APPLICATION OF BUILDING INFORMATION MODEL (BIM) IN BUILDING THERMAL COMFORT AND ENERGY CONSUMPTION ANALYSIS

LI YIYE

M.Phil

The Hong Kong Polytechnic University
2010

THE HONG KONG POLYTECHNIC UNIVERSITY
DEPARTEMENT OF BUILDING AND REAL ESTATE

APPLICATION OF BUILDING INFORMATION MODEL (BIM) IN BUILDING THERMAL COMFORT AND ENERGY CONSUMPTION ANALYSIS

LI YIYE

A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Philosophy

Oct 2010

CERTICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the test.

________________________(signed)

__LI YIYE________(Name of student)

ABSTRACT

Building Information Modelling (BIM) is an emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry, it is argued to be a catalyst for improving efficiency/effectiveness and lowering the high costs of inadequate interpretability (Succar 2009). However, the interoperability of different Building Performance Analysis (BPA) tools is still an area under development. Building Performance Analysis (BPA) tools, such as Ecotect, IES<VE>, eQuest, Energy Plus, Design Builder, and HEED, have been traditionally applied to study the energy performance of buildings for design of more sustainable and energy efficient buildings. This study aims at exploring the significance and barriers of information delivery between BIM and BPA tools (Ecotect, eQUEST, GBS), and exploring how to apply BIM model to building thermal comfort and energy consumption analysis. Two tests have been done for that purpose.

In Test I, three product models, with different detail level and file sizes, were built and delivered from Revit Architecture into ECOTECT, and eQUEST. Comparison studies of three file formats and the two programmes were conducted to guide the further integration analysis. In Test II, a thermal comfort analysis and an energy saving analysis for building envelope were conducted separately in Ecotect and eQUEST. Interventions and specific customisations of the model organisations were recorded during the analysis. PMV average values of three typical floors (6F/19F/32F) were calculated, and the result shows that thermal comfort in typical seasons is acceptable for those three floors. Annual electricity consumption of HVAC system was also calculated based on different building envelope design strategies. Significances, barriers and recommendations for integration design with BIM and BPA tools are also concluded.

ACKNOWLEDGEMENTS

I would like to acknowledge those who made contribution to this dissertation. Without their help and encouragement, this piece of work could not have been completed.

First and foremost, I would like to express deep appreciation to my supervisor Professor Heng Li who has been a constant source of inspiration. I thank him his most appreciated supervision and guidance, as well as for his inexhaustible knowledge, kindness and patience.

I also thank my colleagues in the Construction Virtual Prototyping Laboratory who helped me with the case study, and for other research students and research assistants in the Department of Building and Real Estate, my gratitude to them is no less sincere.

Last but not least, I am deeply indebted to my family for their support. This work is dedicated to them.

TABLE OF CONTENTS

List of illustrations Page No.

CHAPTER 1: INTRODUCTION

1.1 Background to the Research

Building Information Modelling (BIM) is an emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations (AECO) industry. It is argued to be a catalyst for improving efficiency/effectiveness and lowering the high costs of inadequate interpretability (Succar, 2009). It contains a complete set of information ranging from the building's geometric data, spatial relationships, geographic data, construction schedules, fabrication processes, etc.

The advance from CAD to BIM is a very real jump from data to information (Bedrick, 2008). While CAD elements are purely graphical representations of building components without any relevance and meaning - like lines, arcs, circles and sometimes surfaces and solids, BIM elements are building components embedded with their relevance to other components and their meanings to a building. Therefore, BIM elements can simulate the behaviour of an actual building component. VP and VDC represent a range of processes that are not only in the construction industry but based on BIM technology. With the advances in BIM technology, more human intelligence will be given to the BIM model, which can make serious benefits to the management and control of a whole project.

Although most of the initiatives consider BIM application in whole building life cycle, the reality is that, rather than optimisation and documentation in pre-construction and construction phase, the industry still experiences less value in the whole building life cycle. Emerging fields such as Facility Management, Sustainability Analysis, and Civil Engineering are gradually bringing in BIM technology to form a more efficient workflow. As many of the BIM tools, used to measure the environment impact of building design strategies, are not directly accessible within a BIM model itself. Data needs to be exported to another application or imported from a data source based on interoperable file formats. Therefore, information interoperability has become one of the concerns of the research related to BIM technology.

Lots of initiatives have been done to integrate multi-disciplinary software with BIM by interoperable file formats. For such emerging areas as Facility Management, Building Sustainability Design and Civil Engineering, information interoperability with BIM is a developing subject in recent years. There is therefore a need to have a comprehensive understanding of how BIM have been used in these areas, and how to make the integration process more effective.

1.2 Research Objectives

The problem of this research can be concluded as:

How to apply BIM to building thermal comfort and energy consumption analyses at the planning stage?

To solve the problems, two major tests must be done: (1) exploring the problems and difficulties of product model delivery among BIM and BPA tools, take Ecotect, eQUEST and GBS for example in this study; (2) identifying re-work and specific re-input of product model in BPA tools for conducting building thermal comfort and energy consumption analyses. The tests were addressed as follows:

1. What's the current state of BIM technology and application?

The advance form CAD to BIM is a very real jump from data to information (Bedrick, 2008). Building Information model elements are building components embedded with its relevance to other components and its meaning to the building. BIM International Activity indicates that global markets view BIM as an important tool for the future growth and competitiveness of the built environment (McGraw Hill Construction Report).

So far, major successes have been recorded using 3D building models for dynamic viewing, graphical animation, collision detection and process simulation - by linking to the construction schedule. Some progresses have also been made in the area of intelligent buildings modelling. An 'intelligent object' integrates both detailed geometrical and non-geometrical data. Multi-disciplinary analysis can be carried out on the bases of these data. Capturing the richness data of the intelligence and the data flows between the stakeholders is another research concern of BIM technology.

Plenty of standards have been developed, released and implemented in commercial software for testing and application. Based on those accelerating emergence of guidelines and reports dedicated to exploring and defining the requirements and deliverables of BIM, a growing number of projects are carried out in relation to applying BIM in construction industry.

The research has reviewed the status of evolution of BIM technology and its integration application in emerging areas including Facility Management, sustainability analysis and civil engineering by referring to literature related to the development of virtual technology based on BIM models.

2. What framework and process are needed to implement BIM to building thermal comfort and energy consumption analysis?

Integration design based on BIM application is a hot spot in research toward BIM nowadays. Interoperability is defined as the seamless sharing of building data between multiple applications over any or all life cycle phase(s) of a building's development. And there is a growing industry standard called Industry Foundation Classes (IFC) that has been created as an open source and most BIM tools on the market can export to an IFC file type. Besides IFC, the Green Building XML schema, referred to as "gbXML", is also used to facilitate interoperability between BIM models. Based on interoperable file formats and their compliant software, information of BIM can be delivered, modified and re-used during the whole building life cycle. Different functionalities can be realized during this integration process, such as design optimisation, life costs and environmental impact control, and facility benchmarking.

The interoperable file formats make interdisciplinary data exchange between 3D geometric and non-geometric data come true. However, problems also emerge during information delivery process, such as geometric misrepresentations, loss of object information, confusion of re-input, and loss of parametric object information. For example, RIUSKA imports 3D geometry and spatial data from

ArchiCAD, and then exports thermal data via IFC to MagiCAD for mechanical design. After engineers have optimized the HVAC system with MagiCAD, they are exported another IFC file that will then be imported into a 3D architectural model as well as 4D model application.

This research reviews BIM initiatives related to building performance analysis, and then develops a framework aiming at applying BIM to building thermal comfort and energy consumption analysis. It will assist planners to be more efficient in verifying their design strategies.

1.3 Research Methodology

The primary research methodology adopted for this study is action research. It is considered to be the most appropriate for producing insights from the application of BIM to building thermal comfort and energy consumption analysis because it links theory with practice.

The specific methodology of this research is also based on literature review and case study. Detail of the research methodology will be discussed and justified in Chapter 3.

1.4 Significance of the Research

The exchange of product model is the basis for faster and more effective processes. Information is more easily shared, value added, reused and exploited in downstream processes and manufacturing. By controlling life cycle costs and environmental impacts, better customer service can be served and better design strategies can be adopted. The ultimate purpose for product model sharing should be the integration of planning and implementation processes in which government, industry and manufacturers can have a common data protocol and software applications that can interpret those data correctly. In this study, the product model exchange happens among BIM and BPA software applications. Moreover, an environmental analysis based on thermal comfort and an energy saving analysis for building envelope is conducted on the base of information exchange. The benefits of this process can be concluded as follows:

1. Building Information Delivery

a) Product model is delivered from Revit Architecture to Ecotect through gbXML file;

b) Product model is delivered from Revit Architecture to Green Building Studio (GBS), then is imported into eQUEST through INP file generated by GBS.

2. Thermal Design and Analysis

With the imported product model, Ecotect runs thermal simulation to estimate the PMV.

3. Energy Consumption for Different Design Strategies of Building Envelope

With the imported product model, eQUEST runs annual AC system electric consumption based on different building envelope design strategies, and an optimized strategy is developed after the analysis.

4. Exchange of Project Data with IFC and gbXML

a) Ecotect 2010 at beta stage can not read IFC file correctly. While with interoperable file format gbXML, product model exchange can still be conducted and used for thermal comfort analysis;

b) Product model delivery from Revit to Ecotect, and then to eQUEST is time-consuming and unstable. Product model delivery from Revit to GBS, and then to eQUEST does work in the test, though there is certain information loss. Nevertheless, analysis can still be conducted.

