporting from a qualitative study on experts' views on Building Information Modeling (BIM) and industry deployment. Khanzode et al. (2008), Ku et al. (2008) and Manning and Messner (2008) are dealing with the results from case-based research related to building projects adapting 3D/4D tools and BIM. In Eastman et al. (2008), the authors are reporting on experiences made from using BIM in several building projects. These are some examples of interesting studies of practice – however, these are either focusing on the AEC-industry and implementation strategies on general level, or on experiences gained from adapting BIM to single building projects.

The Need for a more Comprehensive Understanding

Wikforss and Löfgren (2007, p. 337) criticize that current research *“has not resulted in a comprehensive understanding of how new technology works (...) if we consider human, organizational and process-related factors in addition to purely technological factors.”* (the authors relate this problem to research on collaborative communication within the industry). We lack a comprehensive understanding and overview of non-technological factors, as well as of the relationships and interdependencies embedded in the encounter between the practice of architectural design and ICT.

This chapter presents the findings from a study that is exploring enablers and barriers, from the national R&D program level down to the individual architect or engineer involved in the real-life project, as well as the benefits and challenges experienced from using and exchanging 3D object models in real life practice. The focus is particularly on non-technological factors. The discussions are furthermore based on the understanding of the design process as a complex conglomerate of predictable and unpredictable interactions, interrelations and interdependencies between actors and their actions. In order to appreciate this complex nature of (the practice of) architectural

design in the explorations of the practitioners' experiences from using BIM, a holistic research approach has been developed.

3 A HOLISTIC RESEARCH APPROACH FOR EXPLORING ICT USE IN PRACTICE

The main idea behind the research approach mirrors the architects' holistic handling of problem identification and solving, and their ability to synthesize and coordinate bits and parts into a whole without having the detailed knowledge about each of these. The approach is based on two elements; a descriptive framework and the use of building stories.

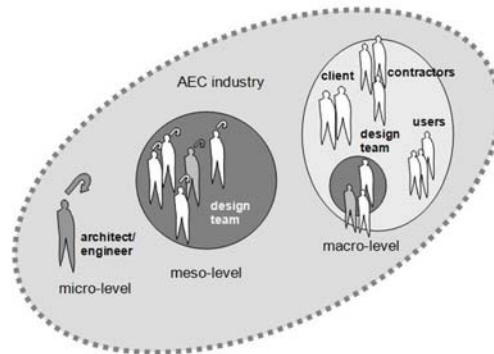
The Descriptive Framework

The descriptive framework has been developed for gaining a better overview and understanding of the implementation and use of ICT in real-life projects (Moum, 2006). The framework is grounded on two dimensions of design practice.

First, is the process dimension. The framework focuses particularly on four central design process aspects; the generation of design solutions, the communication of design solutions, the evaluation of design solutions and decision-making.

Second, the framework is based on the level-dimension, where three levels representing different social constructions in a building project are suggested; a macro-level (overall project), a meso-level (the design team) and a micro-level (the individual practitioner). These three levels are again embedded in the context of the AEC industry, in this chapter represented by the national or international R&D programs (Fig. 4). The development of the framework is based on reviews of relevant literature and research, as well as on observations of practice. The framework and its tools have evolved and improved throughout its application on several real-life projects, and it has

Figure 4. The three project levels embedded in the AEC industry context.



been presented at several workshops, seminars and conferences.

Based on the main framework elements, different tools and models are introduced to provide an overview of the factors affecting the implementation and use of ICT. These tools contribute to an operationalization of the exploration of relations between the architectural design process and ICT.

The ICT impact matrix (Figure 5) is introduced as a tool for organizing the findings from literature and studies of practice. The matrix provides an overview of key benefits and challenges from using ICT in the architectural design process, related to all four design aspects and all three levels. A benefit from use can be quantitative and measurable (e.g. cost and time savings) or qualitative and hard to grasp (e.g. more shared understanding). The term challenge describes a demanding situation or

task due to the use of ICT (e.g. the need to make decisions earlier in the process). The matrix has been used to organize both benefits and challenges explored in current literature, and those perceived by the actors involved in real-life projects.

The multi-level factor model (Fig. 7) provides an overview of enablers and barriers affecting the implementation and use of ICT in the architectural design process (Moum et al, 2009). The terms enablers and barriers are used to describe some key premises for implementation and use of technology in the studied building projects. An enabler supports and facilitates implementation (e.g. extra time and money available), while a barrier impedes implementation and use (e.g. the users' lack of skill).

Figure 5. The ICT impact matrix.

	macro-level	meso-level	micro-level
design generation			
communication			
design evaluation			
decision-making			

Building Stories

“The story format provides a dense, compact way to deal with and communicate the complex reality of a real-world building project, while respecting the interrelated nature of events, people and circumstances that shaped its conception.” (Martin et al., 2005, pp.35).

Heylighen together with Martin suggested (Martin et al., 2005) that storytelling is a vehicle for communicating the knowledge embedded in practice. They have used this technique actively within teaching, where students have carried out case studies of building projects by establishing what they call “Building Stories”. The aim of their case studies was to explore “the knowledge embodied by the best practices of significant architectural firms” (Martin et al., 2005, pp.36).

In this research, this narrative technique has been used to capture and communicate the broad and complex array of the case studies findings into different stories. They represent detailed elaborations of situations and factors identified by using the framework. Each story represents a “spot” on significant bundles of findings and relations addressing the research questions. In addition to being the basis for the further explorations and discussions, the stories are also regarded as contributions in themselves to a repository of knowledge about real-world practice. Flyvbjerg (2004) pointed out that good case studies are narratives in their entirety, whereas summaries and generalizations may fail to communicate important relationships and the contextual value of the study.

Thus, the holistic approach is on the one hand based on, a broad and comprehensive approach to the problem field manifested by the framework and the detailed and reflective exploration of real-life situations identified by its application.

Learning from Practitioners’ Stories

The framework has been applied as an instrument for organizing and analyzing the results of the case-studies from one main and three reference case studies of ongoing or just completed building projects. These projects are middle- to large-scale European projects and, at the time the case studies were carried out (2005-2006) all of them were pioneer building projects in their countries in terms of the interdisciplinary use of 3D object models or BIM in design teams (to the best of the author’s knowledge). The main case is the new Icelandic national concert and conference centre in Reykjavik (the CCC project). Furthermore, the three reference studies were, of the new Akershus university hospital (the AHUS project), of the Tromsø university college (the HITOS-project), both in Norway, and of an Audi production plant in Germany (the AUDI project). The purpose of the reference studies was to provide empirical data that would open a discussion on the findings of the main case in a wider context.

The main case and the three reference cases established together an interesting ensemble of investigation. The experiences gained in the HITOS project provided insight in implementing integrated BIM in the early phases of the building process. The AHUS project is particularly interesting regarding the role of IFC compliant 3D object models in the interface between design and production, and also in the coordination with the users. The AUDI project was a good example of a project where the client also used 3D object models. All the four studied projects were connected to national or international R&D programs for promoting the integration of ICT in the AEC industry. Key persons in these programs were also involved in the projects studied, either as managers or coordinators of the implementation and use of the new technologies. The strategies and aims established in the R&D initiatives, and the efforts to bring these into real-life situations,

affected the situation in the projects studied and the experiences made.

The case-study data have been collected from several evidence sources, i.e., a strategy recommended by Yin (2003) to ensure the construct validity of the qualitative study. The findings presented here are generated from more than forty semi-structured and open-ended interviews (Kvale, 1996) conducted in 2005-2007 period with around thirty practitioners involved in building design and project management. To gain broad insight into the studied project beyond the subjective world of the single respondent, project actors who represent different backgrounds, experiences and points of view have been selected. Further sources of evidence were: passive observations of design meetings, “guided tours” on computers with the users of BIM, observations of the workplace of the design team, as well as investigations of project material.

The case studies focused on technologies supporting 3D object-based modeling or BIM. More specifically, they focused on the implementation and use of these technologies sub-related to the four design process aspects and activities, such as visualization, simulation, consistency controls, data exchange, generation of drawings and take-offs. In the case studies, the focus was limited, moreover, to the meso-level and the work and interactions taking place in the design team. The objects of investigation were the “traditional” design team actors; the architects and the main engineering disciplines (building structures, HVAC and electrical systems). Their interactions with, for instance, the contractors, the building authorities and the users have only been regarded on the overall level, based on the stories told by the architects and the engineers.

Altogether, the holistic research approach and the broad empirical data provide a good basis for discussing the role of BIM in the architectural design process as seen from the practitioners’ point of view.

4 THE ROLE OF BIM IN THE PRACTICE OF ARCHITECTURAL DESIGN

Findings 1: Barriers and Enablers Impacting the Role of BIM

An array of enablers and barriers were identified in the four building projects, located on different levels in the studied projects, and in their context (here the R&D initiatives). The identified enablers and barriers were organized by using the multi-level factor model (Fig. 7).

Particularly three relationships between the identified factors were impacting the role of BIM in the building projects:

1. The power of the implementer vs. the expected benefits and challenges
2. The strategies and guidelines vs. the resources available for learning and the traditions for technology use
3. The level of ambition vs. the skills of the users and the affordance of the technologies supporting 3D object-based modeling and BIM

In the following part of this section, examples of findings from three of the projects (the CCC, the AHUS and the AUDI project) in regard to these three relationships are given. A description of the HITOS project and the implementation strategy there, wraps up this part of the chapter. These factors are presented in order to establish a backdrop for understanding the role of BIM in the projects, which is described and explained in the next part.

The Power of the “Implementer” and the Distribution of the Technology

One of the main strategic enablers for integrating ICT in the Danish AEC industry is the involvement of the (public) client as the “implementer”

and the one demanding the use of technology. However, in the case of the CCC project, the initiative for introducing and testing BIM came from the engineering company – it was not a client demand. The same situation was observed in two of the reference cases, where either the architectural or the engineering companies were initiating the implementation. The main consequence of this situation was a limited distribution of the technology among the project actors, typically to the architect only, or to the design team. Thus, a number of further interactions in the building projects could not reiterate the idea of BIM and BuildingSMART and the seamless flow of information across all actors and phases. A consequence of this situation was for instance a 2D-based project delivery to the contractors and the clients. The variances of technology implementation within the design team resulted in several challenges in building and exchanging the discipline models.

The initiative of the engineering company, the belief in this technology becoming the main tool of design and production and the (expected) benefits from processing the complex geometry of the buildings were important enablers of the adoption of BIM into the architectural design process. An essential barrier for the full implementation of BIM was that the companies involved in these projects had to take the full risk of negative consequences related to the project's costs and timescales. Bearing in mind the current status of few documented experiences of using BIM, this was an important factor. Thus, the degree to which the practitioners used BIM seemed to depend significantly on the power of their "implementers" and what they perceived as the benefits, challenges and risks of working with these technologies.

The Guidelines for Working and the Resources for Learning

The establishment of BIM manuals is a part of the strategies of public and private "implementers"

in several countries, for instance in Denmark, Norway and Finland. In the CCC project, the guidelines and manuals (The 3D Working Method) was established as a part of the national R&D program "Digital Construction" (bips, 2006). In the case of the Danish project, the guidelines and manuals enabled a degree of shared understanding of how to build and exchange the BIMs among the practitioners. However, to ensure that the practitioners actually used the manuals and worked disciplined did require a close follow-up by for instance the BIM coordinators in the projects. Another challenge was the partly limited ability of the manuals to address the actual complexity of practice.

Another barrier to the use of BIM was the different organizational attitudes regarding; "Who should be skilled in BIM?". A typical situation was that the experienced engineers were not used to work with digital tools. They worked traditionally with sketches and hand drawings, which they handed further to draftsmen, who then were building up the models. This was seen as one of the greatest challenges regarding the future implementation of the technologies by some of the engineering companies. In addition to being a generation-dependent issue, raising skills and competences is also a question of educational and organizational policies and strategies, both inside and outside the companies.

Nevertheless, software courses taught most of the practitioners a certain level of basic knowledge. One barrier, however, was the limited time available for the practitioners to learn and test the new technology. This situation was again interrelated with barriers on other levels; i.e. the fact that no extra time or money was made available for implementation, and that the decision to work with BIM was not based on a client demand. However, in all projects the managers reported on steep learning curves among the BIM users.

The Level of Ambition and Reaching for “Low-Hanging Fruit”

In the case of the “Digital Construction” program in Denmark, the readiness of the AEC industry, the current abilities of the technologies and the expected barriers were among the arguments for choosing a perhaps moderate level of ambition and aiming for ‘low-hanging fruit’. In the beginning of the CCC project, the project managers decided to have a realistic ambition level which should reflect the skills of the project participants, the shortcomings of the technology and the limited implementation by the design team. In all projects there was awareness among the interviewed actors that not all the aims and visions related to the ideas of BuildingSMART and BIM could be fulfilled. Making simulations based on the BIMs or exchanging design information linked to the objects, were typical activities not aimed for in the three projects referred to here (exceptions were seen as positive add-ons). Several of these activities would have required IFC or otherwise

compatible software, and were felt to comprise the next step on the companies’ steep learning curve in relation to the adoption of BIM.

In the AUDI project, the client’s moderate level of ambition was mentioned as a factor enabling the design team actors’ adoption of technology by the respondents. The client required the architectural model to address the scale of 1:100, which they perceived as an adequate level of detail in order to coordinate the geometry of the different disciplines. A respondent representing the client, emphasized the importance of not to overload the models with information, which from his point of view would lead to more work in maintaining and updating the models. Further information and instructions needed by the contractors, was provided by traditional 2D details, hand sketches and textual descriptions. The latter was the case in all studied projects.

A last factor to be mentioned here, is the clarity of the concept of working with discipline models and its positive influence on the practitioners acceptance of the new technology. Common for

Figure 6. Numbers and facts of the four building projects.