Experience in this study shows barriers for integration design based on BIM are caused by interoperable file formats, model organisation in receiving applications. Information loss and rework for model modification for specific analysis are unavoidable. It is important to make clear the analysis objectives, the use of the model, then to decide what kind of information it needs to deliver, and which level of detail it needs to have. The problems occurred in the study related to interoperable file formats can be concluded as misreading of model geometry, loss of object information and confusion in revision. The study shows that the various 3D model organisation standards, specific input for receiving software applications and time-consuming one-way conversion could potentially undermine future absorption of the product models sharing.

Recommendations are made for designers and builders towards problems for model building and sharing are also concluded: tailoring the models to fit for the analysis purpose, developing partial model exchanges and model server, etc.

1.5 Outline Structure of the Thesis

The thesis is divided into five chapters according to the need to provide a clear and concise account of the content.

Chapter 1 introduces the background to the study, including identification of research problems, explanation of the research methodology and significance of the outcomes. It is the foundation of the thesis.

Chapter 2 develops the theoretical basis of the thesis by reviewing the literature relating to BIM and sustainable building. Evolution of BIM is examined, including product modelling and visualisation, process modelling and analysis, collaboration and communication. The integration of BIM and Building Performance Analysis (BPA) tools are also studied, including description of commonly used BPA programmes and their application in sustainable building industry.

Chapter 3 sets us the research design and methodology adopted in the research. The primary research methodology adopted for this study is the ‘experiment’ design based on the literature review and case study. Two tests have been developed to test interoperability among BIM and BPA tools; and explore the potential of this technology for supporting sustainable building design.

Chapter 4 demonstrates the implementation of methodology described in Chapter 4, and analyzes the results of the experiments.

Chapter 5 presents the conclusions including a review of the objectives, research contribution, significance and limitations of the study. It also makes recommendations for future research.

1.6 Summary

This chapter has laid the foundation for the thesis. It introduces the background to the study, and highlights the research problems and other related issues. The research methodology, significance of the outcomes, and outline structure of the thesis are discussed. The following chapters will provide a detailed description of each stage of the research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a summary of the literature relating to Building Information Modelling. The evolution of BIM tools is reviewed and a comparison among CAD, VR/AR, VP, BIM and VDC are examined. The research areas of BIM are reviewed based on papers and publicly-available guides and reports, the review shows that, instead of focusing on modelling and analysis of product and process, more and more concerns have raised about collaboration and communication during the whole building life cycle. Moreover, although most of the initiatives consider BIM application in whole building life cycle, the reality is that, rather than optimisation and documentation in pre-construction and construction phases, the industry still experiences less value in emerging fields such as Facility Management, Sustainability Analysis, and Civil Engineering. Finally the researches are related to product model delivery, such as interoperable file formats and BIM compliant software. Information delivery methods are reviewed.

2.2 CAD, VR/AR, VP, BIM,VDC

The original premise of CAD application is to represent two-dimensional geometry via graphical elements. Three-dimensional CAD models are offspring from two-dimensional CAD, and Building Information Modelling (BIM) is the latest generation of OOCAD system in which all information associated with a building can be captured based on a single ‘project database’ or ‘virtual building’. VR/AR technology brings a user experience function to BIM. VP technology has successfully been used in many phases of the manufacturing planning process and some phases of construction planning process. VDC represents a broad range of new processes which are realized by building information modeling technology. Therefore, they have the same technique basis of BIM technology but different applications domains in AEC industry (Figure 2.1). The detail information about comparison of CAD, VR/AR, VP, BIM and VDC is described as following:

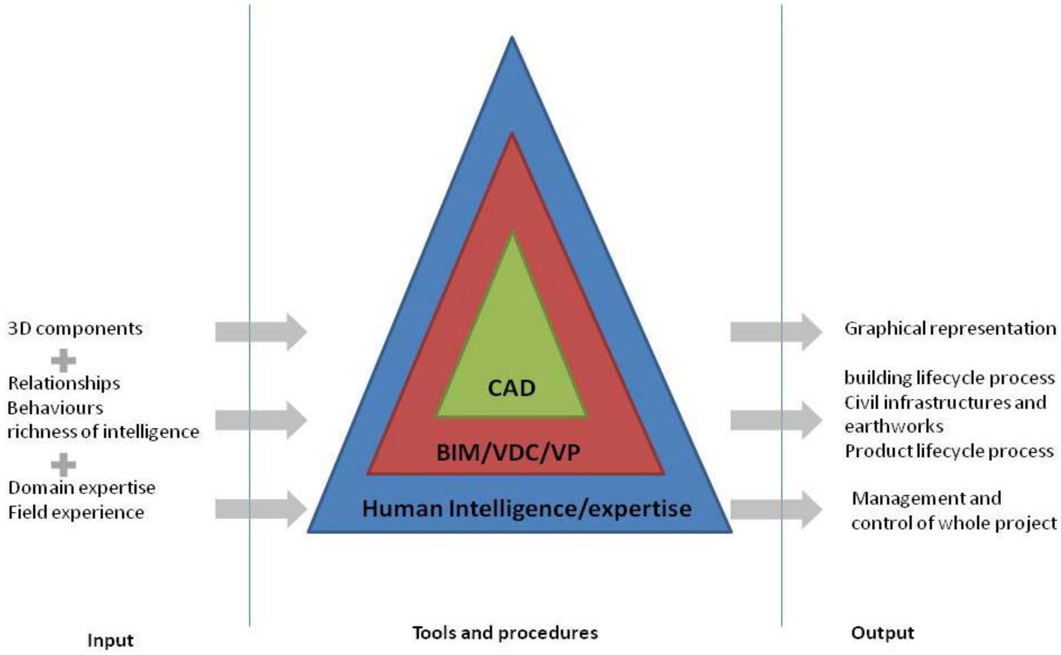


Figure 2.1. Relationship among CAD, BIM/VDC/VP and Human Intelligence/expertise.

2.2.1 CAD to BIM: Data to Information

To understand the development of BIM, a good start point should be CAD. The original premise of CAD application is to represent two-dimensional geometry via graphical elements. Three-dimensional CAD models are offspring from two-dimensional CAD and initially focus on creating geometry in support of visualisation. During the evolution, from three-dimensional curves and surface models to more shape detail and complexity, to solid modelling like realistic rendering and lighting effect - CAD technology gradually develops to meet the increasing demands for realism and complexity in the industry (Kasik, 2000).

Four-dimensional Modelling combines 3D models with time. So far, most uses of 4D visualisation have been in the marketing and preconstruction phase of a project - like explaining designs and describing construction process (Liston, 2001). Other important uses include assistance in cost control and estimation (Staub, 1998). Most recently, object-oriented CAD system (OOCAD) has replaced previous CAD paradigm with building elements (objects). The inclusion of parametric 3D geometry adds "intelligence" to those objects, which permits representation of complex geometric and functional relationships between them. Moreover, abstract objects can be defined, identified, described, and referenced. Capturing these relationships and behaviours and the richness of the intelligence are just not possible in the previous CAD paradigm. Building information modeling (BIM) is the latest generation of OOCAD system in which all information associated with building can be captured based on a single 'project database' or 'virtual building' (Howell and Batcheler, 2003).

The advance from CAD to BIM is a very real jump from data to information (Bedrick, 2008). CAD elements are raw data, like lines, arcs, circles and sometimes surfaces and solids - pure graphical representations of building components without any relevance and meaning, while BIM elements are building components embedded with its relevance to other components and its meaning to the building. Therefore, BIM elements can simulate an actual building component's behaviour. Take a wall for example, BIM can simulate a wall's behaviour including its load-bearing capacity or its response to heating and cooling loads.

According to National BIM Standard Project Committee (2008), BIM is a digital representation of physical and functional characteristics of a facility; it is founded on open standards for interoperability and serves as a shared knowledge resource for information about a facility and thus forming a reliable basis for decision during its life cycle from inception onward. The American Institute of Architects describes it as "a model-based technology linked with a database of project information". Therefore an ideal BIM is conceived as a single building information model for the entire construction industry (Howell and Batcheler, 2003), and a basic premise of BIM is the interoperability and machine-interpretation based on that standard structured data. (Fallon, 1998)

The International Alliance for Interoperability (IAI) defined IFC (Industry Foundation Classes) as an extensible "framework model". It has been directed to address all building information over the whole building life cycle, from feasibility and planning, through to design (including analysis and simulation), construction and finally to occupancy and operation (NIST). There are lots of BIM implementations developed by different software vendors in the absence of a single model - Autodesk Architectural Desktop (ADT), Autodesk REVIT, Bentley Systems, Graphisoft's, Nemetschek, etc.

2.2.2 VR and AR: Adding User Experience Function to BIM

VR (Virtual Reality) can be defined as a computer-generated simulation of a real or imagined environment that a user can experience, like immersion, navigation and interaction (Ammari, 2006). AR (Augmented Reality) is also a technology for application of user experience. It combines the viewing of the real world or video-based environments with superimposed 3D VR models. Thus AR supplements rather than replaces the user's real world (Virtual Reality Laboratory website, 2006). The most recent development in AR is a wearable system in which users wear a backpack with a portable computer and can see through Head-Mounted Display (HMD), hear with headphones and have a motion tracker to place and manipulate VR objects as they move within their real world environment (Halden Virtual Reality Center, 2006).

Integration of VP or BIM within VR enables users to interact with three-dimensional models that are more realistic. VR is used as a tool for the verification of assembly and maintenance processes (Sa and Aschmann, 1999). The University of Salford's "Think Lab" is developing immersive tele-collaboration technologies in the construction industry (Brandon, 2007). AR is now mainly used in the manufacturing industry.

2.2.3 VP, VDC and BIM: Manufacturing and AEC Industry

Virtual Prototyping technology is initially developed to meet the demand of the manufacturing industry. Its digital nature permits revision and optimisation of the functionality of the design parts in a very fast, economic and efficient manner (Zorriassatine, 2003). VP technology has been successfully used in many phases of the manufacturing planning process and some phases of the construction planning process. According to Shen (2005), Xiang (2004), and Pratt (1995), VP is a computer-aided representational process concerned with the construction of digital product models ('virtual prototypes') and realistic graphical simulations that address the broad issues of physical layout, operational concept, functional specifications, and dynamics analysis under various operating environments. In broad meaning, VP is usually mentioned with BIM although they are mainly used in different fields. There are five main categories of VP technology (Huang, 2008): Visualisation, collision detection, testing and verification of functions and performance, evaluation of manufacturing and assembly operation, resource modeling and simulation. VDC represents a broad range of new processes made possible by building information modelling technology. It is the use of models coupled with analysis and simulation tools to prototype the building on the computer. This can then be used to simulate the building, its performance and its construction before breaking the ground. The availability and capability of VDC software in the civil area is increasing in some areas, such as civil infrastructures and earthworks.

2.3 Research Areas of BIM

BIM International Activity indicates that global markets view BIM as an important tool for the future growth and competitiveness of the built environment (McGraw Hill Construction Report). In some states such as Finland, Denmark, Norway, Australia, and USA, the use of BIM has been endorsed while some other states have progressed toward it. The following provides a review and discussion to the publicly-available guides, reports relating BIM around the global and their implications in research and development of BIM in the construction industry.

2.3.1 Parametric Geometry with Intelligence

Overall, three broad research areas of BIM are identified according to the particular areas of application: (1) product modelling and visualisation; (2) process modeling and analysis; (3) collaboration and communication (Huang, 2009). So far, major successes have been recorded using 3D building models for dynamic viewing, graphical animation, collision detection and process simulation - by linking to the construction schedule. These successes are partly attributed to the gradual maturity of 3D modeling and to advancements in visualisation technologies like Virtual Reality (VR), Augmented Reality (AR). These allow users to animate assembly and disassembly sequences, animate 'fly-through, into and around', and simulate people and their interactions with products (CIMdata Inc. 2001).

Some progress has also been made in the area of intelligent building modelling. 'Intelligent object' represents physical elements like doors and columns and encapsulate 'intelligence' (Halfawy, 2002). An 'intelligent object' integrates both detailed geometrical and non-geometrical data. Based on these data, multi-disciplinary analysis can be carried out, such as structural analysis, HVAC design, scheduling, cost estimating, environment impact evaluation, life cycle cost estimating, and thermal performance assessment. Various software are used for both data transmission and analysis, such as BSPro (middleware software), FEA, MagiCAD, COVE, BSLCA, BSLCC, RIUKSA, and Lightscape. Domain-specific standards and software packages are available in this area. Take structural analysis for example: the American Institute of Steel Construction's (AISC) CIMSteel Integration Standards/Version 2 (CIS/2) initiative has proven to enhance the quality and speed of information flow throughout the steel supply chain. Bentley Structural, as part of Bentley's integrated suite of building information modeling (BIM) applications, is a widely used structural analysis tool which can design complex structural systems and perform detailed analysis.

2.3.2 Integrated Project Delivery

Capturing the rich data of the intelligence and the data flows between the stakeholders are both critical variables of BIM maturity. Methodologies and tools for sharing and exchanging data of 'intelligence objects' among users from different domains have become another research hot spot globally (Succar, 2009). The 2004 Construction Users Roundtable (CURT) report, 'Collaboration, Integrated Information and the Project Life Cycle in Building Design, Construction and Operation' (WP-1202), makes clear that there is a compelling need to improve project delivery. The National Institute of Standards and Technology (NIST) studying 'General Buildings Information Handover Guide: Principles, Methodology and Case Studies' (NISTIR 7417, 2007) is one of the first to document the process and quantify the effectiveness of intelligent modelling combined with data flows and sharing across a broad range of applications. In order to improve the interoperability (information delivery/ handover) in AEC/FC dusty, data modelling experts must develop specifications for how the information should be encoded by using structured data standards.

Plenty of standards have been developed, released and implemented in commercial software for testing and application. From 1979, with Initial Graphics Exchange Specification (IGES) in the USA, different national standards for interoperability were gradually developed. Examples include VDAFS in Germany and SET in France. In 1984~1994/95, an international standard named Standard for the Exchange of Product model data (STEP) was developed and released by the International Standards Organization (ISO). Almost all major CAD and Computer-Aided Manufacturing (CAM) contains models that allow them to read and write data defined by STEP Application Protocols (APs) (Ammari, 2006). In 1997, IAI published Industry Foundation Classes (IFCs) - an extensible framework model to cover the whole building life cycle. It is supported by various software vendors and enables applications to efficiently share and exchange project information (Li, Isele et al. 2008). In 2003, U.S. General Services Administration (GSA) examined IFC models and server standards via 10 pilot projects. Many BIM authoring tools have been certified of their fitness for use through this project including Autodesk's ADT, Autodesk's Revit, Graphisoft's ArchiCAD, Bentley's Architecture, and Onuma Architecture &Master Planning (Mihindu, 2008). Both STEP and IFCs are based on the schema language EXPRESS and affected by the XML standard for document representation on the World Wide Web.

Based on those accelerating emergence of guidelines and reports dedicated to exploring and defining the requirements and deliverables of BIM, a growing number of projects are carried out in relation to applying BIM in construction industry. Major public-organisation initiatives in this regard include IAI buildingSMART, the U.S. National Building Information Modeling Standard (NBIMS), the European Commission, the Associated General Contractors of America, the U.S. General Services Administration (GSA), US National

Aeronautics and Space Administration (NASA), General Motors (GM), Cooperative Research Centres (CRC) in Australia as well as in Denmark, Finland, Norway and Singapore (Fallon, 2007; Mihindu, 2008; Succar, 2009).

2.3.3 Integration Application of BIM

Based on the development of open protocol, BIM is capable of being applied to the whole AEC industry. 50 initiatives are studied to have a comprehensive understanding of the integration application of BIM in AEC industry.

Although most of the initiatives consider BIM application in whole building life cycle, the reality is that, rather than optimisation and documentation in pre-construction and construction phase, the industry still experiences less value in the whole building life cycle (Figure 2.2). Emerging fields like Facility Management, Sustainability Analysis, and Civil Engineering are gradually bringing in BIM technology to form a more efficient workflow. As many of the BIM tools used to measure the environment impact of building design strategies are not directly accessible within a BIM model itself, data needs to be exported to another application or imported from a data source based on interoperability file formats (DXF, gbXML, IFC, etc). Therefore, information interoperability has become one of the hot spots of the research related to BIM technology (Figure 2.3).

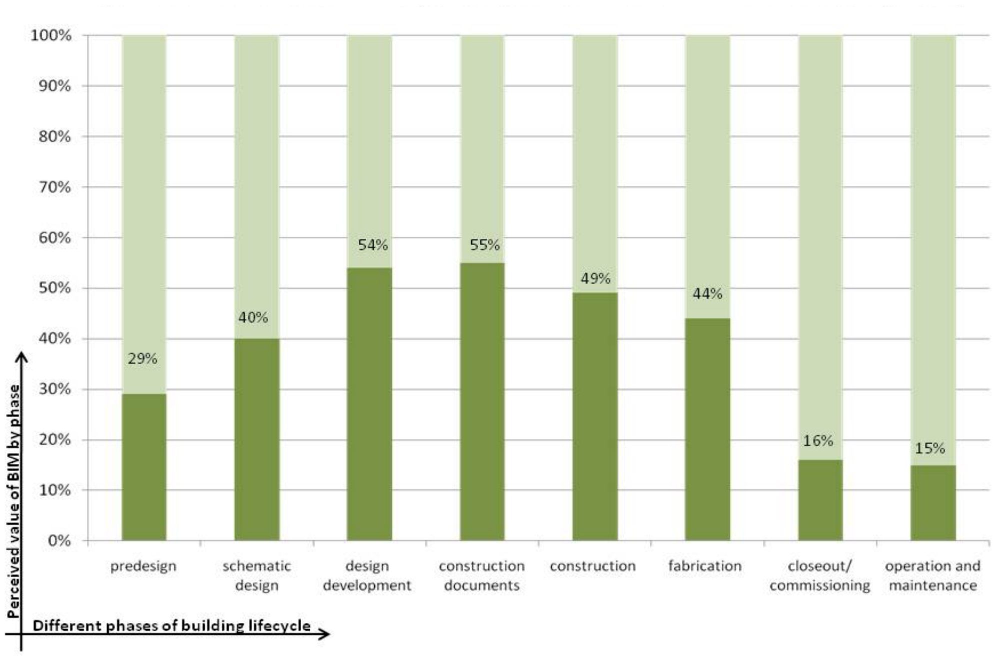


Figure 2.3. Perceived Value of BIM by phase (source: McGraw-Hill Construction, 2009).