	CCC project (main case)	HITOS project (ref. case 1)	AHUS project (ref. case 2)	AUDI project (ref. case 3)
function	Concert and conference center with parking garage	University college	Hospital (focus: front building part)	Production plant for cars (offices and changing rooms included)
gross floor area	32.000 m ² (not counting the parking garage)	5.100 m ² (new buildings)	116.000 m ² (new buildings total) 2.500 m ² (front building)	25.000 m ² (hall N42) 13.000 m ² (hall N24)
schedule	Competition: 2005 Design and construction: 2005 - 2009 Operational: around new year 2009-2010	Conceptual design: 2006 (spring)	Competition: 2000 Conceptual design: 2003 Operational: 2008	Design and construction: 2004-2005 Operational: 2005 (N42), 2006 (N24)
client	Portus Group, Iceland	Statsbygg, Norway	Nye AHUS/ Helsebygg Øst, Norway	Audi, Germany
architect	Henning Larsen Architects, Denmark & Batterid Arkitektar, local architect, Iceland	Arkitektstudio, Norway	C.F. Møllers Architects, Norway/Denmark	Obermeyer Planen + Beraten (architecture and structural systems)
engineers	Ramboll Denmark, Denmark & VGK Hönun HF, Rafhönnun HF, sub-consultants, Iceland	Norconsult (structure and electricity) Sweco Grøner (HVAC), Norway	Multiconsult (structure), Sweco Grøner (HVAC), Cowi/ Interconsult (elt), Norway	FACT (HVAC and electrical systems), Germany

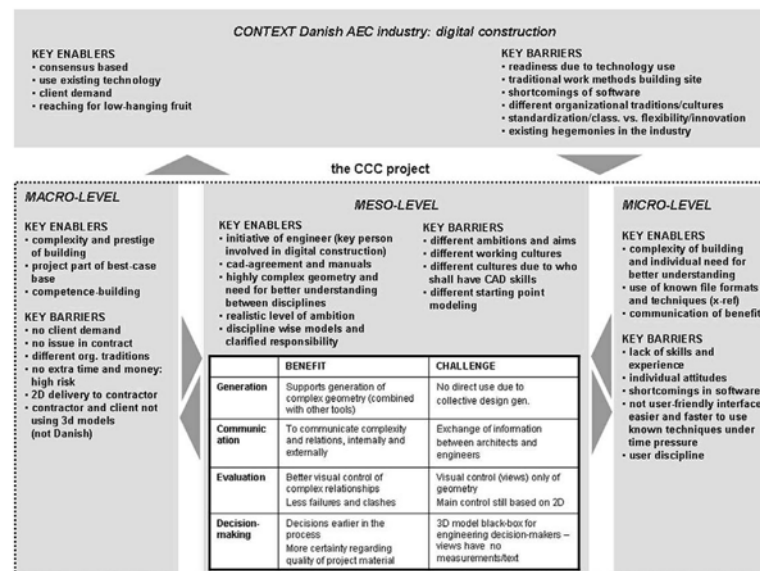
all four projects was that each discipline was responsible for their own model. All changes and adjustments were made in these discipline models, as they were also the basis for extracting drawings. The differences between the projects were related to whether they were exchanging information directly between the models or via a model server or a project web, and whether they were using IFC or proprietary exchange formats. Working with discipline models seemed to match with the traditional ways of working, thus enabling a smooth introduction for the practitioners to BIM (Fig. 6).

In the long run, the key persons behind the implementation expected many challenges to be turned into benefits. Although there were only minor expectations as cost or time savings in the projects, the actors involved hoped to reap a good harvest from the lessons learned, i.e. these then could be applied in the future projects and thus altogether raise their competitiveness within the AEC industry.

The Story of the HITOS Project

The client of the HITOS project, The Norwegian Agency of Public Construction and Property, called “Statsbygg”, is a powerful actor in the Norwegian AEC industry and an important participant in the efforts on national level for integrating ICT in practice. Today, Statsbygg is one of the major drivers behind the implementation of BIM and IFC in Norway, and they are involved in R&D projects on both national and international level (BuildingSMART, 2007). One important feature of their implementation strategy is the ‘doing it in real’, where new technologies are tested, improved and evaluated within the context of ongoing real life projects. ‘Statsbygg’ selected the HITOS project as the arena for such learning-by-doing. All actors involved in the project, from architect to contractor, were required to implement and use technologies supporting BIM. The client established an R&D project to go along with (and to succeed) the ongoing building project. This R&D project was based on a close collaboration between the design team, the con-

Figure 7. The multi-level model and key enablers and barriers identified in the CCC project (Moum et al, 2009).



tractor, the software vendors and the Norwegian BuildingSMART group (BuildingSMART, 2006). Through the R&D project, extra financial means and competence were available for testing and training. The scale of the HITOS project enabled an easier overview of the work and interactions of the project actors. Moreover, the contract enabled the actors to ‘play with open cards’ and to strive for the best solutions without defending positions and responsibilities. Furthermore, the commissioned design team actors knew each other well from previous building projects. Since several of these projects were college buildings, the team was familiar with the challenges related to the room program and to the functional constraints. And finally, particularly the architects and the HVAC engineers were trained in working with 3D object models. Thus, an important feature of the Statsbygg implementation strategy in the HITOS project, was their elimination of the “noise” and barriers that the practitioners were facing in the other cases, in order to establish the best possible basis for driving the implementation forward and to strive for a higher level of ambition.

The original ambition was to test out integrated and IFC-compliant BIM as well as conducting a series of related activities throughout the whole life cycle of the building; from programming to design, construction and service and maintenance of the building. Benefits, in the terms of saved costs or planning time were not expected. In the ongoing project situation, the ambitions had to be adjusted to the tight time schedules and to the fact that 2D drawings were the statutory documents of the project. According to several respondents, the implementation required more time than expected. Although several shortcomings of the technology could be solved throughout the project, the client and the design team actors pointed out that the BuildingSMART visions cannot be achieved in one project alone. Many challenges must be turned into solutions before IFC and BIM enable an operative working environment. The project was stopped after the conceptual design phase

for reasons not related to the use of technology. A report has been published regarding the experiences gained, however, these were related to technological aspects and the usability of the tools (Statsbygg, 2006). Statsbygg is following up these experiences in further pilot projects.

Synthesis

The findings above show that factors affecting the role of BIM are linked both to the implementation efforts and the strategies formulated (within national R&D programs or by the project stakeholders and managers), and to the experiences gained from using them in real-life building projects. An important and overall finding is that understanding and balancing upstream and downstream interrelations between these factors is crucial for the successful implementation and use of the new technologies (Fig. 9).

Findings 2: The Role of BIM in the Practice of Architectural Design

“What are the processes, strategies and routines within the building projects related to the generation of design solutions, communication, evaluation of design solutions and decision making? How do the architects and the engineers use the tools to perform these tasks? What do they find are the main benefits and challenges from this use?”

Based on identified barriers and enablers concerning the use of BIM, and the data explored, analyzed and organized by using the framework tools, the storytelling technique were used to communicate the broad and complex array of findings in the case studies. Five themes were identified as the most relevant and central issues regarding the use of ICT technology in architectural design processes:

- developing complex geometry
- achieving shared understanding

- the painful processes of change
- formalizing processes in a dynamic design environment
- from design to production

In the following some main points related to these five design team stories are presented.

Developing Complex Geometry

“...Not even in my dreams I can imagine how we could have developed this façade manually. We would then have no precise opinion about what we are developing (...) I have experienced that a detail at the foot of the building (...) triggered a chain reaction affecting the whole façade (...) I have no possibility to overview my problem complexity in a 2D drawing.” (Quote: Architect in the CCC project).

The architects were using several tools for supporting their design development, depending on the situation. Although BIM (alone or with rendering applications) was playing a crucial and positive role in the architects' individual development of the complex geometry in the CCC project, the technology had limited abilities for being the actual medium of the “design conversation”. The architects in all projects were using the BIMs rather for testing and evaluating the design ideas and the consequences of changes, than for creative sketching. In the case of several of the engineers, the BIMs played an even more limited role in their individual design development. Since they had no or minor skills in using CAD, a second party (the draftsman) was involved in the testing and evaluation part of the creative cycle.

“...we sometimes arrange small workshops where we discuss different issues in the building (...) then we go home and make some calculations and sketches which we send to the architect (...) Then the architects say; no, this is not what we want (...) it is a ping-pong; back and forth, back and forth, slowly getting closer to a solution.”

The structural engineer quoted above was describing the development of the design solutions in the CCC project as a “ping-pong” process between the architect and the engineer. The media used for collaborative design generation were in all projects rather traditional. The BIMs were playing an indirect role, as they were not used directly and real-time in meetings where architects and engineers together were developing the design.

Another challenge indicated by the practitioners, was the tightrope act between the appropriate level of detail for controlling and developing the complex geometry, and the abstraction needed for creative freedom; allowing change and improvement in a stage where a design solution still has not reached enough maturity. However, the use of BIMs was in all projects supporting the control of relationships and consequences of change, within both individual and collective design development. A last and related point to be mentioned here, was the strive for an information rich model at an early stage in the design process. In order to populate the models with the required information, the practitioners had to deal with decision-making traditionally related to the later phases in the process.

The need for an overview and control of a large amount of information and geometrical and functional relationships versus the ability of the technologies to address these needs (for instance through visualizations, consistency controls and automated take-offs) was a match that secured BIM an important role in evaluation and quality assurance of design solutions, and in decision making among the actors directly involved in design tasks. However, the BIM technologies could not replace the traditional tools in the intuitive and creative “conversation” between the designer and the design situation. Furthermore, the relation between the need for creative freedom and the striving for early precision was perceived as challenging.

Achieving Shared Understanding

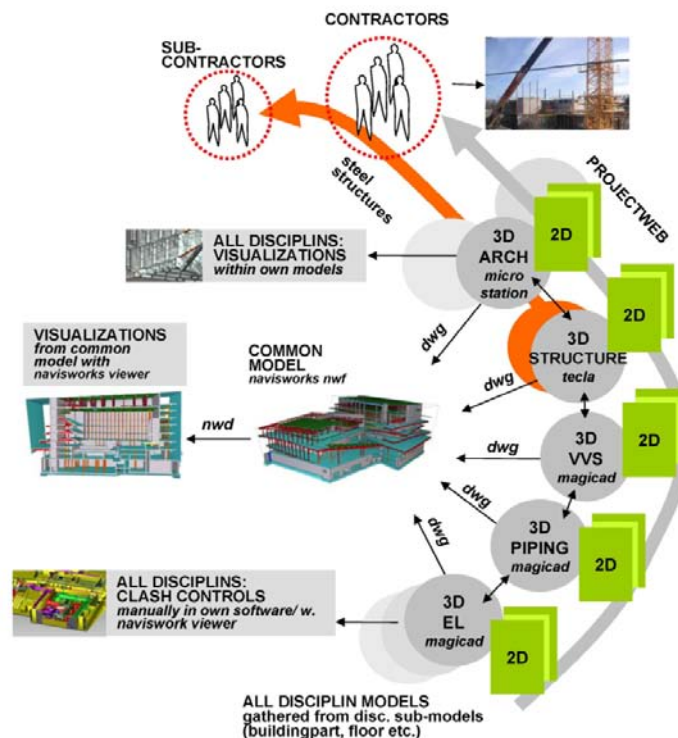
“... I do have problems with participating in [some workshop] discussions, because I cannot understand and overview the geometry in such a complex building (...) one [design meeting] topic has been the [rain] water drainage from the roof, and I was simply not able to understand where the rainwater would flow when it hits the roof (...) here it would have been enormously good to have a 3D model. Since 2D is flat, you lose some information. It would have been great to use the 3D model and a projector, where you can turn the building around, seeing the rain water flow in the wrong or correct direction.”

The project manager of the engineering team in the CCC project, points in the quotation above on a powerful benefit of using BIM in building projects. In all projects the interdisciplinary use

of BIMs contributed essentially to building up a shared understanding of intentions, needs and geometrical relations among actors representing different backgrounds, interests and positions (Fig. 8). Through visualizations and clash detections, geometrical conflicts and errors were easily recognized. Eliminating as many errors and conflicts as early as possible and to develop an understanding of the building and its performance *before* it gets built, was the central motivation for implementing and using BIM in all projects. The possibility to merge the different discipline BIMs contributed to -the design team actors’ - shared understanding of architectural intentions, structural constraints and the need for space.

Although all respondents pointed out the importance of the new technology in achieving a shared understanding of the building, they also emphasized the crucial role of face-to-face meetings in the initial phase of the project where they

Figure 8. The BIM system; software and applications in the CCC project.



The Role of BIM in the Architectural Design Process

discussed and worked out the prerequisites and outline for the further design development. In these settings, the BIMs were not used directly (with very few exceptions).

The many interests, backgrounds and experiences represented by the actors involved in the

architectural design process versus the potential of the technologies to enhance shared understanding (for instance through visualizations, views on the discipline models or the merged models, animations, and so on) was a “match” which, -in all four projects resulted in- several benefits and

Figure 9. Exploring the relation between strategies for implementation and the experiences gained from using them.

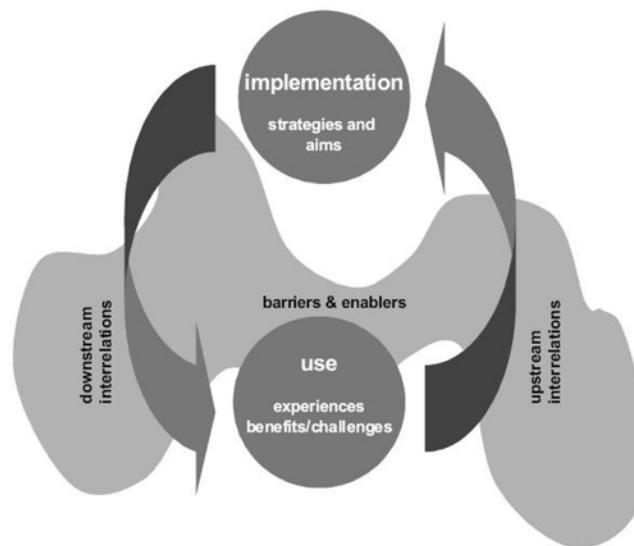
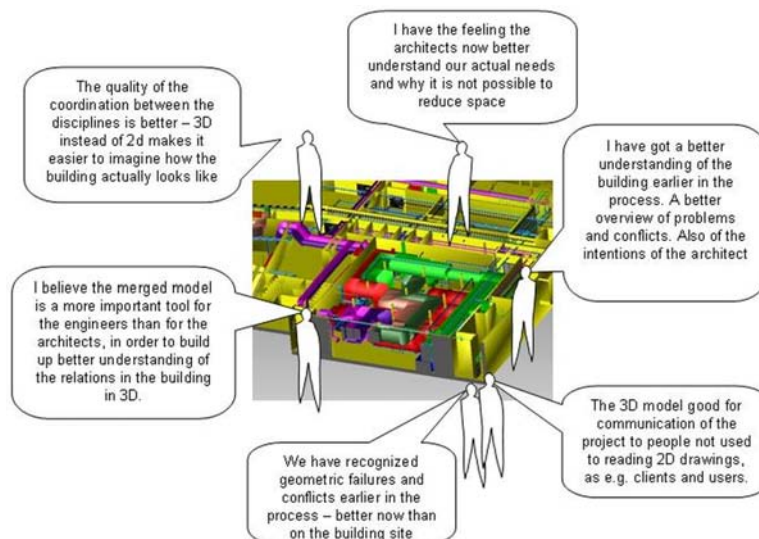


Figure 10. Shared understanding was perceived as a key benefit among the practitioners involved in the CCC project.



secured BIM an important role in the communication between practitioners on all levels.