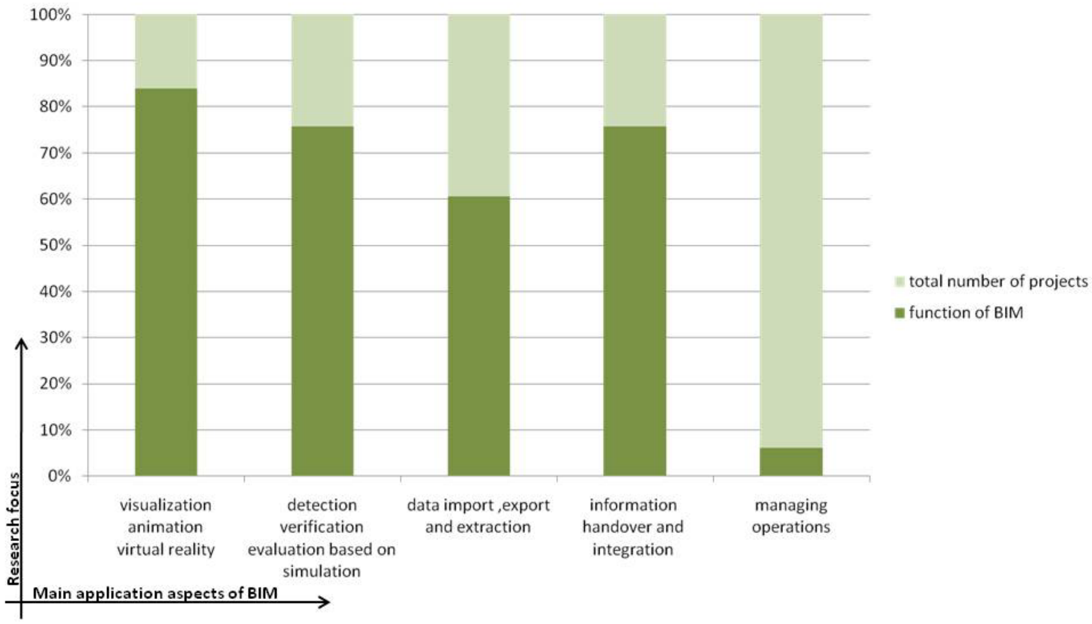


Figure 2.4. Research focus of BIM technology (source: case studies from NewForm whitepaper and website 'BIM source@Georgia Tech').

Lots of initiatives have been done to integrate multi-disciplinary software with BIM by interoperability file formats (Table 1.1). For these emerging areas, like Facility Management, Building Sustainability Design, and Civil Engineering, information interoperability with BIM is a developing subject in recent years. There is therefore a need to have a comprehensive understanding of how BIM have been used in these areas, and how to make the integration process more effective.

2.3.3.1 Application of BIM in FM

Based on the development of building data protocol, BIM is capable of being applied to the whole building life cycle, while industry still experiences less value in areas of AM/FM Which includes closeout or operations and maintenance, refurbishment and upgrade, disposal and discompose. It is recommended that the FM industry adopt IFC to support FM processes such as benchmarking, procurement and service delivery, for the sharing of FM information for asset management (AM) applications, and ultimately to support broader business objectives. Therefore, the research involving Facility Management was mainly about information sharing delivery method, rather than handling substantial tasks of decision support through scenario checking and evaluation (PM4D, CIFE Report 143, 2002). There was fewer research which concerned the management solutions ("Adopting BIM for facilities management-solutions for managing the Sydney Opera House", CRC 2007, ifc-mBomb, the U.K. DTI 2004; COBIE).

For specific domains such as refurbishment, research regarding BIM is almost blank, which shows an imbalance between increasing demand and a lack of attention. During the long time life cycle period of housing, most residents are undoubtedly faced with refurbishment requirements. However, it is not easy to make assessment and refurbishment related decisions due to the lack of knowledge and experience. Computer-aided tools are needed to help residents conduct the housing condition assessment and offer optimal refurbishment actions considering the trade-off between cost and quality.

(1)Management Solutions

'Adopting BIM for facilities management-solutions for managing the Sydney Opera House' (Ifc-m Bomb, CRC) aims at devising a method that will allow seamless flow of information to pass from design and construction to operation and maintenance - and then decommissioning and demolition if needed. Such a system will have to include underpinned robust technology. Creating and storing designs in an object database through different software packages would help achieve this. The database is based on the IFC model and property sets-information-rich standards that allow a wealth of data on a building to be assembled, exchanged, stored, re-used and updated during the life cycle. The project is chosen to concentrate on HVAC (heating, ventilation and air-conditioning) services. Several high-level processes have been identified that could benefit from standardized BIM:

1. Maintenance processes using engineering data;
2. Business processes using scheduling, venue access, and security data;
3. Benchmarking processes using building performance data

The function that can be realized including:

1. Quickly find the responsible person/contract when an element fails;

2. Retrieve all objects (walls, doors, etc.) scoring on the BPI (number or level) which have had a major maintenance;
3. Retrieve all history of cleaning scores of objects before and after a new cleaning contract for comparison;
4. List the location of assets and their performance including maintenance history
5. Query vacated spaces and their BFI scores; and Simulate and visualize the effect of taking a service out of commission.

(2)Refurbishment

(Morris, 2006) BIM has not been tested that much in renovation projects yet, although the importance of renovation and restoration is remarkable within the total volume of western construction sectors. (Juan and Kim, 2009) the refurbishment market has faced increasing needs worldwide. During the long time life cycle period of housing, most residents are undoubtedly faced with refurbishment requirements. “Life cycle support – the model supports the FM data over the complete facility life cycle from conception to demolition, extending current over - emphasis on design and construction phase.” (Senate, 2007). However, it is not easy to make assessment and refurbishment related to decisions due to the lack of knowledge and experience. Computer-aided tools are needed to help residents conduct the housing condition assessment and offer optimal refurbishment actions considering the trade-off between cost and quality. Little work has yet been accomplished in the use of BIM for the management or renovation of existing buildings. Barch and Gillard (2009) discussed a few pilot initiatives which indicated that the building information modelling of existing buildings requires a substantially different approach to that taken on new projects.

First of all, for refurbishment and state review of an existing old building, a new model reflecting the current state is often required. Such surveying instruments include Laser Scanners. Murphy et al outlined the following data capture process based upon “user interactive stages”:

- Processing image and laser survey data;
- Correlating laser and image survey data plotting the parametric objects onto the point cloud and image survey data;
- Modifying parametric objects to fit accurately the geometry, scale and rotation of the point cloud survey;
- Mapping more complex shapes as textured models onto their component parametric objects; and
- Creating the entire building, a system referred to as Historic Building Information Modelling (HBIM), i.e., full engineering survey drawings.

Then a BIM model reflecting current state will be built based on a photographic survey, digitized paper record drawings, or a 3D scan survey, as Murphy has discussed. Correspondingly some researchers have created IFC compatible BIM from laser range images before. Li and Isele, (2008) presented an approach designed by the German Research Center in Karlsruhe to create an IFC compatible building information model from laser range images. Also some researchers have been able to transfer 3D models into IFC-format (Barch and Gillard, 2009). In the pilot of The HUT, AutoCAD’s 3D model was transferred to Solibri Model Checker SMC in IFC-format and it was then analyzed and visualized based on the attribute data (Solibri is one of the emerging IFC based code compliance checking engines - used in automated building regulation approval in Singapore).

After transferring current building states into IFC-compatible BIM models through certain survey methods and corresponding software packages, then the data can be exported from one package and imported into the others for further analysis based on a single synchronized model. Schedules of renovation processes can be established and supplied to the Quantity Surveyor to ensure that cost estimates are fully related to detailed design, and Ecotect studies can be conducted to find an optimal balance between projected expenditure on the construction fabric and compensatory energy cost saving. In the study of the Atlantic College renovation (Barch and Gillard, 2009), heat generated by lighting and other equipments and people was identified; peak demands projected; the most effective insulation tactics (from air-tightness to heat-recovery) identified; and effective performance parameters for the heat pump calculated. Therefore, there are usually three steps for BIM application in the renovation of existing buildings:

1. Survey for current state;
2. IFC compatible BIM Modelling for current state; and
3. Shifting and analysis using IFCs.

Current research is focused on the three aspects: the way for surveying current building state; the way for building BIM model based on surveys; and the way for multi-disciplinary analysis with a single synchronized model.

2.3.3.2 Application of BIM in Sustainable Building

(Stumpf and Kim, 2009) An emerging area of interest within the A/E/C industry is designing sustainable buildings, as evidenced by the increasing use of the US Green Building Council (USGBC) LEED® (Leadership in Energy and Environmental Design) green building rating system. Green building (also known as green construction or sustainable building) standards have seen a significant rise in popularity, as evidenced by the United States Green Building Council (USGBC) and the Living Building Challenge (LBC-Cascadia Green Building Council). According to the McGraw-Hill Construction Analytics' SmartMarket Trends Report 2008, "the value of green building construction is projected to increase to 60 billion by 2010".

Many contractors have started to specialize in sustainable design within the industry to further delineate themselves from their competition (Hardin, 2009). Many code enforcement agencies are looking at their own standards and implementing green standards into their code manuals for the industry. In the end, every construction company will be required to adapt their organisation to comply with any industry green standards being adopted into building codes and local ordinances around the world. BIM is a fairly recent technology for sustainability design. The book *Green BIM* by Eddy Krygiel and Brad Nies is dedicated especially to BIM. It involves green construction, and design strategies and it is an excellent source to dig more in depth into how project teams are utilizing the power of BIM to create a truly informative tool throughout the design process (Krygiel, 2008).

The LEED (Leadership in Energy and Environmental Design) manual is a series of credits that provides scalable and real goals for new construction projects to attain. For LEED certification to be attained, the project team must achieve credits from the following six categories : sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation and design processes. The Building Information Modeling (BIM) can be used in a number of ways in relation to the LEED projects. It assists the construction manager for more accurate procurement of materials and verifies actual building performance to the estimated performance using compatible multi-disciplinary software. Moreover, as LEED measures and credits the project, the project team can virtually construct a model and make better assumptions based on the credits the project is eligible for. The effort to construct a sustainable building improves the life cycle process to follow a more integrated approach.

As Grobler (2005) presented, building designs (conceptual and detailed designs) affect most of the life cycle costs of the construction and operation of a building. It is also worth noting that several researchers proposed to combine Lean and BIM technologies in order to improve the modeling process in sustainable development (Riley et al, 2005). Yezioro (2008) conducted assessing building performance using 3D CAD model for energy analysis in the early design stages. (Stumpf and Kim, 2009) describes a process of exploring different energy saving alternatives in the early design phase using 3D-CAD/BIM technology. A prototype energy modeling process was developed and tested on a construction project of the Community Emergency Service Station at Fort Bragg, North Carolina, with a team led by the U.S. Army Corps of Engineers. Hardin (2009) concluded that BIM can be used in pre-construction, construction and salvaging and recycling phases mainly for material and site management - such as material selection and use, site selection and management in preconstruction phase, setting of sustainability plan, job site surveillance and material management in construction phase, and material management for salvaging and recycling phase (Table 2.1).