The Painful Processes of Change

“We normally say; when we make decisions, there are loops, getting smaller and smaller, but they probably never disappear in our attempt to find the optimal solution. The process among the engineers is linear. They can get frustrated about the architects’ making changes, that things get re-designed. (...) Perhaps the architectural profession is more flexible regarding changes. We are used to doing last minute changes ourselves; in the case we get good ideas. Then the engineers often say no and stop; we are finished, we cannot change anything anymore. Here there is sometimes a cultural gap, since we all the time like to optimize. And then there have been all the changes we have no influence on, coming from outside (...) Of course, this leads to some frustration, but often this also motivate us.”

Crucial changes during the design process are triggered by many issues; for instance the architects’ initiatives and driving force to improve and partly re-design solutions, or new requirements emerging within the client organization. In the quotation above, the project manager of the architectural team in the CCC project pointed out a cultural gap between the architects and engineers regarding the handling of design changes, i.e. caused by different working methods, different consequences of re-design, and asynchronous time schedules (the engineer must deliver project material to the contractor before the architects).

In the projects, the frequent need for re-design and change before the overall design concept reached a certain level of maturity, was pointed out by several engineers as the reason for their hesitation in starting modeling in the early design phase. At the same time, it was necessary that all models had reached a certain level of detail before some interdisciplinary BIM activities could be

carried out (e.g. clash detections, simulations). This represented one contradiction between how the architects and engineers used to work, and what was required in order to could harvest the interdisciplinary benefits of using BIM.

In the HITOS project, the engineers reported that to model the HVAC and electrical systems required more work and accuracy than to rapidly draw some lines on a piece of paper. To change what was already modeled was perceived as time consuming. Despite the BIMs potential in enabling a high level of detail and information richness, this issue resulted in an “inner resistance” among the practitioners in changing or modifying solutions.

The need for maturing phases and time to think through and understand consequences on the one hand (leading to many changes), and the striving for saving time and speeding up processes on the other is another challenging contradiction. This “tightrope act” between allowing innovation and creativity, and optimizing and formalizing processes, leads us to the next theme.

The “two-steps-forward-one-step-back” process and the need for continuously improving and modifying design solutions versus the ability of the implemented technologies in enabling these interactions was a “mismatch” relation which resulted in several challenges with respect to collective design generation and to the exchange and communication of data and information between the design team actors.

Formalizing Processes in a Dynamic Design Environment

“We have a rule that says sometimes the detail wags the dog. You don’t necessarily go from the general to the particular, but rather often you do detailing at the beginning very much to inform.” (Lawson quoting Robert Venturi, 2006, p. 39)

The architects’ improvement of their design solutions and the complex decision-making pro-

cesses involving all project participants, are some of several factors leading to a dynamic design environment in the sense of being “cyclic” rather than linear. In the CCC project, the architects were continuously and rapidly switching between abstract and highly concrete level of details, without no logical direction from the general to the particular. The development of the building envelope in this project seemed to take place in a highly iterative and partly unpredictable design environment, where the design team worked with different design solution versions and media simultaneously, representing different levels of detail and what Lawson (2006) calls “parallel lines of thought”. The development of the building envelope with its tiresome and two-steps-forward-one-step-back process, and the up-and-down from the overall to the detail seemed to be essential for improving and optimizing the design idea. This relation between the dynamic design environment on one hand, and the potential of the technology to formalize, control and master the architectural design process on the other, was a hard-to-grasp but important issue in the projects, based more on observations than on explicit statements made by the respondents.

If we would remember the metaphors of “baking bread” and “playing jazz”, the BIMs were useful in supporting the “baking bread” part of the design process. For instance routine based activities, such as production of drawings or controlling of clashes, but when it came to support the “playing jazz” processes, there was a rather “mismatch” between the needs and the affordance of the technology. An issue which came up in several interviews was that the technologies used could not match the actual complexity of the architectural design process and the interactions of the practitioners involved.

From Design to Production

“We know that there is a benefit to work with 3D design. But it is also a big work load, at least

right now (...) The process of making the extractions, costs much energy (...) With the 3D model, you must decide 1-1 ½ week before we deliver [the 2D drawings]. Then we must make a plan about who is supposed to do what, because the 3D model comprises several models (...) there are many people involved in delivering these extractions, and there are many things that can go wrong. (...) it has been blood, sweat and tears, every time we must deliver; it is very real and very frustrating.”

The project manager in the architectural team of the CCC project pointed here a challenge, which was common for all projects. On one hand, the practitioners attempted to switch from a 2D based to a BIM based work method. On the other hand, they still had to produce traditional 2D drawings since these were the statutory documents of the project (the use of BIM limited to the design team). For example here a challenge was that the information embedded in the BIMs could not easily be ‘transported’ to the 2D environment, or the other way round. In all projects the 2D material had to be supplemented manually as textual information and measures, which was an error prone process. However, in the large-scaled AHUS project, the possibility to extract all necessary 2D drawings from one model, represented a big benefit due to the vast amount of project material required.

In the same project, they were facing another central problem. What about the instructions for the building site given by the traditional details? In all projects these were prepared manually by hand. In the AHUS project, the practitioners had to handle several challenges arising out of the unavoidable information overlap between the 2D details and the 2D sections extracted from the BIM. Since there was not enough time to update the sections due to other activities with higher priority, the details were more updated than the (derived) sections. This situation resulted in confusion among the contractors about where to look for the updated information. The respondents called here for a

possibility to implement an “intelligence” between the 2D details and the BIMs.

A long term approach to “untie” this knot of challenges could be to strive for a situation where the BIMs replace the need for 2D material throughout the whole building lifecycle. The project participants did however agree that there is still a long way to go until the BIMs have replaced the 2D drawings on the building site. They thought that the contractor will likely play a more active role due to the use of BIMs in the future (at least regarding the bidding, the tendering and the construction management), but doubted a rapid adoption by the building site’s craftsmen. However, in two of the studied projects, 3D printouts from the BIMs were used as a visual aid regarding complex geometrical relationships (e.g. the “spaghetti” of pipes and ducts in technical rooms) on the construction site.

A happy story told in the CCC project was about using the 3D object model for pre-fabrication, which appropriately rounds up the experiences explored in this paper. The BIM of the steel structures were sent (via the Icelandic contractor) to a Chinese subcontractor, who supplemented the model with the necessary information needed for production. Shop-drawings were then sent back to the engineers in Denmark, who controlled them carefully, before the steel elements finally were pre-fabricated.

Altogether, the interface between design and production versus the potential of the technologies to enable consistent information flow between project phases comprising different tasks, needs and actors, was a source of many challenges in the daily work of the practitioners involved in the architectural design process.

5 FUTURE TRENDS

The practitioners involved in the current AEC industry face a shift from 2D and document-based design tools to technologies supporting 3D object-

based modeling and BIM. However, a paradigm shift as suggested at an international information seminar on IFC and IAI in Oslo 2004, has not yet found its place in the case studies reported in this chapter. The respondents generally agreed that the fulfillment of the R&D visions formulated by, for instance, the IAI and BuildingSMART, is some years in the future. However, the experiences gained in these projects indicate some future trends within the practice of architectural design. These trends are here related to the three levels proposed by the framework; the macro-, meso- and micro-level.

The Macro-Level: The Overall Project

Typical benefits in the studied projects were related to the achievement of a shared understanding of the building before it gets built, and to the certainty that the design solutions address the requirements of the clients and users. In these and in many other current projects, the use of BIM is limited to some few actors or to single phases (even in the projects rewarded with the TPA BIM-reward in 2008). The usefulness of BIM is, however, closely related to the distribution of the technologies across *all* actors and phases. Such a full distribution would require a powerful “implementer”, well working technology for all parties involved and available resources for the upgrading of competences and skills.

Central challenges here are related to the interfaces between actors and phases. Future trends addressing these challenges could be the shift to integrated practice and the use of partnering contracts. Today, there seems to be a trend that companies controlling bigger parts of the horizontal (architectural and engineering companies) or the vertical value chains (design-build companies) are the ones most interested in implementing the new technologies.

Furthermore the findings of the research indicate that more effort is necessary earlier in the process (for the designers), in order to harvest

benefits later in the process. The strive for more certainty and an elaborate level of detail and information richness earlier in the process, as well as the involvement of actors traditionally contributing in the later phases, increase the complexity of the architectural design process even more. This “front-loading” of efforts requires a comprehensive understanding of interdependencies and interfaces among the project and design managers, which reaches beyond their own discipline and company. A crucial challenge is to define the appropriate level of detail to be addressed in the BIMs.

Another trend is related to the interface between design and production. The prefabrication of building components offers a fertile soil for BIM to bridge gap between design and production. Hereby new market situations and business models could arise, impacting on the whole value chain of building projects; from the existing hegemonies on AEC industry level, to contracting issues on project level, to collaboration forms on design team level, down to the role and work of the individual designer. These trends are likely to be further triggered by current research efforts for pre-defining and standardizing building objects, components and processes (for instance the IFD libraries and the IDM process descriptions).

The Meso-Level: The Design Team

An obvious benefit of using BIM is the better control of geometrical relationships between the disciplines at an earlier stage in the process. A more shared understanding of aims and intentions supports the collaboration between the architects and engineers. Although there were no precise documentation of actual savings of costs related to errors and conflicts in the drawing material in the studied projects, there seems to be a clear trend towards the delivery of more coordinated and correct project material to the future construction sites.

The findings indicate a need for simultaneous development and specification of geometry and design information across the design disciplines to enhance the potential of the technology to support interdisciplinary work. In many projects, the architects and engineers tend to develop their design solutions successively (for instance; at first the architect, then the structural engineer, followed by HVAC and the electrical systems). This sequential approach is empowered by an array of factors, from contracting models, payment issues, to how the time schedules are organized. An effect of BIM could be enabling more integrated ways of working and collaborating – an effect which is promising in regard to building down established barriers and reducing fragmentation in the AEC industry. Nevertheless, this will result in the need for organizational reorientation and rethinking, and the handling of many challenges, i.e. related to the upgrading of the practitioners skills in modeling, or related to setting up schedules or dealing with late changes. The time schedules in many current building projects are based on an overlap between design and production (for instance in the CCC project), where the different disciplines are delivering their “packages” to different points in time. An effect of BIM could be the need for completing the design phases among all design disciplines before the delivery to the construction site or to the production companies.

The Micro-Level: The Individual Practitioner

To “see” the design solutions in 3D before it gets built, or to test and evaluate the consequences of the own or others contribution on the building design, can be listed as powerful benefits of BIM. The possibility to generate drawings and quantity lists from the model is timesaving, at least when the software enables the extraction of project material addressing the actual requirements of the deliveries.

What would be the consequences for the practitioners involved in building projects where BIM is broadly implemented? First, they will need adequate skills in using the tools, which again requires enough time and resources for learning and testing. They should work precisely and disciplined, as unrecognized failures and inconsistencies in the models would impact on the correctness of take-offs, simulations and calculations. They must start early with building up models. They must handle the challenges of making early decisions and of populating the models with required information in a phase where much still “flows” and has not settled down. These are only some examples of effects the architects and engineers might face in future projects.

One of the respondents in the AHUS project commented;

“The designer should not only learn to model, but also to think in an object-oriented way”.

In all four real-life building projects, BIM was adapted to traditional processes and established practice of architectural design. The implemented technologies have not fundamentally changed the practitioners’ work and interactions. A shift from established practice to a new practice (which we still do not overview), would require that practitioners do not only have to adapt new tools, but also new ways of working. Additionally, the questions arise; What would be the future role of the traditional professions? What would be the required competences of architects and engineers, involved in design and management of building projects? An array of unpredictable factors are likely to impact the future practice of architectural design. For example, the designers of tomorrow are the children of today, growing up with high-tech devices in their nursing rooms. The new generation of practitioners will have a much better basis for dealing with computer interfaces than the practitioners of today.

6 CONCLUSION

The findings presented in this chapter show that BIM is powerful in its support of many central activities in the architectural design process. The role of BIM in the architectural design process seems to have gained foothold particularly related to what could be seen as the “baking bread” parts of the processes. However, the findings also clearly show that there is an array of barriers and challenges to be handled before the full concept of BuildingSMART and BIM is operable in real world practice.

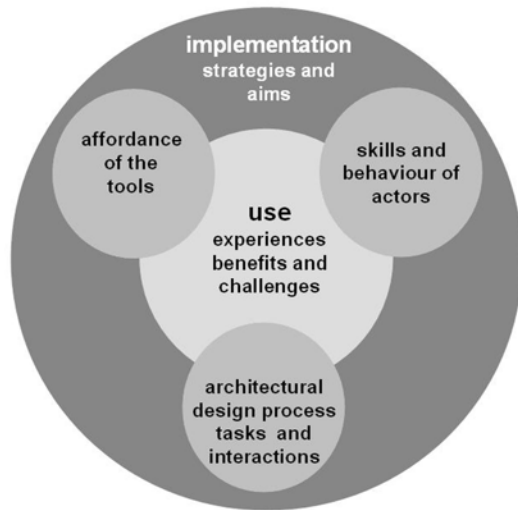
The many enablers and barriers presented in this chapter can be particularly related to three main areas:

- The skills and behavior of the project participants when it comes to adapting to new tools and related work methods
- The affordance of the tools with respect to the complexity of the work and the interactions of its users
- The tasks and interactions embedded in the practice of architectural design

The “wheel of tasks, tools and skills” below attempts to illustrate the relation between the efforts for implementation, the three main fields of enablers and barriers, and the practitioners’ perceived benefits and challenges from using BIM (Fig. 11).

It is likely that skills and tools will be substantially upgraded in the next few years. Also in the case studies, much of the focus of both the R&D efforts and the project actors was on upgrading skills and on improving technology. The practitioners could report steep learning curves and a continuous (although slower than expected) improvement of the tools. Nevertheless, a large number of the identified barriers and challenges are linked to the nature of the architectural design process, particularly to the “hard-to-grasp” and

Figure 11. The wheel of tasks, tools and skills.



“playing jazz” features of individual and collective design development.

One of the practitioners interviewed pointed out that the world of practice is not as easy as some software vendors might believe. A conclusion of this research is that the role of BIM in the architectural design process is affected by the many interdependencies, relations and interfaces embedded in the highly complex and partly unpredictable real world practice. A future challenge of implementing and using BIM would be to understand, master and balance these relationships - upstream and downstream across multiple levels and across processes and activities. The elements of the wheel illustrated above must be brought into balance before it can roll smoothly into the future of architectural design practice.

The presented holistic research approach and the findings generated by its application contributes to research which aims to embrace the complexity of real-life problems and to gain a more comprehensive understanding of what is going on in practice. Each identified enabler, barrier, benefit and challenge would merit further examination. More knowledge *about* current practice, together with appropriate approaches and methods for “unlocking” knowledge *in* practice,

establish an important foundation from which to tackle and have impact on the changes to come. This work represents one of many bricks in this foundation, where the connecting and stabilizing mortar should be the practitioners’, researchers’ and academics’ shared responsibility for ensuring good architecture and physical environments.

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KEY TERMS AND DEFINITIONS

BIM: Building Information Model or Building Information Modeling. According to Kiviniemi et al. (2007): "*BIM (Building Information Model) is an object oriented, AEC-specific model – a digital representation of a building to facilitate exchange and interoperability of information in digital format. The model can be without geometry or with 2D or 3D representations.*" Bazjanac (2004) defines BIM to be: "*(...) an instance of a populated data model of buildings that contains multidisciplinary data specific to particular buildings which they describe unambiguously (...) a BIM includes all relationships and inheritances for each of the building components it describes unambiguously. (...) A three-dimensional 'surface' model of geometry alone that is used only in visualization is usually not a BIM.*" **A BIM does not have to be connected to a geometrical model**, and a 3D object model is not necessarily a BIM. However, on the CIB W78 conference in Maribor 2007, "Bringing ITC knowledge to work", some of the key persons behind the development of these technologies agreed to use BIM as a "collective term" for both 3D product and object models, and "true" BIMs. In three of the real-life projects referred to in this chapter (CCC, AHUS and AUDI) the main focus was on geometry-related 3D object model activities. The single discipline models were to some extent populated with object information and attributes, and can this be regarded as being "small" BIMs. However, the actors were not exchanging and sharing this information with

other project actors. In the HITOS project the actors attempted to implement integrated BIM, by Kiviniemi et al (2007) defined as:

“A Building Information Model whose information needs to be shared and thus warrants open international standards for information sharing.”

BuildingSMART: An introduction to BuildingSMART, from the public web site of BuildingSMART, Australasia Chapter of IAI (International Alliance for Interoperability), <http://buildingsmart.org.au>, retrieved June 2008:

“BuildingSMART is integrated project working and value-based life cycle management using Building Information Modelling and IFCs.”

Architectural Design Process: Positioned between the statement of the brief (more or less defined) and the start of the building production. The expression “practice of architectural design” is in this chapter used to emphasize that this chapter deals with the architectural design process related to practice and to situations in real-life projects. A thorough description of various characteristics of the architectural design process is given in part 2 of this chapter.

Practitioner: From an overarching view, in this chapter practitioners are the actors involved in the AEC industry. The main focus is, however, architects and their interactions with other actors involved in the architectural design process.

Enablers and Barriers: The terms enablers and barriers are in this chapter used for describing some central premises for implementation and use of technology in the studied building projects. An enabler supports and facilitates implementation (e.g. extra time and money available), while a barrier impedes implementation and use (e.g. the users’ lacking skills).

Benefits and Challenges: A benefit from use of BIM can be quantitative and measurable (e.g. cost and time savings) or qualitative and hard to grasp (e.g. more shared understanding). The term challenge describes a demanding situation or task resulting from using BIM (e.g. the need for making decisions earlier in the process).

Implementation of BIM: Means here activities putting the use of BIM into effect.

Use of BIM: Relates in this chapter to how the actors involved in the architectural design process practice BIM in their work and interactions; individually and within a discipline, and collectively and across the disciplines.

Chapter 27

Lean Enabled Structural Information Modeling

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ABSTRACT

Lean production revolution started in manufacturing with origin in the Toyota Production System (TPS). Since Womack, Jones, and Roos (1990) announced this concept as a new production paradigm, various industries including the Architecture, Engineering and Construction (AEC) Industry have paid attention to its possible applications. While design, engineering and building practices in AEC are substantially different from manufacturing, the ideas drawn from Lean Production can be tailored for the AEC environment. The synthesis of lean production principles and techniques applied in AEC form the basis for a Lean Project Delivery System™ (LPDS). The principles of LPDS and Building Information Modeling (BIM) technologies offer new approaches and opportunities to improve the quality, cost, schedule and productivity of building products in a highly fragmented multi-disciplinary sector. The case study presented in this chapter provides an overview of the synergy between the principles and tools of LPDS with BIM technologies used at the California Pacific Medical Center's (CPMC) Cathedral Hill Hospital (CHH) project in San Francisco, California.

1 INTRODUCTION

AEC industry is one of the largest and most complex industries in the world. Yet, it has lagged behind many other sectors in embracing new technologies that add more value to all the parties who participate

in the process. The traditional tools and techniques of information flow (2D drawings, Gantt charts, spreadsheets, tables, etc.) fail to engage the critical players (stakeholders) who need to analyze opportunities to improve the project design and execution from multiple perspectives in a timely manner. As a result, the project development process is often not efficient nor effective. Opportunities to improve

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Figure 1. Five Big Ideas



the constructability and usability of the design are missed, and the seeds for process inefficiencies such as overproduction, rework, and poor allocation of resources are sown.

This chapter explores the current state of Structural Information Modeling (SIM) practices in LPDS. The “Lean enabled SIM” processes described here are the best practices adopted by the “structural cluster” to enhance the collaboration between the design team and trade partners at the CHH project.

CHH is a new Acute Care and Women’s and Children’s hospital in San Francisco, California with 1,113,249 Building Gross Square Feet. The parcel size comprises approximately 105,800 square feet measuring 385 feet by 275 feet. The Preconstruction phase, including a Validation Phase, Design Phase and Construction Documents phase, began in 2007. Construction is scheduled to begin in 2010 and complete by the end of 2014.

Sutter Health, one of northern California’s largest health-care providers, is committed to “lean practices” as a new design and construction philosophy to execute major capital projects. As a part of this lean implementation, Sutter Health intends to reform the way buildings are designed, engineered, and constructed. Sutter Health em-

phasizes the following “Five Big Ideas” with its project delivery teams:

1. Collaborate, Really Collaborate
2. Manage as a Network of Commitments
3. Increase the Relatedness of the Project Participants
4. Tightly Couple Learning with Action
5. Optimize the Project as the Whole

This chapter focuses on LPDS techniques that are tailored for the effective use of SIM technologies to optimize design and planning during preconstruction phase. Design professionals and trade partners must embrace “Lean enabled SIM” processes and ideas to find the innovative approaches that maximize the value in the project.

2 BACKGROUND

The AEC industry is on the verge of a major transformation in terms of tools, processes and relationships precipitated by the advent of two major developments: LPDS and Building Information Modeling (BIM).

Figure 2. CPMC Cathedral Hill Hospital – Conceptual Rendering



BIM is a concept that many people in AEC industry talk about these days; even though there is no agreed definition of BIM. Professor Charles M. Eastman at Georgia Institute of Technology may have coined the term which is basically the same as Building Product Model, which Professor Eastman used extensively in his book and papers since the late 1970s. BIM involves designing, analyzing, integrating, and documenting a building's lifecycle by developing an intelligent virtual building prototype using a database of information. Besides simply developing the design in these parametric modeling tools, BIM software can embed information into the design which allows numerous opportunities for analysis of the design, ranging from cost estimates to energy analysis, and many more. While the tools offer benefits in terms of 3D visualization and parametric modeling, the BIM analysis tools have garnered much attention. These tools are valuable to perform analysis (more easily) on the building design, and to share the comparative analyses of design and performance factors. As BIM spreads in the AEC industry, structural engineers as well as other design professionals will explore how to best utilize this technological advancement. Some

recent statistics (McGraw-Hill 2007) state that the U.S. structural engineering industry will reach a critical point regarding BIMs in 2008.

The Lean Construction Institute (LCI) defines LPDS as the intersection of projects and production systems. In LPDS, the projects are managed as value-generating processes. All stakeholders are included in the planning, design and optimization efforts to ensure a reliable work flow through “pull-scheduling techniques” that organize the flow of materials and information. LCI proposes the following essential features for LPDS:

1. A clear set of objectives to establish the delivery process. Customer needs and requirements must be well understood.
2. A cross-functional team designs product and process concurrently to give more value to the customer. This parallel design process encourages positive iteration within the process and discourages negative iteration.
3. A work structure of the entire process to increase value and reduce waste at the project delivery level. Improved performance at the planning level increases performance at project level.

The adoption and adaptation of these lean production concepts and principles have been increasingly employed in AEC industry, especially after 1992, when Koskela conceived an overarching production management paradigm for project-based production systems by using TPS. Koskela presented the “Transformation-Flow-Value” theory of production. Production was conceptualized in three complementary ways, namely as a;

1. Transformation (T) of raw materials into standing structures,
2. Flow (F) of the raw material and information through various production processes,

3. Value (V) generation and creation for owners through the elimination of value loss.

3 LEAN ENABLED SIM

SIM Overview

SIM can be defined as a subset of BIM: it contains information related to structural engineering and therefore also information that fulfills the structural analysis procedure. The elements within the SIM model contain geometry, materials, sectional properties, load groups etc. as well as their purpose within the structure, resulting in a wealth of information that is used for various applications. With the use of SIM technologies, information needed for a project's design, engineering, planning, construction and operation will be contained in digital models. Advantages of SIM in design and construction include better communication and visualization, greater predictability of cost and schedule, avoidance of construction conflicts through simulation, higher quality, less rework, better site planning and logistics,, and a repository of design and construction data for use in facilities management.

The design and engineering BIM platform used in the project is Autodesk Revit 2009. Smithgroup (Architect of Record) was on Revit Architectural 2009, Degenkolb Engineers (Structural Engineer of Record) was on Revit Structural 2009, Silverman & Light (Electrical Engineer of Record) was on Revit MEP 2009 and TJEG (Mechanical Engineer of Record) was on Designline.

In CHH, Degenkolb Engineers took the lead in creating and maintaining the SIM; hence, SIM started within Revit Structural model and its development involved the following steps:

- Import of the design model into the analysis models (ETABS lateral and gravity models & SAFE foundation model)

- Creation of floor 2D plans by extraction from 3D model
- Development of cross-sections of composite plans
- Coordination with the architectural model
- Creation of drawing sheets from the composite plans
- Creation of drawing sheets for permitting agency

The use of SIM allows the following functions:

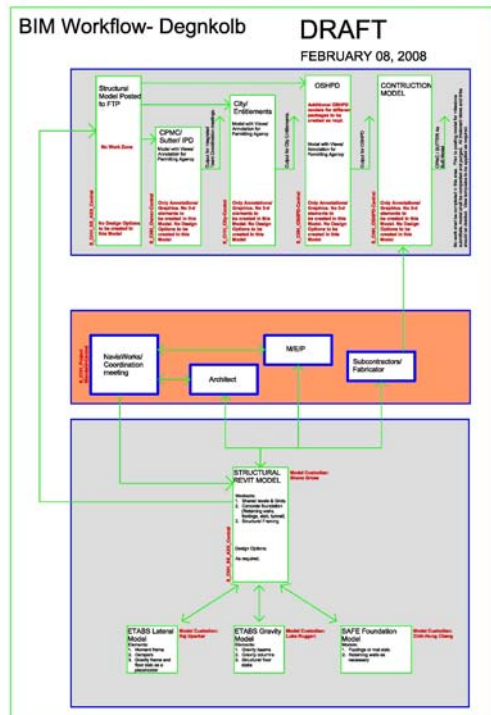
- Sharing of SIM with the integrated team on a regular basis (weekly)
- Visualization of project geometry
- Interference detection with other trades and disciplines
- Generation of 4D simulations to analyze construction options
- Analysis of multiple design options
- Creation of quantity schedules for steel, concrete, metal deck and shoring system
- Storing and managing loading requirements and design code related information
- Managing drawings for the government permitting agency
- Coordination of site logistics – tower crane placement, truck traffic, temporary construction barricades

Structural Design and Permitting Process

The gravity load resisting (structural) system consists of concrete fill on composite metal decking, supported by steel beams, girders and columns. The foundation consists of shallow spread footings at the interior columns and an eccentric strip footing at the perimeter basement walls.

The lateral force resisting system (LFRS) design is controlled by seismic design forces. Steel moment resisting frames and supplemental viscous

Figure 3. BIM/SIM workflow by Degenkolb Engineers



damping devices constitute LFRS. This system provides superior performance when compared to a conventional steel moment resisting system. The damping devices substantially reduce the inter-storey lateral floor displacement and accelerations, thereby reducing the overall quantity of structural steel required to resist seismic forces. This reduces the (risk of) displacement and acceleration-based damage to nonstructural components.

The Office of Statewide Health Planning and Development (OSHPD) is one of the thirteen departments within the California Health and Human Services Agency. OSHPD administers programs that implement the vision for “Equitable Healthcare Accessibility for California”. Existing law requires OSHPD to review the design documents and to inspect hospital construction or alteration projects to ensure that such buildings comply with applicable standards. Hospital

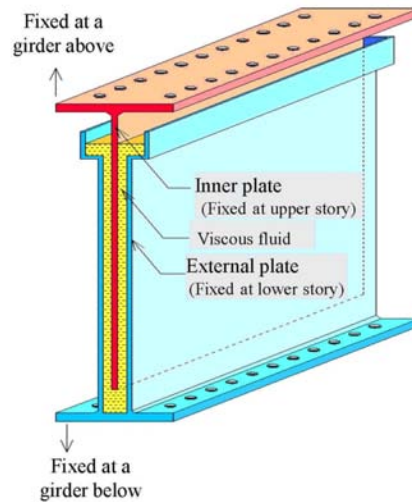
projects are usually very complex projects that take three or more years from design to permit. Limited resources, working with large batches, changes in hospital equipment technology and poor integration of design and construction create additional challenges during the review and approval process.

To improve this process, leaders from the AEC industry and the hospital owners initiated the adoption of lean principles and tools to enable a more collaborative relationship between the OSHPD and the AEC industry. Following the initiatives led by the AEC representatives, the lawmakers passed SB 306 bill, dated 2007 to allow OSHPD to enter into a written agreement with a hospital to provide a “phased submittal” and “conditional approval” of the hospital’s construction plans. In “phased submittal” agreements, the design team and OSHPD agree on a detailed list of items and/or systems that will be reviewed and accepted for each “phase,” and a realistic timetable for the submission and review of each “phase.”

Phased-review offers the potential to reduce the overall time to permit by Agency and to reduce engineering rework by establishing early agreements in criteria. As the code is not absolutely clear in all areas, the phased-review process identifies areas of ambiguity and reduces uncertainty. The process reduces engineering rework by catching the problems early, and correcting them before they propagate into later design.