Phases	Application areas	Utilisation of BIM file
Preconstruction	Material selection and use	To add information to building components for further analysis and estimation
	Site selection and management	To add information to site components for further analysis and estimation
	System analysis	To add information to building components for further multi-disciplinary analysis later
Construction	Setting of sustainability plan	To develop a model coordination and information exchange plan
	Job site surveillance	To teamed with handheld tablets to limit travel time and improve construction managers' efficiency; To be used to create a list of potential issues using Adobe Acrobat, Mavisworks, or similar RFI software
	Material management	To built project phasing models to show the anticipated delivery date of materials on a job site either through animation to through a series of

		stills
		To estimate the quantities of materials, and quantify one-time material needs for non-repetitive work
Salvaging and recycling	Salvaging	To establish Material BIM library
	Recycling	To identify the location of bins and rolloffs; To limit the amount of printed documentation on-site

Table 2.1. Application of BIM files in green building projects (based on "BIM and construction management: proven tools, methods and workflows")

2.3.3.3 Application of VDC in Civil Engineering

BIM has not advanced as quickly in civil engineering as it has in architecture (Casey, 2008). BIM promotes the coordination of different design disciplines (e.g. structure, mechanical, fire safety) "inside" the building or literally under one roof. Civil engineering's domain has traditionally been site specific or "outside" the building. While with The success of the BIM concept within the building sector, major CAD vendors are now trying to promote the same concept within the civil structures area - such as bridges, earthwork, landscape, roads and highway design and construction space management (Drogemuller, 2009).

(1) Bridge

The bridge software from Bentley (2009) has had good market penetration, especially in the US, but Autodesk have just released bridge extensions to the Revit Structure software (Mangon, 2009). Bentley has started using the acronym

BrIM (Bridge Information Modeling) in their marketing material. Consequently, we can assume that BrIM will achieve a similar level of promotion as BIM.

(2) Earthwork

(Drogemuller, 2009) The preparation of Gantt charts for structural projects normally follow a logical sequence – by constructing the components that support others first. This simplifies the preparation of construction simulations to support visual assessment of construction schedules. Earthwork projects do not necessarily present the same underlying logic. When large amount of earth needs to be moved and there are no obvious spatial or access constraints, the sequence of excavation often comes down to personal preference. A Disney California Adventure project was used to assess the use of geometry-based modelling to support 4D simulations (Akbas, 2004). Methods were developed to ensure that there were no spatial conflicts between the activities necessary for the project across the lagoon, restaurant and roller coaster.

(3) Landscape

There is also research for information integration between BIM and application of civil engineering and landscape design. This is not an area in which much work has been done as the IFC model currently covers the building components that are inside of the building itself. The intention was to extend the 12D civil engineering software to support some of the information exchange requirements as a proof of concept (Drogemuller, 2009). One example is “interoperable standards” project of CRC. At the first stage, each group of civil engineers and landscape designers provides documents that establish their information exchange needs. Then information exchange of ground surface data is conducted through the platform of 12D (civil side) and ArchiTerra (landscaping side). The result identifies a problem - CAD systems and 12D use different approaches for modelling objects, and conversion between two types of representation is a time-consuming exercise.

(4) Road and Highway Design

Pinnacle Cad is now emerging as a provider of BIM for road and highway design. Designers apply software like "AUTOCAD CIVIL 3D" and "InRoads" to explore what-if scenarios. They will optimize project performance for civil engineers in designing facilities like bridges, roadways, sidewalks, and buildings. Many other BIM software vendors also extend their application in road and highway design such as "Allplan road construction package" of Nemetschek and Autodesk solutions for roads and highway. Compared with solutions for building construction, the enhancement of functionality can mainly be embodied by following four points:

a) Terra modelling: To precisely model terrain reality. Every terrain model can contain one or more layers of earth. Breaklines, line structures and fillets can be defined as well in order to precisely match reality.

b) Automated generation of parametric 3D models of roads: Many kinds of routes can be defined and can interactively appear graphically on-screen. Synchronously, site plan, longitudinal profiles and transverse profiles can be displayed and edited. Based on the parameters setting, the programme automatically creates the basic 2D geometry and the corresponding dimensions for the predefined road plan such as traffic circle types. And through parametric 3D models of automated generated road - transverse profiles, perspective views and quantities can be managed. Profiles for the road surface, slope and shape are all contained in a library where the structure of the roads is stored profile by profile. Cants can be automatically calculated or manually changed.

c) Quantities: To satisfy the other functions demanding caused by outdoor working, more functionality in relation to site management are developed such as automated cut and fill calculation, automated road volumes, surfaces and finally segment lengths calculation as a basis for tenders.

d) Path simulation: With traffic current simulations, the process of designing intersections, traffic circles and road openings can be visualized. For example, you can check tight road details or even plan delivery by articulated truck.

The benefits can be concluded as four points:

a) Design optimisation: Designing a roadway should take into account several safety considerations, including the road slope, turning radius and signal location that are tied to roadway speed limitations. BIM provides a visual environment which engineers can use to get a more complete view of the project area.

b) Smart drawings – multi-disciplinary analysis: Create proposed surface earthwork volumes, material totals, drafted cross sections, and more.

c) Traffic capacity, noise, lighting, drainage, and signage analysis are all detected earlier in a project as part of the design process - well before significant effort is invested in construction documentation.

d) Better information handover: Provide assistance for the creation of design deliverables directly from the information model that can be leveraged for quantity take off, construction sequencing, as-built comparisons, and even operations and maintenance to achieve an optimal roadway design.

e) Specific design demanding: Provide contractors with 3-D proposed surfaces for driving machine control grading projects. This decreases survey costs, minimize equipment operating costs and saves time and money during construction.

(5) Construction Space Management

As a critical source at construction sites, increasing attention has been paid to using IT technology for space management. A lot of research has been made to develop space-scheduling strategies to eliminate spatial conflicts between activities. While in order to model space management processes and apply it to more standardized application, it is necessary to formalize ontology for time-space features of construction space. (Akinci, 2002) formalised time-space conflict analysis as a classification task and developed taxonomy of time-space conflicts are to be used in categorising and prioritizing the spatial conflicts. Six types of spaces were identified based on space attributes of when and where it exists, who and how much volume it occupies as follows:

1. Building component space;
2. Labor crew space;
3. Equipment space;
4. Hazard space;
5. Protected space;
6. Temporary structure space.

Then a construction time-space analysis process was automated by three steps:

1. Detection of spatial conflicts in all x,y.z and time dimensions;
2. Categorisation of detected conflicts according to taxonomy;
3. Prioritisation of conflicts categorized when conflicts appeared between the same activities. They also implemented these formalisms in a prototype system-4D WorkPlanner Time-Space Conflict Analyzer (4D TSConAn).

2.4 Product Model Delivery

As described above, integration design based on BIM application is hot spot in research toward BIM nowadays. Many of the BIM tools used to support mechanical, engineering design are not directly accessible within a BIM model itself; therefore, data needs to be exported to another application or imported from a data source. In this vein, interoperability among those programmes is essential for the integration application of BIM. Interoperability is defined as the seamless sharing of building data between multiple applications over any or all life cycle phased of a building's development. And there is a growing industry standard called Industry Foundation Classes (IFC) that has been created as an open source and most BIM tools on the market can export to an IFC file type; besides IFC, the Green Building XML schema, referred to as "gbXML", is also used to facilitate interoperability between BIM models. While the only open global standard is that published by the International Alliance for Interoperability (IAI) called IFC. And software that can support the exchange of BIM model through the IFC file format can be called as IFC-compliant software, there are also software can only read IFC file formats indirectly with the help of middleware tools. Based on interoperability file formats and their compliant software, information of BIM can delivered, modified and re-used during whole building life cycle. Different functionality can be realized during this integration process, such as design optimisation, life costs and environmental impact control, and facility benchmarking. Detail information about interoperability file formats, information delivery whole building life cycle and compatible software applications are described as follows.

2.4.1 Interoperable File Formats

2.4.1.1 AutoCAD DXF/DWG:

DXF (Drawing Interchange Format, or Drawing Exchange Format) is a CAD data file format and was developed by Autodesk for data interoperability between CAD and other programmes. DWG is a more common and widely used format for data interoperability, since certain object types such as solids, regions and blocks are not documented or partially documented in DXF's for commercial developers.

2.4.1.2 GbXML (Green Building Extensible Markup Language)

The green building XML schema was developed to facilitate the transfer of building information stored in CAD building information models, enabling integrated interoperability between building design models and a wide variety of engineering analysis tools and models available today. It facilitates the transfer of building information including product characteristics and equipment performance data between manufacturer's database, CAD applications and energy simulation engines. It carried a detailed description of a single building or a set of buildings for energy analysis and simulation. This file format is widely used by manufacturers such as Autodesk, Graphisoft and Bentley for data exchange. Table 2.2 shows the hierarchy of information organisation in the gbXML schema.

Component	Characteristics	Information that it carries
Campus	A group of buildings that are geographically similar	Id, name, description, location
Building	One building	Id, name, description, street address, square area, its spaces
Zone	A group of rooms located in a building that are serves by the same HVAC plant or VAV box. Each zone may contains a group of spaces (or rooms) that have their own unique set of characteristics such as similar orientation or temperature set point	Id, name, description, flow, airflow changes per hour, flow per area, flow per person, outside air flow
Space	A room defined by its own set of walls, ceiling, and/ or roof. A space may be an office, conference room, warehouse, or any other entity	Id, name, description, infiltration flow, number of people, people heat gain, lighting power per area
Surface	A wall, floor, ceiling, or roof. Each space (or room) will have its own set of surfaces	Id, name, description, construction type, geometry, and any openings
Opening	Opening in a space, such as a door or window	Id, name, description, u-value, shading coefficient, transmittance, reflectance

Construction type	A type of composite construction that makes up a wall, roof, ceiling, or floor	Id, name, description, u-value, absorbance, roughness, reflectance

Table2.2. Hierarchy of information organisation in the gbXML schema.