“Lean enabled SIM” allowed the design and construction team to produce earlier design documents with higher quality and greater confidence for regulatory review. It also enabled the integrated team to study the constructability issues early in the project and to produce cost models to inform both the design and the owner’s business plan. In these ways, the SIM functions as a collaborative tool by which the regulatory agency team members are integrated into the process to minimize the rework and overproduction. Phased review process encouraged the team that there is more potential to use the SIM in support of the code enforcement

Figure 4. Viscous wall damper by DIS



role digitally and virtually (as a participating and contributing team member).

Contractual Framework and Team Formation

Sutter Health promotes the concept of a “self assembled” team; that is, a team that selects its members collectively as it grows. In CHH, as Sutter Health adopted lean principles, it demanded that the trade partners learn the skills needed for LPDS, develop an internal implementation strategy (with measurement of progress), commit to continuous improvement and share the learning in our project community.

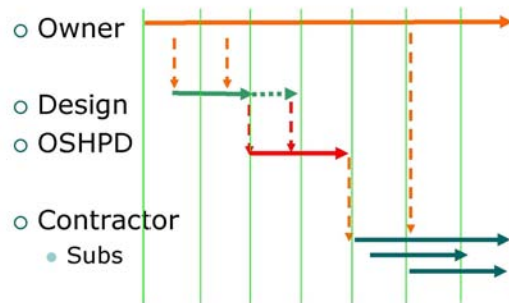
Initially the contract established ties within a core group, and subsequently added members to the team through “joining agreements.” The structural “cluster” team initially comprised HerreroBoldt (HB) as the Construction Manager (CM)/General Contractor (GC), SmithGroup (SG) as the Architect, Degenkolb Engineers (DE) as the Structural Engineers of Record (SEOR), Dynamic Isolation Systems, Inc. (DIS) as the vendor for viscous wall damper devices, and Pankow Builders (PB) as the concrete and rebar trade partner.

These companies formed the “Structural Cluster” during the first “Validation Study”- a process of business validation to assure project ends, means and constraints are aligned at the very outset of the project.

As design evolved, the IPD team needed more expertise for better decision making in design and cost management. The core structural team proceeded with the selection of an additional companies for various scopes: The Herrick Corporation (THC) for the structural steel fabrication & erection; Pacific Erectors (PE) for the metal deck fabrication & installation; Malcolm Drilling (MDCI) for design/build earth retention system; Olson Steel for the metal stairs and miscellaneous metal work. The design team and the trade partners selected the new partners using the Request for Proposal (RFP) process to define the expertise and skills complementary to the cluster, and to make sure that the incoming members showed a willingness to embrace true collaboration and the Integrated Project Delivery (IPD) process.

The Integrated Form of Agreement (IFOA) is crucial for the Implementation of “five big ideas”. The IFOA, a “relational contract”, fosters an environment of collaboration and innovation on the

Figure 5. Conventional OSHPD Permitting Process



project. Relational contracts involve a philosophical change from traditional construction contracts and are instrumental for the implementation of lean project delivery. The traditional contract approach binds specific individuals to specific tasks by separating the owner, design professionals, contractors and suppliers into discrete worlds; relational contracts create a system of cooperation, shared responsibility, rewards and risk, all tied to the amount of value generated by the end product. More specifically, relational contracts encourage the following principles:

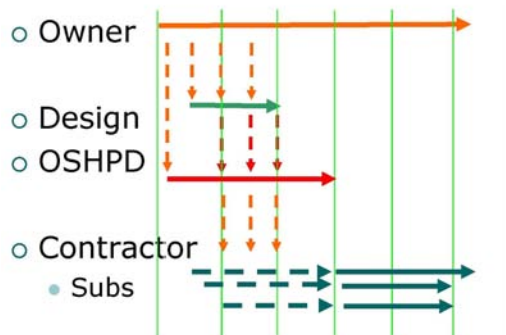
- Promote Integrated Project Delivery Team (IPDT)
- Select cost-plus CM/GC early
- Select specialty trade partners early
- Share risk among owner, designers, and contractors

- Explore incentives for achieving goals
- Share intermediate design documents
- Include CM/GC and trades in the design process
- Include the design team in the construction process
- Identify risks and opportunities throughout design
- Manage design and construction risks jointly

Lean Design Principles

Recent changes in project delivery methods in design and construction affect the roles of the design professions and the supply chain players. Currently, it is not very clear how the new design collaboration will take shape. In this uncharted area, design professions that traditionally took

Figure 6. “Phased Review” OSHPD Permitting Process



the role of design manager now find themselves participating in previously unforeseen contexts, working in multidisciplinary teams led by contractors and with new responsibilities at the design stage. At the same time, supply chain members, not previously involved during the early project definition phases, are engaged at the earliest phases of the project life cycle. In addition to these changes, the introduction of BIM technologies adds another level of complexity and ambiguity on traditional responsibility. Lean design has the following essential features;

- 1) Set based design
 - An iterative process of developing sets of solutions that satisfy cost, function and quality
 - Sets of solutions are advanced until the last responsible moment
- 2) Sharing incomplete information often
 - Willingness of team members to continuously share incomplete information
 - Daily or at least weekly sharing of design and budget information
 - Design and budget evolve simultaneously
- 3) 3D design/modeling and digital prototyping
 - Use digital prototyping to integrate design and cost characteristics
 - Provide widespread team access to the design model as it evolves
- 4) Detailed design by specialty contractors and vendors
 - Designers and engineers produce only those deliverables needed for permitting and needed by specialty contractors or other suppliers for detailing and for permitting agency
- 5) Multidisciplinary design teams
 - Designers, constructors, major specialty contractors and suppliers are contracted early

- Value-based proposal process
 - Specialty contractors and suppliers work together early in the design phase to simultaneously develop the design and budget
 - Multidisciplinary teams meet at least weekly
- 6) Production planning and management
 - Production planning and management are applied during the design phase
 - Design and budget production are planned and managed to emulate a continuous flow process

At the start of the project, the “information gap” requires a massive amount of information to be exchanged. At this stage, the team members organized the information to validate the initial design assumptions, optimize and influence design, to validate cost and schedule, and to analyze constructability issues. The “design optimization” process between Degenkolb Engineers and THC involved some good examples of this.

First, THC worked with Degenkolb Engineers to establish column splice locations so they could be accurately portrayed within the model. This becomes important to define the sequence of erection using 4D software tools to sequence erection and to define items that are required early to accommodate other trades.

Second, the automated Bill of Materials (BoM) allowed the team to identify and quantify constraints on material availability. By overlaying the BoM over rolling schedules from foreign and domestic mill, Herrick segregated and priced the materials based on source. The IPDT also identified structural element in the model that are not readily available from any source.

Third, Degenkolb Engineers “tagged” structural elements in the Revit SIM by system (gravity and lateral) to identify those structural elements that require supplemental seismic provisions, such as impact testing and special weld inspection, from gravity elements, where no such requirements

Lean Enabled Structural Information Modeling

exists. Although the premium may only be \$20 or \$30 per ton, this is a substantial variable on a 10,000-ton project.

The typical collaboration cycle at CHH project, depicted in Figure 7, involves the major data-sharing and communication between the various team members within the structural cluster.

The model provides a clear and vital understanding of the “upstream” and “downstream” players and their needs in the project. Understanding the ‘upstream’ and ‘downstream’ players’ concerns requires implementing lean techniques such as process mapping, weekly work planning (WWP), a scope matrix, and weekly design coordination meetings.

Communication and Information Exchange

The structural cluster used a number of tools during the design meetings to maximize the com-

munication and facilitate the discussion. Figure 8 shows the screenshot of the programs opened in a typical structural cluster session.

The Autodesk Design Review, a viewer program, has a “compare” capability to compare two versions of the same 2D drawing file. Differences are identified as additions and deletions, thus, if a piece of geometry changes, it shows up once as added information and again as deleted information. Designers and trade partners very quickly see the changes. Weekly model changes narrative also played a very important role for the downstream users to see the changes made in that week. The bullet point list typically included 8 to 12 highlighted items with clear descriptions and the reasoning for the change.

A constraint log is used to track and document the issues that affect the design development with action items. A key challenge of a large project is the transmission of information to downstream players in a way that is meaningful for them. Revit

Figure 7. Structural Cluster Weekly Work Plan

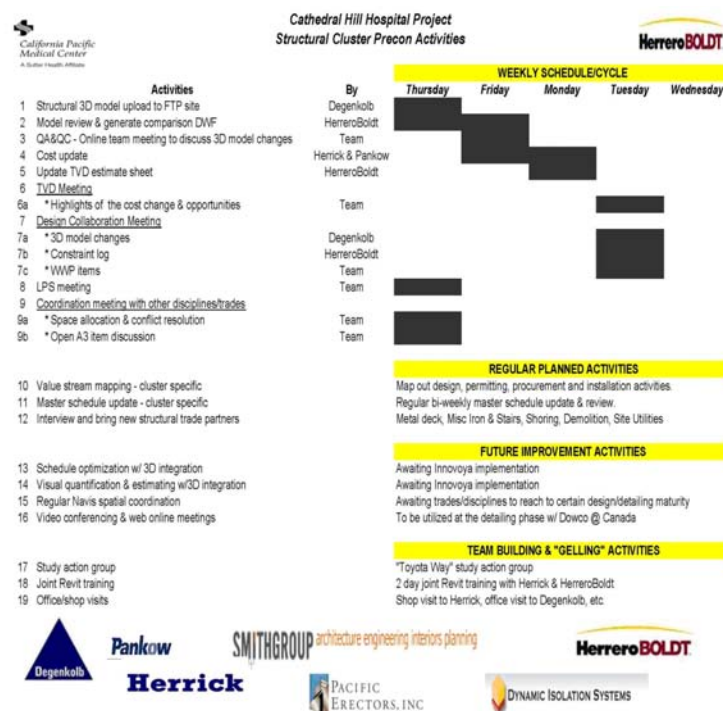
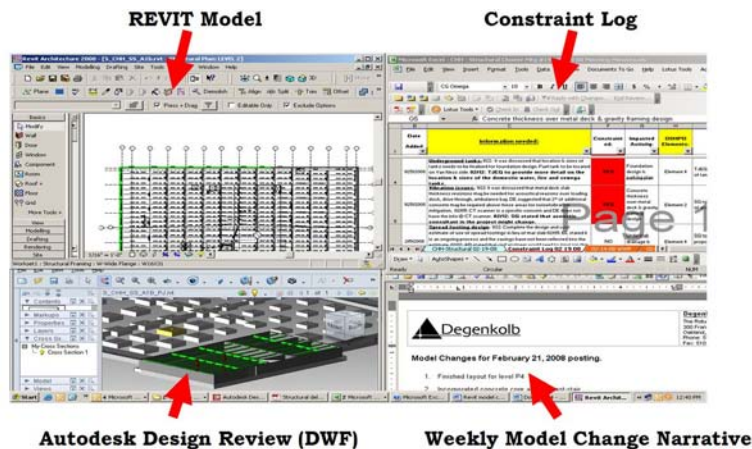


Figure 8. Tools Used for Information Exchange



offers several options for collaboration modes for this purpose. Structural cluster used importing/exporting standard CAD file formats (such as DWG, DXF, and DGN), bidirectional linking from/to AutoCAD Architecture (architectural models), linking directly to an existing Revit Architecture (building model), and OpenDatabase Connectivity (ODBC) compliant downloads to other programs used for cost estimates and other reports. ODBC connection is useful for integrating data-centric applications (such as specification management and cost estimating) with BIM software.

Target Value Design (TVD)

The Owner's basic value proposition is to build the project for no more than the "Expected Cost". The IFOA is used on this project in conjunction with target costing to achieve this goal. Cost targets are set for the scope of the work, and each set of design alternatives is evaluated for total value. The aim of target costing is not to minimize project cost; rather, it is to maximize value generation while remaining within the allowable budget. This effort can result in shifting costs from the construction phase to the design phase, or between target cost categories (e.g., on Cathedral Hill, fabrication drawing production which typically

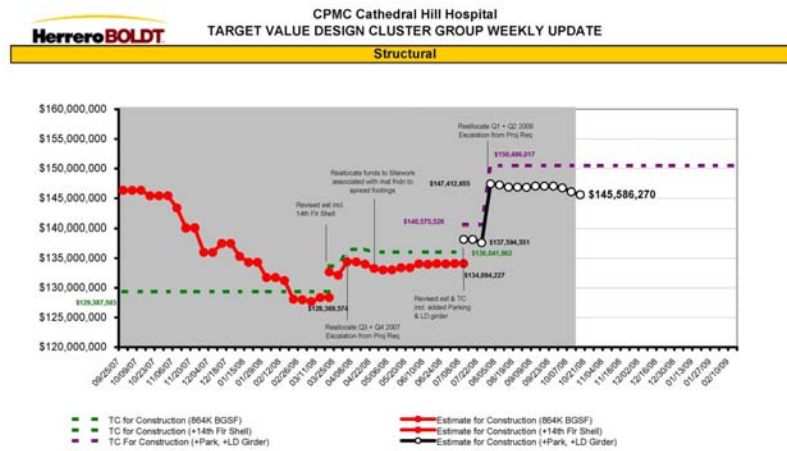
is accounted for as a construction cost, took place during design). The owner's willingness to invest upfront pays for production of details well before construction begins.

Continuous cost analysis and reporting procedures ensure that "Target Value Design" (TVD) is maintained. The cross-functional teams (clusters) monitor estimated costs against target costs each week. The key concepts of TVD are:

- Continuous cost analysis and reporting procedures within the cross-functional teams (clusters) for monitoring estimated costs against target costs
- Method for forming and meeting structure for cross-functional teams (clusters) of designers and trade partners for major components and systems of the structure
- Work together to define the issues and produce decisions then design to those decisions

Continuous cost updating is necessary for "real time cost information", and integration of the intelligence within SIM. The trend/graph in Figure 9 shows a "weekly" cost update for structural cluster. As collaboration within the structural cluster matured, Degenkolb Engineers created quantity

Figure 9. Structural Cluster TVD Graph



schedules in SIM so that trade partners could get the quantities from the model and provide cost updates. Degenkolb Engineers developed a quality assurance procedure to verify the quality of SIM information, which also increased the reliability of SIM model used by other team members. During the first 20 weeks of design optimization meetings, THC produced the weekly cost models by extracting the quantities from the SIM. Each cost update required less than 4 hours. The typical breakdown sheet, shown in Figure 10, outlines the material groupings. To validate these weekly automated cost updates, THC also performed a traditional material quantity take-off using drawings. The results were almost identical. The traditional quantity take-off, however it took about 2 ½ weeks and 80 man-hours to complete.

There may be a natural tendency to inflate cost projections with hidden contingency and adopt a protectionist attitude during a traditional cost estimating process. Hence, another important ingredient of TVD is to bring transparency and sharing of cost information with the entire team including design professionals (structural engineer, architect, etc.) and trade partners. It is very important to coach the participants and establish an understanding that the project is to forecast the true cost to the best of our knowledge. This TVD

process enabled the structural cluster to review the cost update as a team and align the design, scope, and cost.

Model Based Sequencing and Visual Controls

Visual sequencing is currently possible using SIM when utilizing 4D functionality as a programming and time reversal tool. The structural cluster team performed a 4D study of the installation of a typical Viscous Wall Damper (VWD). The VWD installation presents a challenge for the field operations and logistics team to further explore different schemes and solutions for VWD. The VWD Installation alternatives discussed and simulated are:

- Alt 1: (1) Bottom girder with WT - (2) Top girder with WT pre-bolted with VWD
- Alt 2: (1) Bottom girder with WT - (2) Top girder with WT - (3) VWD
- Alt 3: (1) Bottom girder with WT - (2) VWD - (3) Top girder with

Figure 10. Herrick's Structural Steel Breakdown

CPMC Cathedral Hill Hospital
The Herrick Corporation - Weekly Cost Update

Model Date: 10-Jul-08 17-Jul-08

QTY (Tons)	QTY (Tons)	PRICE	Material	Sales Tax	Fabrication	Transport	Galvanize	Freight	Erection	Sub-Total
IN SCOPE/BUDGET & IN THE MODEL										
Import WF	820	822								
Domestic WF	7,114	7,086								
Domestic WT	71	146								
Built-up Girders	58	59								
Channel	134	42								
HSS	448	375								
Angle	68	68								
Base Plates	39	39								
Detail Material	610	898								
Bolts, Weld Wire, Etc.	281	238								
Install 174 Viscous Wall Dampers	N/A	N/A								
Sub-Total	9,647	9,772	Tons							
IN SCOPE/BUDGET & NOT IN THE MODEL										
Allowances										
OSHPD Peer Review Comments	0	207								
Q/R Boom Supports	0	100								
Beam Penetrations	0	0								
Misc Iron	0	400								
Sub-Total	0	707	Tons							
Total	9,647	10,478	Tons							
NOT IN SCOPE/BUDGET, DEDUCTED FROM THE MODEL										
Roof Screen @ 7th floor		103								
Roof Screen @ 15th floor		103								
Sub-Total		206	Tons							

First Run Study (FRS)

In the lean design, First Run Study (FRS) is a trial execution of a process in order to determine the best means, methods, sequencing, etc. to perform it. It is used to analyze critical assignments as part of a continuous improvement effort and to include productivity studies and review working methods by redesigning and streamlining the different functions involved. The studies commonly use 3D models, renderings, photos, or graphics to show the process or illustrate the work instruction. The first run of a selected detail and/or condition should be examined in detail, bringing ideas and suggestions to explore alternative ways of doing the work.

In CHH, FRS principles are applied to study and analyze various slab/edge conditions where the exterior skin system and its attachments meet with the structural system. These conditions are notoriously problematic due to complexity of design different tolerances between sub tracks and coordination between multiple trades.

As part of the FRS, the PDCA cycle (plan, do, check, act) is applied to the FRS process:

- Plan refers to select work process to study, assemble people, analyze process steps,

brainstorm how to eliminate steps, check for safety, quality and productivity.

- Do means to try out ideas on the first run.
- Check is to describe and measure what actually happens.
- Act refers to reconvene the team, and communicate the improved method and performance as the standard to meet.

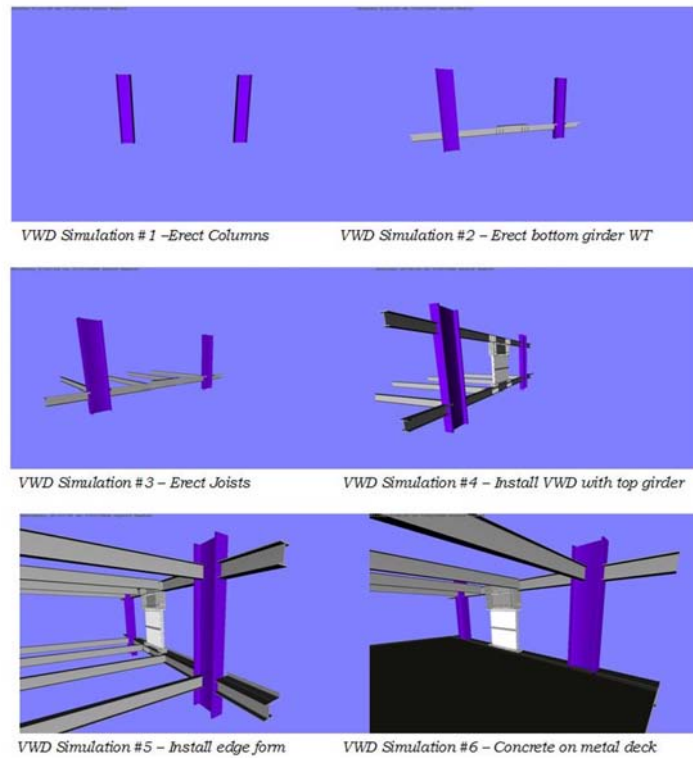
This tool is similar to the combination of the lean production tool, graphic work instructions, time and motion study.

Process Mapping

Process Mapping (PM) has emerged and has been successfully applied to control workflow reliability on simple and complex construction projects. It is used to analyze the flow of information and materials and identify opportunities for improvement in lead time. Although PM is often associated with manufacturing, the structural cluster found it very beneficial to the value adding and non-value adding activities in structural design optimization.

During a two-day workshop, the structural cluster applied the principles of “pull scheduling” for the planning and scheduling. The team

Figure 11. VWD Simulation of Alt#1



performed a pull schedule session early in the process to map the major design, preconstruction, modeling, fabrication and installation activities. In the pull schedule sessions, our objectives were to identify the major steps in the process, identify the information flow and handovers and draw the current state and future state maps. In this way, we identified both the interdependencies within the structural cluster group and the external dependencies with other trades and disciplines.

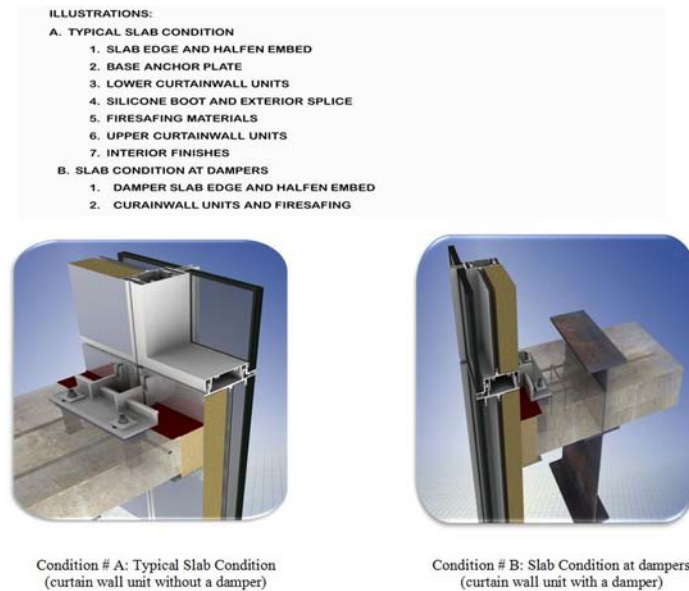
Degenkolb Engineers, Smithgroup, THC, Can-draft, DSI, Pankow, HerreroBoldt participated in the PM workshop. The team first draws a current state map that shows the current steps and information flows required to deliver the OSHPD design packages as well as the intermediate milestones to produce cost and schedule feedback loops. Following the completion of the current state map, the cluster assessed the current state process map to eliminate waste and draw a preliminary future

state value stream map. The team agreed to revisit monthly the ideas proposed to implement in the future state map to refine and adjust depending on the progress.

One of the challenges of the PM is to deal with uncertainty when there is lack of information particularly from the OSHPD side. Despite the promising new “phased review,” the process is new for everybody involved, and there is a lack of clarity on what information needs to be produced. To deal with this, the structural team has decided to identify iterative design loops to evaluate which assumptions made in the process proved to work best in the situations of imperfect information. We have also observed that there may be rework due to iterative design and permitting activities when assumptions do not meet the expectations.

During PM workshop, SIM was at the center of the discussion:

Figure 12. FRS of slab edge conditions



“What should be modeled in SIM and/or in 2D? How much detail is required and needed in the SIM model? What is the cost/benefit analysis of modeling a component weighed against the effort required? What is the right content in the SIM?”

Discussions led to the conclusion that these “open-ended” questions need to be continually revisited as the process evolves to make the necessary adjustments. A “scope matrix” outlines the major structural elements and the production of information flow between players and tools. The scope matrix is in continuous refinement with minor adjustments in roles and responsibilities.

During the mapping session, we also considered the timing of migration from the Revit “Design” 3D model to Tekla “Construction” 3D model, and the content of each 3D models. The team agreed to hold on to the migration to Tekla model, until design settles and OSHPD’s comments are incorporated so that unnecessary detailing is avoided. The team will test both IFC and CSI/2 as translators from Revit to Tekla. An-

other issue during the PM was the “Level of detail (LOD)”, i.e. the difficulty of defining the LOD and accuracy needed for reliable handoff among parties. The team quickly realized that the LOD needs to be constantly redefined during design, permitting, shop drawings, and production.

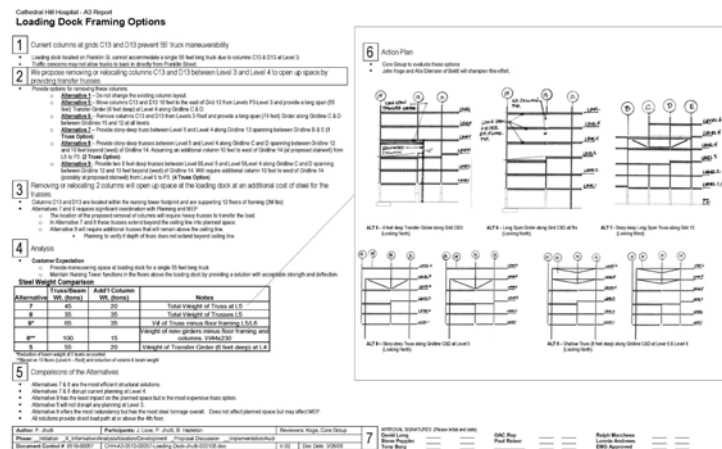
A3 Process

The A3 report is a tool that the Toyota Motor Corporation uses to propose solutions to problems, provide status reports on ongoing projects, and report results of information gathering activity. Typically, the A3 report is used to document the learning, decisions, and planning involved with solving a problem, facilitate communication with people in other departments, and provide structure to problem-solving to maximize learning.

In the structural cluster, we adapted the A3 problem-solving report in conjunction with SIM for problem solving and decision making and have successfully applied it to a number of problems.

First, an A3 was used to eliminate base isolation as an option for primary seismic resisting system.

Figure 13. A3 Report for Loading Dock Options (All design options are generated by Revit)



SIM was very instrumental in visualizing the building with two design options, and the resulting proposal was requesting approval to proceed with Viscous Wall Dampers and Moment Resisting Frame as the primary seismic resisting system.

Secondly, we used it to address foundation design (mat slab versus spread footings). Here, SIM was employed to calculate the concrete and rebar quantities very quickly and produce a cost comparison between two options; and the proposal was to change design to conventional footing design if more economical (further study needed to construction schedule, cost, etc.).

Third, we used it in evaluating loading dock framing options. Figure 13 shows the A3 report with various alternates and costs associated with respective option.

Degenkolb Engineers modeled all design options in SIM and reviewed with other disciplines to eliminate spatial conflicts. The proposal was to remove or relocate columns C13 and D13 between Level 3 and Level 4 to open up space by providing transfer trusses.

4 FUTURE TRENDS

BIM technologies and particularly the integrative use of SIM during the building life cycle can catalyze many improvements as the industry moves toward new approaches. The wider adoption of both BIM and SIM in the industry requires rather interdisciplinary workflows, creative business models and individuals with the right skills. The upcoming future trends and issues include:

1. The need for well-defined transactional business process models. In CHH, IFOA changed the financial compensation for the entire IPD team and provided the contractual and financial framework to design a process where design professionals and supply chain members can work effectively. With IFOA, project risks and their associated costs are shared amongst team members including owner, architect, engineers and trade partners. The owner jointly with all other key members of the IPD team put certain portion of their fee into a shared risk pool to be used, if the project actual final cost exceeds the project estimated cost. The IFOA also has

- an incentive sharing provision used to support the IPD team if the IPD team delivers the project under the project estimated cost. This pay structure supports true collaboration with the goal to “optimize the whole” rather than the “maximize” the individual needs.
2. New methods of team collaboration require new definitions for individual responsibility and liability. It is very important to have the key person(s) internally with the right set of skill and provide training. It is crucial that the individuals have not only the strong technical and process knowledge but also have the right personal skill set; perseverance, creativity, patience, humility, respect, trust and humor.
 3. Change in drafting and engineering roles in structural firms. In this new workflow, the engineering and drafting roles are no longer separate but instead shared and integrated in the same model environment. The production team is entering the documentation process later than the traditional workflow. They are still involved in setting up the models; however it is the engineers who primarily guide the model through the schematic design (SD) and design development (DD) phases. It isn't until late in the DD phase and construction documents (CD) phases that CAD/BIM technician play a significant role in developing and managing models.
 4. Users need to interact with the SIM and the model output at a level to which they are most likely unaccustomed. Therefore, technological competency has to be built with necessary training and be available for this “temporary organization” with dozens of parties. It is very crucial that users are engaged with the technology and knowledgeable about the tools and hence comfortable with the technology that they're using.
 5. Little confidence to interoperability links; too many mistakes during the import/export process. Considering the level of interoperability, it can be concluded that the interfaces generally work very well when linking one way. When it comes to linking both ways it does not look quite as good as with the one-way link.
 6. There has to be a strong focus of workflow built around SIM with a clear understanding of LOD and content of the model. Collaborative process mapping sessions are very effective techniques to improve the information flow.
 7. Expand the model based quantity take-off in other trades such as structural metal decking, shoring, mass excavation, etc.
 8. Simulation of construction sequencing for structural trades. Construction (process) simulations are very powerful communication and validation tools for better production planning. Simulations can be designed both for, high level with limited detail or (focused and) great detail depending on the objective of the exercise.
 9. Improvements in software and hardware capabilities would greatly enhance IPDT to collaborate more effectively.