2.4.1.3 IFC (Industry Foundation Classes)

IFC is developed by the IAI (International Alliance for Interoperability) to facilitate interoperability and is an open data exchange format that is used by model based applications to exchange data (Khemlani, 2004). It is an international standard that stores building data in a database, permitting information to be shared and maintained throughout the life cycle of the construction project. That is: design, analysis, specification, fabrication, construction and occupancy (Khemlani, 2004). The IFC model consists of tangible components such as walls, doors, beams, and furniture, as well as the more abstract concepts of space, geometry, materials, finishes, and activities. There have been several releases since IFC was first launched in 1997, starting from IFC version 1.0 to the IFC 2x2, the seventh version. In order that a programme is IFC compatible, that is, it is able to import and export IFC files, it needs to be "IFC certified". The IFC model is posted online and provides a framework for software developers to incorporate the IFC import and export capabilities within their programmes. The IFC is organized into sections that address different core areas and domain areas.

The IFC Model architecture for 2x3 consists of the following 4 layers (Figure 2.5):

(1) Resource layer: the resource layer forms the lowest layer in IFC architecture, this layer provides common resources that are used by classes in the upper

layer. For example, all information concerning basic concepts of costs is collected in the cost schema, ifcCostResource in the resource layer. Any classes in the core, interoperability or domain layer that need to use cost will reference this source. (Eastman, 1999)

(2) Core layer: the core layer forms the next layer in the IFC model architecture. Classes that are defined in this layer can be referenced by the classes in the upper layer, that is, interoperability and domain layer. This layer included two levels of generalisation- the Kernel and the core extension (Eastman, 1999). The Kernel schema defines the most abstract part of IFC architecture and defines objects and their relationships. Core extension includes generic concepts, for example, the “product extension” contains the classes of objects that make up the physical description of a building; such as generalisation for walls, space and roofs.

(3) Interoperability layer: the layer defines concept or classes common to two or more domain models and enables interoperability between them. For example, these include building elements and building services (Eastman, 1999).

(4) Domain layer: this layer is the domain specific application layer, and supports application used by architects, engineers and contractors.

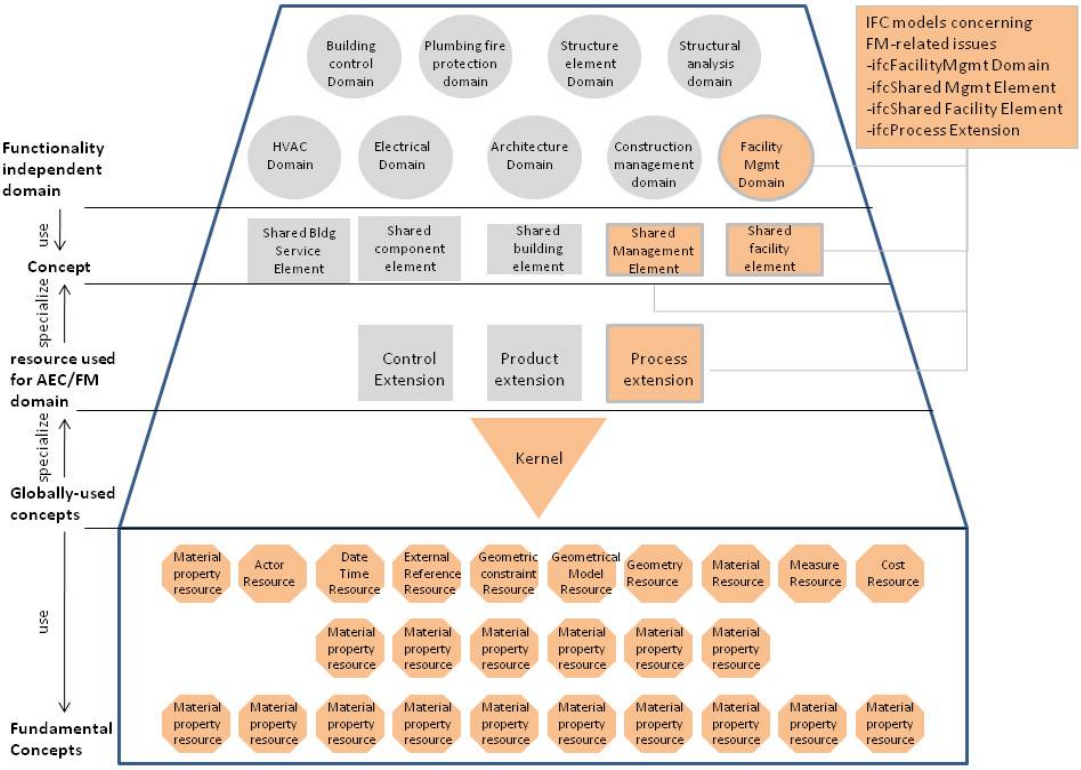


Figure 2.5. Hierarchy of information organisation in the gbXML schema.

Based on the information above, information that is carried by a DXF file is rudimentary, and primarily consists of geometric information represented by the drawing. gbXML files carry more information than mere geometry (area, volume, cartesian points, co-ordinates) and include definitive information pertaining to hierarchy of components such as Campus, Building, Zone, Space, Surface, Opening and Construction types. The information carried by the IFC file is also comprehensive, which carries geometry information as well as that encompassed by type and instance parameters defined by the user in the building model.

IFCs, as a whole-building life-cycle interoperable schema, allow data exchange of every aspect of buildings. However, gbXML, as its name shows, "extensible markup language for green building", focuses more on building thermal load properties. This has made it easier for a wide variety of vendors to make their tools gbXML-compatible. Simply, from a thermal analysis point of view, gbXML is superior to IFC. However, from a whole building life-cycle points of view, IFC allows for more information.

2.4.2 Information Delivery of Whole Building Life Cycle

In the CIFE project PM4D, the application of BIM brings benefits to processes of conceptual planning, construction documentation and design, the research focus on data sharing and multi-disciplinary analysis (which are based on object-oriented product models and the IFC interoperability standard). The IFC standard makes interdisciplinary data exchange between 3D geometric and non-geometric data come true. For example RIUSKA imports 3D geometry and spatial data from ArchiCAD, then exports thermal data via IFC to MagiCAD for mechanical design. After engineers have optimised the HVAC system with MagiCAD they exports another IFC file which will then be imported into a 3D architectural model as well as 4D model application. COVE maps calculate internal costs and resource database, as well as export IFC files for scheduling and cost estimating. CIFE' s 4D team then import IFC files through middleware software BSPro and 3D geometric data from the architects, contractors and engineers for 4Dsimuilation. BSLCA and BSLCC can import architect's IFC file through BSPro for life cycle studies. The project also identifies the shortcomings of IFC interoperability that were caused by IFC-supported software and middleware. Problems also emerge during information delivery process such as geometric misrepresentations; loss of object information; confusion of re-input; and loss of parametric object information.

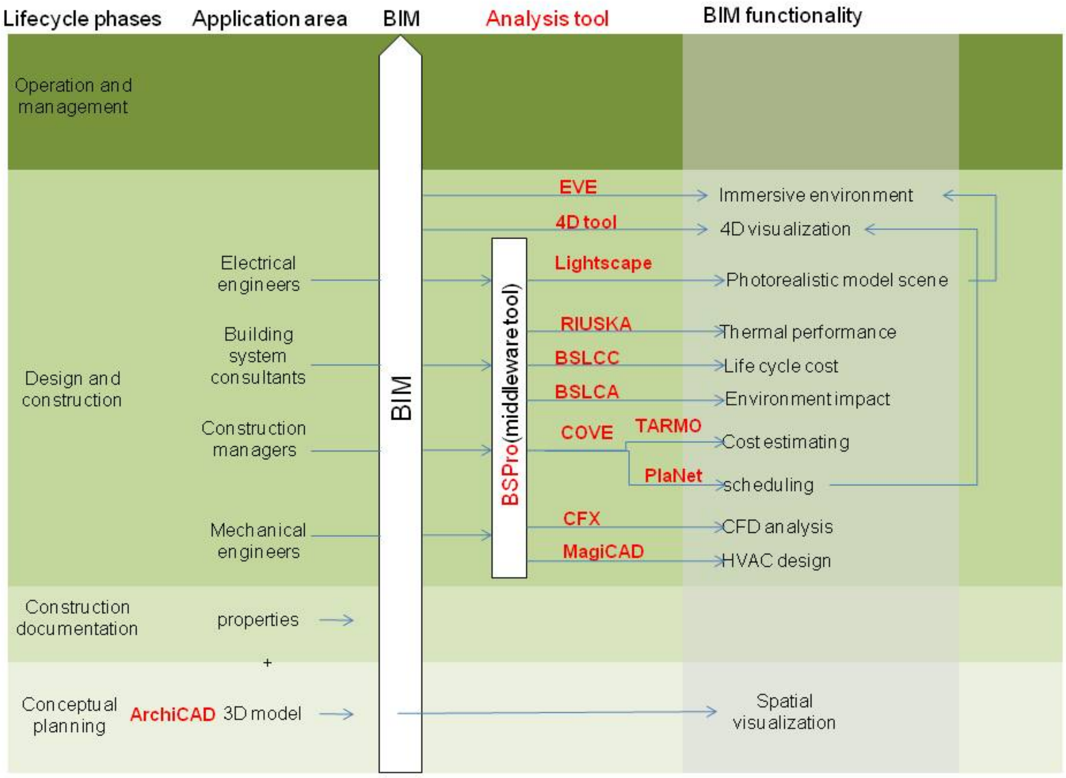


Figure 2.6. Information delivery process In the CIFE project PM4D.

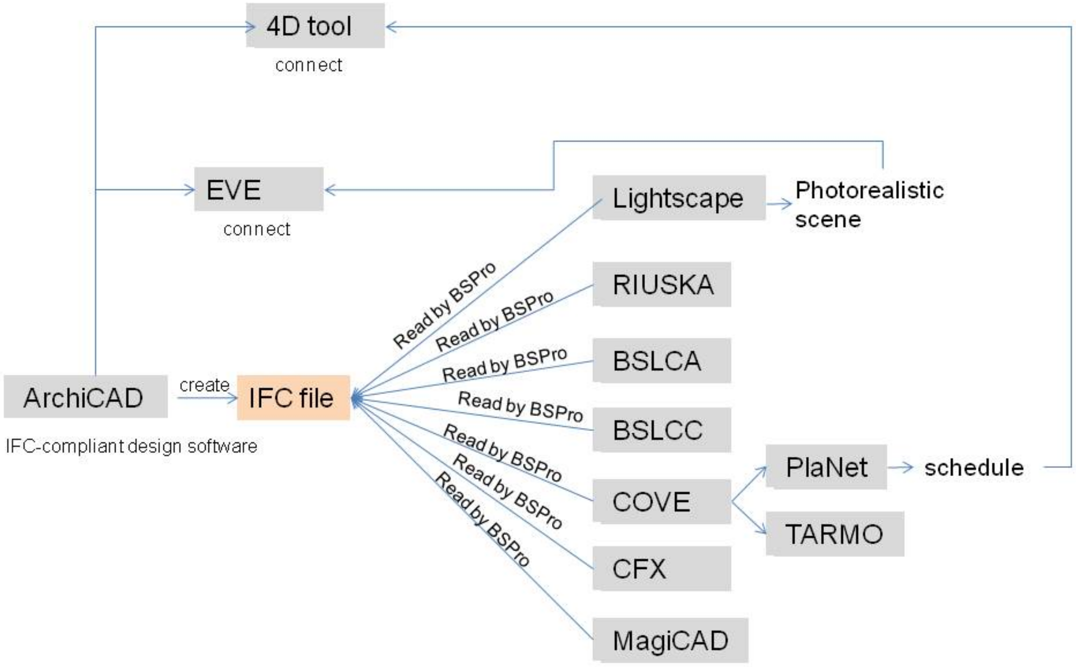


Figure 2.7. Data exchange process based on IFC.

In the project of "Adopting BIM for FM-solutions for managing the Sydney Opera House", to demonstrate the feasibility of IFC-based data, Arup's structural model has been exported from Bentley's Microstation in IFC format

2.4.3 Software Applications for Integration Design Based in BIM Application

A wide variety of software applications have been developed to support design of the whole building life cycle including architectural, mechanical, engineering design, FM/AM management, civil engineering design and sustainability analysis. Study shows there are little initiatives have been conducted to apply BIM to analysis related to environment impact of building design strategies, therefore an experiment of trying to apply BIM to building thermal comfort and energy consumption study can be a starting point of integrating to BIM every aspects of building performance analysis.

In this study, "Building Performance Analysis" (BPA) tools means applications which can support this kind of analysis and at the same time interact with BIM application directly or indirectly. A wide variety of Building Performance Analysis (BPA) tools have been developed, enhanced, and applied in Sustainable building design (Stumpf, Kim et al. 2009). Examples of these tools are BLAST, EnergyPlus, eQUEST, TRACE, DOE2, ECOTECT and Green Building Studio (GBS). GBS (Autodesk, 2008) is a web-based service that works with a gbXML file exported from various BIM applications including ArchiCAD, Revit and TriForma (Beta version). It uses the building information to perform an energy evaluation with established tools such as DOE-2, eQUEST, and EnergyPlus. It allows various changes in design alternatives to the building design (such as orientation, glazing, roof and wall construction, lighting, and HVAC) to be quickly analyzed to determine which options are the most energy-efficient.

2.4.3.1 Ecotect

Ecotect is a building design and environmental analysis tool that covers a broad range of simulation and analysis functions required to understand how a building design will operate and perform. ECOTECT is unique in that it combines a highly graphical interface with a broad range of analysis tools. The types of analysis directly available within the software are shading, shadows and reflections, solar, lighting, thermal, and acoustic. The target audience are architects in the schematic and design development phases. Its appealing interface and output are one the reasons for its wide application. A climate analys is module packaged with ECOTECT, Weather Manger, provides clear diagrams of climate information which can be derived from several weather file formats. While it performs a multitude of analyses, the thermal, acoustic, daylighting and the calculation methods it utilizes lack sufficient detail for reliable investigation. They may be adequate for the earliest stages of design, but intensive analysis required for useful design development must be done in other software. ECOTECT addresses this by offering the ability to export to several popular analysis formats, but specific modeling conventions must be followed for each format type, limiting the ability to move one model freely among different tools. Modeling conventions also required for each analys is also make it difficult for one model to be used for all calculations within the tool as well.

(1)Information Input, Edit and Delivery

The interface of ECOTECT is controlled through a series of tabbed views each with a specific function for setting up, creating, viewing and analyzing the model. The drawing interface, or 3D EDITOR tab, is the most CAD-like of the analysis tools evaluated in this study. With buttons activating commands such as line, plane, and zone to generate the geometry of the model. This is also where windows, doors and other openings are assigned to surfaces. There is a parent-child relationship between surfaces and the openings that are common in other analysis tools. In ECOTECT this relationship must be explicitly modeled, whereas in Energy-10 and eQUEST, it is automatically generated. When any object is created a default set of material properties are assigned to it. These properties are required for every analysis, and the default types can be changed from a menu of existing material definitions. Custom materials can also be defined by the user, but because ECOTECT uses a thermal calculation method peculiar to England (the Admittance Method) some of the properties required are difficult to obtain for uncommon materials. The 3D EDITOR tab provides a wireframe view of the model, and this is the only view in which the geometry and object properties can be edited. The VISUALIZE tab displays an OpenGL rendering of the model and is used for most of the analysis of shading, sun-path and sun-penetration.

The Ecotect model has a range of import and export capabilities. The Ecotect model can be exported to a host of programmes including website-based tools Autodesk Green Building Studio (*.gbXML), lighting simulation software like Radiance(*.RAD, *.OCT), ray-tracing programme like POV Ray(*.POV), VRML models(*.WRL) and even thermal simulation and analysis softwares like

EnergyPlus(*.IDF) and HTB2(*.TOP). It can export AutoCAD (*.DXF)files and DOE-2 Input files(*.INP) as well a range of others. Ecotect can import files that carry geometric information as well as general data files. Some of the files carrying geometric information that it is able to import include AutoCAD drawing files, (*.DXF), Lightscape(*.LP), Lightwave (*.LWO) and VRML (*.WRL). Some of the general data files that it imports include Green Building XML(*.XML), ASCII model files(*.MOD), Energy Plus Input Data files(*.IDF), Weather data files(*.WEA) and Radiance Scene files(*.RAD), while Ecotect is not yet an IFC compliant.

(2)Energy Loads and Data Analysis

Ecotect uses the Chartered Institute of Building Services Engineers (CIBSE) admittance method, an internationally regarded method used by building services engineers and designers. (Ecotect n.d.) In the admittance method, the temperatures and load calculations are two separate processes. Once detailed hourly internal temperature is known, a second calculation is performed to determine the absolute heating and cooling loads. Ecotect calculates heating and cooling loads, which are essentially room loads (and not plant loads) for a space. Plant loads depend upon the efficiency of the system; for the same space load requirement, an inefficient system may require far greater loads than efficient system. The user can set a host of thermal properties in Ecotect ranging from type of HVAC system and its efficiency, the thermostat range, occupancy, internal gains and infiltration rates.

(3)Output

While the ease of modeling and access to multiple types of analyses make

ECOTECT an attractive tool for designers, the manner in which it displays results is the most valuable feature of the software. Tabulated data can be exported to the programme Excel for post processing. Graphs of data for the various analyses map the information in clear, almost expressive formats. With the analysis grid, the results of several types of analysis can be displayed in conjunction with the geometry being measured, or represented directly on the surfaces themselves. This also applies to the use of data from some of the third party tools that ECOTECT can generate exported files for. Most notably is Radiance lighting software, which can provide accurate simulation of daylight and artificial lighting. An additional feature is the ability to quickly save the results of all analysis in both of raster (.jpg, .bmp) and vector (.wmf) formats for editing in graphics software.

In conclusion, ECOTECT is the closest to a one tool solution for providing early phase performance analysis to designers. Its ease of input, ability to import several types of geometry, clear graphics, ability to export results for presentation and evaluation, and its ability to model information for use in more advanced tools show it to be a suitable starting point for the integration of simulation into the design process. Some aspects of a building design, i.e., those dealing with shading and solar control, can actually be refined to a high level within ECOTECT alone. But many of the analysis methods lack the rigour or rely on overly simple calculations that make them insufficient for use in final performance design decisions. ECOTECT attempts to address this with the ability to generate several file formats for more complex simulation tools. Aside from the Radiance interface for lighting studies though, most formats require such strict modeling protocols that their use is limited. As a starting point for designers looking to improve building performance from an energy and comfort standpoint, these shortcomings do not outweigh the benefits of the analysis feedback ECOTECT can provide, as long as the designer knows when the limits of the tool have been reached and can turn to the appropriate methods for future development.