5 CONCLUSION

As the AEC industry going through a fundamental transformation, Sutter Health chose to embrace this change, and created a collaborative and innovative project team to build the Cathedral Hill Hospital. Implementation of Sutter Health's “Five Big Ideas” along with the effective use LPDS techniques and BIM technologies offered a unique environment to AEC professionals. The collaboration process and the business culture put in place created high performing teams and spurred innovation in design, engineering, permitting, production planning. The project has achieved its target cost at the end of 2008 while continuing the OSHPD permitting process. Yet, the challenges of construction in an urban area will require continu-

ous improvement on “Lean enabled SIM” practices for a successful outcome. This chapter presents a proposal of a framework to enable a systematic integration of LPDS principles and tools with the SIM. The synergy between two would greatly transform the AEC and beyond.

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KEY TERMS AND DEFINITIONS

Building Information Modeling (BIM): A three-dimensional, object-oriented, AEC-specific digital representation of the building process to facilitate exchange and interoperability of information in digital format.

First Run Study: Trial execution of a process in order to determine the best means, methods, sequencing, etc. to perform it. First-run studies are done a few weeks ahead of the scheduled execution of the process, while there is time to

acquire different or additional prerequisites and resources.

Integrated Project Delivery Team (IPDT): Team of individuals representing different functional disciplines and/or different process segments who tackle a specific problem or perform a specific task, frequently on an ad hoc basis.

Lean Manufacturing or Lean Production: The philosophy of continually reducing waste in all areas and in all forms; an English phrase coined to summarize Japanese manufacturing techniques (specifically, the Toyota Production System).

Process Mapping (PM): Method for depicting a process, material or information flow in a diagrammatic form. This structured process helps stakeholders understand the flow of both material and information through their operation and develop plans to move them closer to the ideal state.

Pull Scheduling: Initiating the delivery of input based on the readiness of the process into which they will enter for transformation into outputs.

Structural Information Modeling (SIM): structural informational model that contains as much as possible structural engineering related project data.

Toyota Production System (TPS): The manufacturing strategy of Toyota, widely regarded as the first implementation of Lean Manufacturing.

Value: A capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer.

Process Mapping: A Lean planning tool used to visualize the value stream of a process, department or organization.

Visual Control: The placement in plain view of all tools, parts, production activities, and indicators of production system performance so everyone involved can understand the status of the system at a glance.

Waste: Lean deals with the reduction or elimination of many types of waste with lowest cost and

Lean Enabled Structural Information Modeling

customer defined quality as driving forces. Lean identifies seven types of waste; over-production, inventory, conveyance, correction, motion, processing, waiting In Lean, waste is called MUDA, which comes from the Japanese term for waste.

Weekly Work Plan: A list of assignments to be completed within the specified week; typically produced as near as possible to the beginning of the week.

Chapter 28

Building Lifecycle Information Management Case Studies

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ABSTRACT

A number of industries in other sectors have experienced substantial improvements in productivity due to the implementation of new technologies and associated working practices. In the industry of the built environment these new technologies and working practices are helping to bring about global “construction industry transformation.” Very large and complex three dimensional design and construction information databases can now be aggregated and managed collaboratively over the internet by large project teams working remotely from each other. Whilst person to person meetings are still essential for project teams, a certain amount of remote working can be accommodated. In the past, construction projects experienced many problems resulting from incompletely coordinated and two dimensional construction information that often contained inaccuracies and inconsistencies. The improved quality of design and construction information that is being produced now is making it possible to deliver better quality buildings. By reducing abortive works on site, buildings can be delivered on time and with reduced post construction claims and penalties. Accelerated and enhanced innovation is being enabled by connecting state of the art modelling and simulation technologies directly to the three dimensional design and construction databases. This is making it possible to deliver previously impossible designs. Affordable mass customization and the potential for industry supply chain integration is being enabled by the application of automation to design and construction information management. Additional improvements in efficiency and innovative design, delivery and facilities management are being made possible by this integration of all aspects of the supply chain (i.e. industry supply chain integration). In addition, substantial improvements to the everyday quality of life throughout the world will be brought about by the growing application of parametric generative computer-aided design, virtual prototyping, and lifecycle analysis and simulation.

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1 INTRODUCTION

Over the past three decades, new information technologies and working practices have been increasingly adopted in industries such as aerospace and automobile production. This implementation of new ways of working has steadily increased, resulting in improved effectiveness and efficiency in these industries. Two dimensional paper-based processes result in more mistakes and abortive works that have a negative effect on the overall design quality and production efficiency of the resulting -mass produced- products. Increasingly, the reduction, and even complete removal of two dimensional, paper-driven processes from design and production, is making -increased efficiency, quality and safety- possible in numerous industries throughout the world.

These same new technologies and working practices are now beginning to deliver similar value to the industry of the built environment as is being realized in other industries. This chapter will introduce a number of large design and construction projects which are demonstrating this trend. The value and process innovation that is already being achieved is demonstrated by the virtual pre-coordination, analysis and simulation of the life cycles of these substantial design and construction projects. Ever increasing improvements in value, quality and safety enhancements to the industry as a whole, are being made possible by the growing trend towards the “virtualization” of the design and lifecycle information management process.

2 THE ADVANTAGES OF VIRTUAL PRE-COORDINATION

Description of the Virtual Building Lifecycle Management Process

The implementation of new technologies and working practices is pervasive throughout the en-

tire lifecycle of building. From preliminary design, through coordination, procurement, construction and into to facilities management, the trend is towards validating building design, construction and management in advance. What initially began as “Building Information Modeling” (BIM) has now evolved into Building Lifecycle Information Management (BLM). BIM contains the 3 dimensional geometric information about the building, including all of its associated 2D data such as quantity, cost and engineering information. BLM goes beyond that, to include the integration of all of the data relating to the fabrication, construction process and facilities management phases.

BLM begins at the preliminary design stage, when the basic information about the project is analyzed and integrated into one 3 dimensional database. The building lifecycle information model is likely to include the project brief, pro forma and business model, site geometry, existing services, cost information, zoning information, the structure of the project consultant team and, increasingly, specialized “captured project knowledge,” which passes from project to project. An experienced construction advisor from a contracting firm is always beneficial to a project team at the preliminary stage.

As the project moves further into the design phase, all the information about the project continues to be added to the one Building Information Model. Fully automated, internet-based, 3 dimensional submissions for code compliance review and the issuing of building permits may soon be required by regulatory authorities throughout the world. Submissions to regulatory authorities are likely to be made over the internet via standardized formats such as (for example) Industry Foundation Classes (IFC) compliant ‘3 dimensional data exchange’. This will enable efficient and automated code compliance checking (and the issuance of building permits) over the internet. The way sophisticated 3 dimensional spatial relationships and building information is shared across the industry is steadily being evolved through standards such

as IFC. New technologies can be helpful tools to balance standardization with mass customization and the need to innovate.

By the time BIM enabled projects are ready to tender, the process has provided enhanced coordination information, automated production of 2D construction documents, a detailed, automated bill of quantities and a preliminary construction schedule and methodology with simulation. The reduced risk that results from projects having been pre-coordinated with BIM means that tender prices are likely to be lower, with less of a spread between them (they can be within 1% of each other).

If the legal profession in general embarks upon the trend toward virtualization of the industry of the built environment, then the BIM can also form the contract document. The design BIM transfers to the constructor on site and is used as the central repository of all of the construction information. The construction process benefits greatly from the 3 dimensional coordination, construction process simulation, supply chain management, cost control, and operating and maintenance reference information. On-line databases and interfaces replace the traditional paper manuals and binders that used to be produced by the contractor.

“Upon completion of the project, the Building Information Model passes back to the owner. This is the stage at which the BIM makes the transition into being a BLM, because it forms the basis of the management of the completed project for its service life.”

After completion the BIM can be “hard wired” to the building management system (BMS) and the fire control systems. The owner’s facilities management team can use this total system integration, to monitor, control, optimize and maintain the actual building equipment remotely and over the internet. Using this arrangement, the same building information database is used from the start to the end of the life of the building.

“Using BIM technology has major advantages for construction that save time and money. An accurate building model benefits all members of the project team. It allows for a smoother and better planned construction process and saves time and money and reduces the potential for errors and conflicts.”(Eastman et al., 2008)

Table 1 summarizes the advantages of Virtual Pre-Coordination.

3 EXAMPLE PROJECTS USING VIRTUAL PRE-COORDINATION

One Island East Hong Kong

The One Island East Tower in Hong Kong is an example of the emerging transformed industry of the built environment. Swire Properties Limited, the owner, commissioned BLM consultant Gehry Technologies (GT) to implement Digital Project software and GT’s proven working practices, to help the project to reduce waste on the construction of this new, 70 storey office tower in Hong Kong. The objective was to try to save at least 10% on the cost of the project and to complete the construction in 24 months – if not sooner. Many expert professionals working together collaboratively on one 3 dimensional database containing all of the project information produced the 3 dimensional Building Information Model of One Island East.

The winning contractor, Gammon Construction Limited of Hong Kong, and the project consultants, successfully integrated Building Information Modelling into this large commercial project. One building information database contained all aspects of the building, including 3 dimensional virtual pre-coordination, cost management, and advanced construction process simulation and facilities management. The Building Information Model was used to vet all 2 dimensional information used to construct the building. The Building

Table 1. List of Advantages of Virtual Pre-Coordination

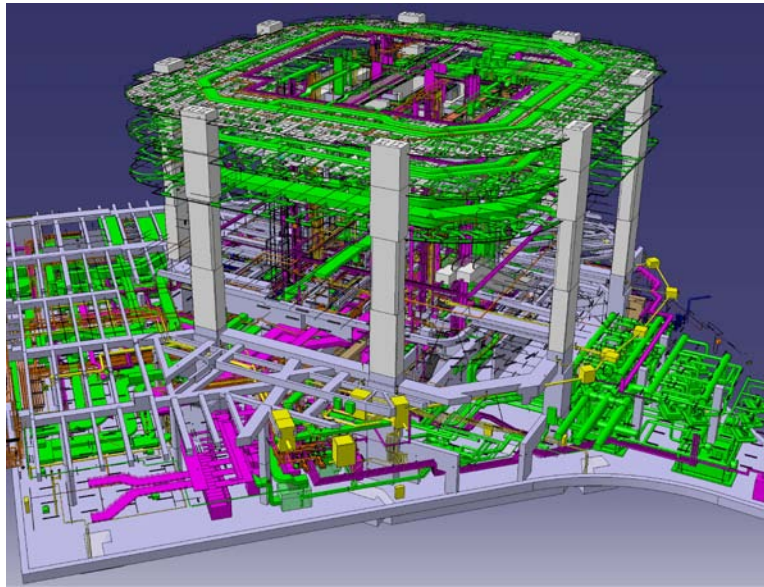
	Advantages of BIM That Have Delivered Value on Actual Building Projects
1.	3-dimensional geometric pre-coordination of all elements of a building project. This alone is widely accepted as enabling a significant reduction in waste and cost on construction projects.
2.	Detailed, automated reports about coordination issues, clashes and conflicts are produced. This takes place in parallel to the aggregation of major systems in a 3 dimensional model of the building at every stage of the life cycle. An automated audit trail of errors and resolutions is produced as a record of the evolution of the design and construction information.
3.	Integration of new collaborative technologies and working practices into the process of the development of design and construction projects is enabling process improvement which is not achievable with traditional practices.
4.	Quantity take-off from the 3 dimensional model is automated, which improves the speed and accuracy of the preparation of the bills of quantity prior to tender and quantity control during construction. Accurate and complete project cost knowledge can be managed as often as is necessary during the course of design and construction.
5.	More accurate and lower tender prices result from the significant reduction of contractors' "unknowns" brought about by better quality tender information. Project complexity is documented and visualized earlier on, which allows risks to be quantified and managed more effectively prior to tender.
6.	The actual elements of the project design and construction database can be linked to the pro forma and business model of the project. This automated linkage creates a project control dashboard that enables increased transparency and control for all project members.
7.	2-dimensional documents are automatically produced from the 3-dimensional Building Information Model data. Generally a certain amount of manual embellishment is still required, but the automated production of 2-dimensional general arrangement drawings – including Combined Services Drawings (CSD's) ensures that design and construction geometries are always coordinated and correct.
8.	Substantial additional reductions in the cost of construction can be achieved by implementing simulation and visualization of the construction sequence (4D). This process simulation using the BIM elements can be highly detailed – including every reinforcing bar and human resource task.
9.	The need to "redraw" can be eliminated by the automated production of fabrication level information such as shop drawings and supply chain integration. A single composite project Building Information Model is produced which contains construction quality information at the pre-tender stage that continues to be developed iteratively during the construction process.
10.	The BIM elements can be used as a basis for an integrated facilities management and facilities maintenance framework using web-based tools.
11.	The number of contractor requests for information (RFIs) and claims on site are reduced
12.	Architects and consultants can integrate structural analysis and simulation, enhanced energy analysis, fire safety analysis and other analyses by referencing the same Building Information Model.

Information Model was kept ahead of construction at all times. Prior to tender, fabrication and construction, thousands of clashes were identified and eliminated. In recognition of its success, the project was awarded the American Institute of Architects BIM Award for Design / Delivery Process Innovation in May, 2008. Part of the 3 dimensional geometric information prepared by the contractor -for the construction of the basement to third floor is shown in Figure 1.

Taikoo Hui Guangzhou

Building Information Modeling has been taken to the next level of scale on the Taikoo Hui mixed use project in Guangzhou. It is three times the size of One Island East being approximately 4.5 million square feet. To prepare the tender Building Information Model, ten Architectural (BIM) modelers and eighteen MEP modelers from China collaborated together for over a year. Thousands of clashes and coordination issues were identified and managed by the team prior to tender using virtual pre-coordination techniques. The project is now progressing quickly on site, and the construc-

Figure 1. One Island East BIM (Courtesy of Gehry Technologies)



tion information being used is coordinated in the construction Building Information Model.

This is an example of how a large scale construction project can be effectively managed on site by large networks of collaborators working over the internet. Large portions of cities, including their entire related infrastructure, are being managed in a similar way.

Sanlitun Beijing

One of the first city-scale BIM projects in Asia is the Sanlitun commercial project in Beijing. It incorporates detailed building services such as sprinkler heads, lights and public infrastructure services. Every element of this nearly 3 million square foot project has been modeled and coor-

Figure 2. Taikoo Hui BIM (Courtesy of Gehry Technologies)

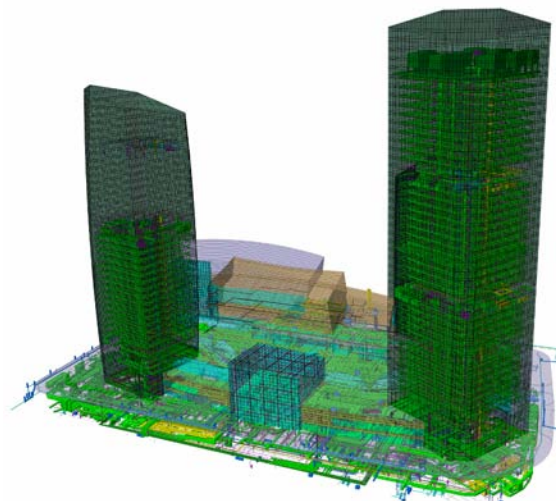
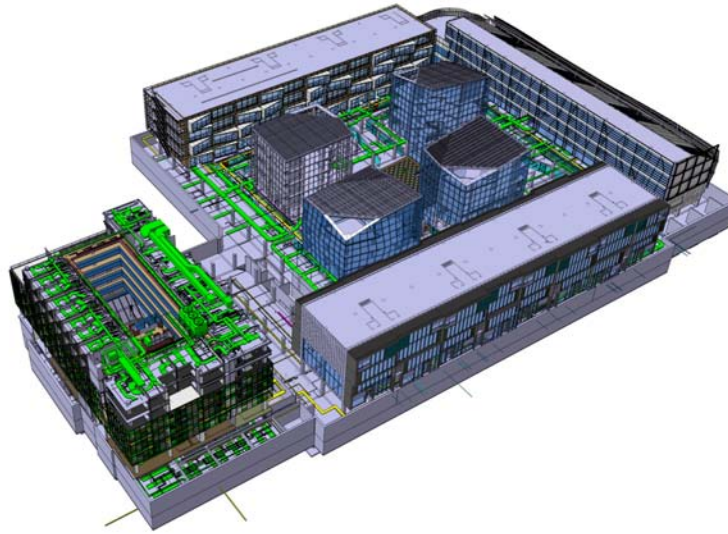


Figure 3. Sanlitun BIM– North Section (Courtesy of Gehry Technologies)



dinated. Extensive virtual pre-coordination was used to review and analyze hundreds of changes that were required by the owner during or after construction.

Also, to lead a series of substantial tenant modifications the BIM consultant was hired for the construction phase. Ongoing changes to the works were incorporated and updated in the Building Information Model to reflect the actual built works. The Building Information Model was used to manage the many changes that were being made, particularly in the area of MEP.

Hong Kong Hotel Project

The new technologies and working practices can deliver value at any stage of a project and with any existing information. The new Hong Kong hotel project demonstrated this because the BIM process began after contract award. Substantial design changes, brought about by a late change in tenant, needed to be analysed, managed and incorporated by the owner and the contractor. Construction BIM was a great help in this process.

The construction -Building Information Model- was managed by the contractor, and helped to identify and manage hundreds of clashes and coordination issues before they caused problems on site. The cladding, MEP services and structure were modeled to fabrication level detail as shown in the cutaway image in Figure 4.

Existing Hong Kong Hotel Renovation Project

This large hotel had to remain operational during the substantial renovation and re-construction that was required. A large existing tower required detailed coordination of MEP and structural changes, and again the owner and contractor used the BIM processes to manage this process. Large amounts of design and construction information had to be reviewed and coordinated prior to the actual construction. The Building Information Modeling process was often the first place in which problems were encountered.

Construction process simulation was used in advance to ensure that the construction sequence

Figure 4. Hong Kong Hotel Project BIM (Courtesy of Gehry Technologies)



and methodology were optimized. The added value resulting from construction process optimization can potentially be larger than the benefits of geometric pre-coordination itself.

4 KEY FUNCTIONS OF THE NEW TECHNOLOGIES AND WORKING PRACTICES

Automated Clash Detection and Management

An essential foundation of effective building lifecycle management is internet-based collaboration and automated clash detection and management. Consultants and project team members anywhere in the world can collaborate effectively over the internet with owners and other project team

members. Clashes are identified automatically by the BIM software as shown in Figure 6. One of the essential functions of clash detection is that the definition and tolerance of a clash can be pre-defined. The software automatically generates lists of hundreds of design clashes which previously often remained undetected until installation on site. Man power previously used to do identify and manage these problems later on can now be used for the job of resolving the actual design issues.

Automated Quantity Take Off and Bills of Quantity

On a BIM enabled project such as One Island east for example, all necessary information about building elements such as size, material, weight, location and sequence is organized and integrated into one 3 dimensional Building Information Model. On One Island East, automated scripting functions were used to format quantities taken from the BIM into Hong Kong Institute of Surveyors format. The database of quantities was automatically updated as the design was developed by the team. During the design process, project quantity surveyors were able to track costs more quickly and more accurately. In the past, quantity surveyors had to spend a lot of time trying to take quantities from different sets of large-scale 2-dimensional paper drawings. Often these drawings were out of date. With a BIM enabled project, the quantity surveyors are able to spend more time researching the market to find where the best prices for the project can be obtained. This helps the design team to get quicker feedback on the development of the design and helps the owner to save money on the project.

Automated Two Dimensional Drawing Extraction From the BIM

For the time being, two dimensional drawings are still required to communicate various important pieces of information to the operatives on site. 2

Figure 5. Hotel Renovation Project BIM (Courtesy of Gehry Technologies)

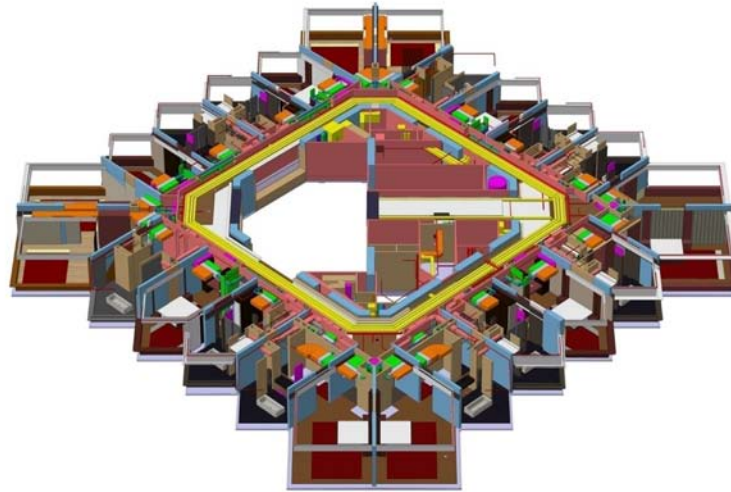
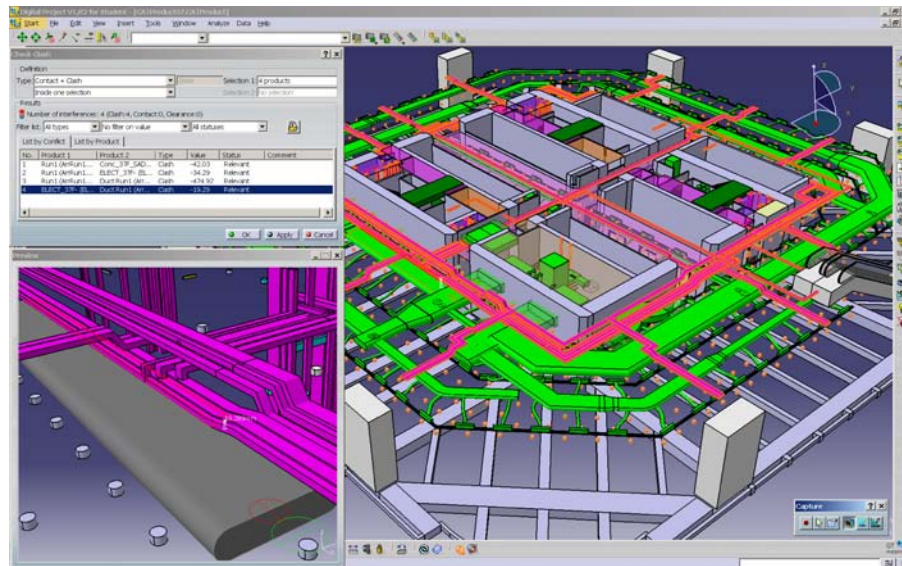


Figure 6. Automated Clash Detection and Management (Courtesy of Gehry Technologies)

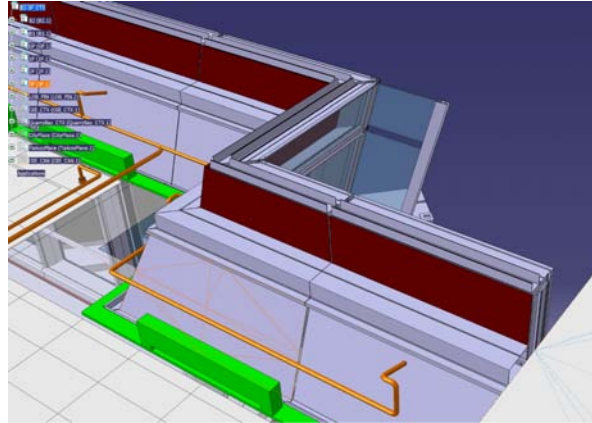


dimensional drawings which are produced automatically from the Building Information Model have less mistakes than manually produced drawings because they incorporate all of the coordination information developed in the 3 dimensional Building Information Model. Also revised drawings incorporating coordinated changes can be produced more quickly.

The Importance of Internet-Based Supply Chain Integration

The integration of the supply chain is very important to successful Building Lifecycle Management because it completes the singular repository of knowledge about the project. Figure 9 is an

Figure 9. Cladding Elements Modeled By Cladding Subcontractor in the BIM (Courtesy of Gehry Technologies)



example of this. The cladding subcontractor for the project modeled the 3 dimensional geometry information for the cladding of the One Island East tower. The cladding contractor produced fabrication level detailed information and incorporated it into the main contractor's construction -Building Information Model (BIM)-. Mistakes that might traditionally be found later in the process – even on site –were eliminated earlier on, because the cladding was coordinated with the other elements of the building in the BIM prior to fabrication. The fabrication, delivery and installation of the cladding on time was made much easier by this BIM engagement.

Construction project teams can develop and share large, complex BIMs over the internet using available forms of 3 dimensional data compression, combined with emerging file sharing protocols. The virtual project office of any modern construction team can take advantage of the highly effective project team collaboration that took place on all of these example projects. Full, continuous and instant visibility into the current state of the project Building Information Modeling database is now available to owners and project managers without the need for drawing issues or special meetings. Instant collaboration at any level of the decision making chain – over the internet is

enabled through the linkage of all elements of the BIM via hyperlinks to individuals, manufacturers or design teams relating to those elements.

Figure 10 shows the installation of the cladding on site, which was informed and improved by prior analysis in the main Building Information Model. The various elements of the project can be tracked and linked with the Building Lifecycle via radio frequency identification (RFID).

Construction Process Simulation

Process visualization tools from the aerospace and automobile industries are being used to model and simulate every step of the construction in 4D (4D being the application of time and sequence to the database of the 3 dimensional geometry of the project). Mistakes, inefficiencies and errors are identified and improved prior to construction, thereby validating and optimizing the build methodology long before construction. Traditionally expensive claims were caused when these problems would cause cost and time penalties during construction. These claims were often ultimately paid for by the owner, but can now be virtually eliminated. Some industry practitioners, who have built careers on managing claims, need to adjust to the new environment of pre-validated

Figure 10. Cladding Elements Being Installed On Site by the Cladding Subcontractor (Courtesy of Gehry Technologies)



build information. The “claims culture” is too expensive for the industry as a whole to afford and so a “culture change” is required from some organizations and individuals.

5 CONCLUSION

The Advantages of Virtual Pre-Coordination

Virtual Pre-coordination in the process of Building Lifecycle Information Management is changing the nature of the industry, because it is greatly enhancing the ability of project team members to collaborate effectively. It is also helping to reduce waste across the entire industry. The integral connection into the entire building process benefits the supply chain by making it more efficient. Many thousands of elements of the project can be tracked from the factory to the site and then through their service life in the building through the implementation of Radio Frequency Identification (RFID).

A vastly improved building lifecycle process results on projects like the One Island East tower,

and this is typical of how projects will be procured and managed in the future. This way of working is a pre-requisite to the process of achieving more sustainable development.

The Future of Building Lifecycle Information Management Technology

The integration of building lifecycle information is one of the main trends for the future in the industry of the built environment. Increasingly, design, construction and facilities management teams are being united around singular databases of information and knowledge about specific projects. They will work more intelligently, more efficiently and will be able to achieve consensus more easily.

“15 years from now, the construction industry will have been transformed into a highly efficient unified process that integrates design ideas that are fully informed by exhaustive, iterative engineering analysis and simulation, with a seamless, factory-based, optimized manufacturing and assembly process. Construction will have become a holistic organism in which all stages in the process inform

Figure 11. Virtual Simulation of the Build Methodology Optimizes the Actual Construction (Courtesy of Gehry Technologies)



each other through a technologically enabled network of collaboration and information exchange that is shared by man and intelligent machines alike.”(Brandon and Kocaturk, 2008)

The quality and sophistication of the process at each stage of the building life cycle will be influenced and improved by this unified, internet-based access to project information and knowledge. Collaborative process simulation will make it possible to represent and analyze large and complex branches of industry information. Processes will be optimized in the best interests of the entire supply chain and building life cycle, and errors will not be repeated.

Cultural change will necessarily be brought about by technological change in the industry, and the successful competitor may well prevail by delivering the *best value*. The quality of life and long term sustainability of in the built environment throughout the world will be improved by these new ways of managing the industry of the built environment.

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KEY TERMS AND DEFINITIONS

Building Lifecycle Management: The integrated coordination, organization and control of all of the information about a building project in advance of its design and construction and continuing throughout its entire lifecycle, i.e. from the inception of the project pro forma through design, construction and the day to day operation of the building until and including its demolition.

Construction Process Simulation: The virtual optimization and pre-validation of the construction methodology of a project prior to the commencement of the actual works.

Internet-Based Collaboration: The implementation of fully integrated software tools that function entirely over the internet to enable large project teams to progress the coordination and integration of all project information via a single three dimensional data base that permits concurrent data engagement.

Full Supply Chain Engagement: The integration of all project design and fabrication information in a single, internet-based three dimensional database that enables fabrication level data to flow in all directions without interruption or transfer between platforms.

Parametric Object Oriented Design: The implementation of technology that enables local and/or global changes to three dimensional design data before, during or after the formulation of the initial design.

Automated Two Dimensional Drawing Production: The implementation of technologies and working practices that create two dimensional drawings from three dimensional Building Information Modeling databases automatically and without the need for further manual embellishment.

Automated Quantity Management: The implementation of technologies and working practices that produce bills of quantity directly from three dimensional Building Information Modeling databases automatically and without the need for further manual adjustment.

Automated Clash Detection: The implementation of technologies and working practices that produce clash lists directly from three dimensional Building Information Modeling databases automatically and without the need for further manual investigation.

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