2.4.3.2 IES<VE>

IES <VE> Integrated Environment Solutions is a software system for integrated building performance analysis, providing tools for thermal analysis, value engineering, cost planning, life cycle analysis, airflow analysis, lighting, and finally occupant safety in one unified system (Khemlani, 2006). IES <VE> contains the Integrated Data Model or IDM, which captures all the information about the building, including the geometric data that is needed to carry out a range of analyses. The model is created inside the “Model IIT Building modeler” that contains a number of 3D shape options that can be used to create rooms (Kumar, 2008).

(1)Information Delivery Capabilities

3D geometry can be imported straight from CAD or Revit packages using gbXML. Materials and constructions can be selected from a built in database called the Apache construction database. The programme also contains a building template that automatically assigns information to the model, and may include occupancy profiles, constructions, surface colors and building control information. These values can be edited in the building template manager. The site location and weather data can be selected from a database in the ‘ApacheLocate’ engine while the „Apache Systems feature simulates HVAC systems.

(Kumar, 2008) IES<VE>, unlike Ecotect, is unable to import a large number of file formats and the primary import format it uses is gbXML. The IES file is saved in a number of folders apart from the main *.ve file - such as apache, lights, cfd, macroflo, Radiance and suncast corresponding to the various IES applications. Interoperability takes place in the form of data exchange between several applications existing inside the programme. For instance, the integrated data model(IDM), can be used for thermal simulation in ApacheSim application and for more detail HVAC analysis in ApacheHVAC. ApacheLoads can also predict air supply rates that are used by the IndusPro duct sizing module application. The effects of thermal shading can be imported from the SunCast application to enhance heating load calculations.

(2)Energy Loads and Data Analysis

(Kumar, 2008) The IES <VE> engine called 'Apache loads' uses the procedures laid down by the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) "Heat Balance Method" to calculate the design heating and cooling loads. These calculations use the IDM to undertake two principal calculations:

1. Steady state heat loss calculations to predict the heating requirements for the building;
2. Heating loads calculation, to predict the building cooling requirement. (IESVE)The heat gain calculations and cooling load calculations can be performed for a selected design day of the week, and for a range of design months. Load results are available in both graphical and tabular forms .

Unlike Ecotect, which gives primarily annual and peak loads, the results for calculation are quite comprehensive in IES<VE>.

2.4.3.3 eQUEST

eQUEST is a graphical interface to the DOE-2 analysis engine, which is one of the most robust simulation tools available. It can be used to demonstrate compliance with California Title 24 and ASHRAE 90.1 standards for building performance. As such, it has become a standard of performance analysis for projects pursuing LEED certification. It is similar to Energy-10 in its interface and methodology, but does not have the limitations on size and complexity. The geometry of the building can be modeled as designed, although it is best to simplify as much as possible for analysis. System zoning and controls sequences can be highly refined and there are dozens of system types available to simulate. Other features include the ability to perform daylighting calculations and link these to lighting controls to determine energy savings.

eQUEST also offers the ability to perform batch simulations incorporating multiple parameters for aspects of the building envelope and system design, called Energy Efficiency Measures. These can then be used to analyze “what-if” scenarios. Batch processing allows for the iterations to run automatically which is a significant improvement over Energy-10, which requires the parameters to be manually changed, re-simulated and reported.

(1)Input

eQUEST offers three stages of model development. Beginning with the Schematic

Design wizard - information about building use, location and utility rates are input though a series of drop down menus and data fields, similar to Energy-10. The building footprint and zoning can also be developed by tracing an imported .dxf file. Each window in the wizard asks for a different function of the building to be input. While it is called the Schematic Design Wizard, the level of detail requested in each field seems to suggest that eQUEST is best started after some consultation with the project's engineers.

The next phase is the Design Development Wizard, which again uses a series of pull downs and data fields. The DD wizard expands the number of system types available and allows for the modification of schedules and more detailed input of envelope information and controls set points.

The third phase of building a model in eQUEST is through the Detailed Interface. This give the modeler access to every aspect of each component in the model and allows for fine tuning of the inputs to make the simulation as accurate as possible. For the nature of the cube exercise, only the schematic design wizard was utilized, accepting several default values through the process.

(2)Output

The initial output eQUEST delivers provides a breakdown of energy consumption by end use for the design. While this provides a quick overview of the performance of the model, the most valuable information lies in the one thousand plus pages of charts and tabulated data with information on everything from total annual electric and gas consumption to daylight levels in skylight spaces and even static pressures for every air handler. While the cube exercise does not exploit this, in a building with dozens of systems and multiple zones within each system, this becomes a tool that allows a knowledgeable designer working in conjunction with a good engineer to create a highly refined design in terms of energy efficiency.

In conclusion, eQUEST is the benchmark for whole building simulation, with decades of development and thousands of users providing each other support through online listing. While it claims to be an easy to use design tool, the complexity of the tool requires knowledge of building systems and performance characteristics that the typical designers do not have. That said, anyone with this knowledge can systematically construct a thorough representation of a design as well as several iterations for analysis and expect reliable results to form good design decisions.

2.4.3.4 DOE-2 and Green Building Studio (GBS)

DOE-2 is a free energy analysis utility created by the Department of Energy. Unfortunately, this programme is not very user-friendly. Green Building Studio is a web-based appliance recently bought out by Autodesk on June 26, 2008. GBS uses a gbXML file type export form Revit. GBS is a graphic user interface that wraps around DOE-2 and creates a more user-friendly environment. Certain parameters are entered (global position, season, energy cost) and GBS creates a tabulated energy analysis. This is based off the parameters entered and calculates information from DOE-2. While besides a graph or two, all the information is not visual.

Ecotect is designed to be used for early energy analysis. This programme provides better utility and visual data than GBS and DOE-2. This programme also recently became part of the Autodesk family along with GBS. The programme has a "wide range of performance analysis function…but its main advantage is a focus on feedback at the conceptual building design stages." The aim of Ecotect is to provide useful feedback in a visual and interactive environment. Calculations may not be precisely accurate at a pinpoint level, and some assumptions or averages are used to simplify calculations. The programme is not designed around highly accurate models (but can use and export formats where more detailed analysis can be performed). It appears that Ecotect will be a good choice for architect and designers, early usage proves to help prioritize energy efficiency

2.5 Summary

This chapter aims at concluding the research areas and technology character of BIM, It has provided the theory basis for the following case study. The emerging application field, technology research focus and application tools have been compared and discussed. Ecotect, eQUEST and GBS were used for tests in chapter 3.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter sets the research design and methodology adopted in the current study. Programmes involved include Revit Architecture 2010, Ecotect 2010, eQUEST3-5, Green Building Studio (GBS). The aims of this exercise are:

1. Three file formats (DXF, gbXML, IFC) : Information loss during delivery process;
2. Four programmes (Revit Architecture, Ecotect, eQUEST, and GBS): significance and barriers of product model sharing among the programmes; and
3. Two analysis (thermal comfort, energy consumption of building envelope design): application-specific input/ output for imported model.

To approach the three aims of the exercise, two experiments were designed as presented in 3.2 and 3.3.

3.2 Test I – Product Model Delivery

To figure out the problems and difficulties of product model delivery among BIM and BPA tools. Two processes need to be identified:

(1) Procedures for product model delivery from BIM to BPA tools

(2) Information delivery from the BIM tools toward the BPA tools. Information occurring during the transfer is supposed to be complete, understandable and ready to use by receiving applications;

The test consists of the three procedures:

(1) Three building models, with all its geometry and data about materials and their behavior, were built in the BIM tools Revit Architecture. One is a detail-designed house with furniture and topography; the second is a less-detailed seven-storey residential building; and the last one is a 33-storey Y-type residential building with same detail level. The first two were used to test information delivery among those programmes, and the last one was used to conduct building performance analysis in Test II;

(2) The second step consisted of exporting three models from Revit Architecture and importing them into Ecotect. Three interoperability file formats (DXF, gbXML, IFC) were used and information loss during the delivery were concluded

(3)The third step consisted transferring gbXML into INP through Ecotect and GBS, then INP model was imported into eQUEST and information during this delivery were concluded

3.3 Test II – Building Performance Analysis with Imported Product Model

In Test II, two analyses are conducted in Ecotect and eQUEST separately. One is for thermal comfort, and another is for energy consumption of different building envelope design strategy. To identify problems of performing building sustainability analysis based on sharing product model), two processes need to be identified:

(1) Application-specific input for imported model

(2) Application-specific output and interpretation

(3) Procedures of product model delivery from BPA to BIM tools. The type of

> data that can be actually transferred back to the BIM tools is of a much more limited nature, such as bitmapped files and spreadsheets which need to be interpreted, manually handled or inserted into the original BIM systems.

Thermal comfort is a condition of mind which expresses satisfaction with the thermal environment. In this section of study, the Predicted Mean Vote (PMV) is used to evaluate the thermal comfort level in a typical floor during typical summer, winter and mid-season (spring or autumn). The Predicted Mean Vote (PMV) model uses heat balance principles to relate the six key factors for thermal comfort. The calculated PMV may fall into seven categories which define the thermal sensation (comfort level) as shown in Table 3.1. According to ASHRAE hand book 2005, the input parameters and assumptions are listed below for the calculation of PMV in different seasons. The software "ECOTECT" is utilized to perform the Dynamic Thermal Modeling (DTM) for the building.

PMV	Thermal sensation scale
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 3.1. ASHRAE thermal sensation scale.

To develop an optimized strategy for building envelop design based on annual AC system electric consumption, a process known as 'elimination parametric' was referenced to, to design the experiment. The effects of one factor in the buildings performance (e.g. insulation, glazing, internal gains) are “eliminated” from the model by setting its contributing value ridiculously high or low to see how it effects energy use (Bulter, 2008). For instance, to see if the area ratio of window to wall (ww%) is a primary contributor to annual electrical consumption for heating/cooling, a parametric run is done with the ww% set to 100%. The difference in annual electric consumption between this model and the base model are compared to see the effect. This can be done for several attributes, e.g., exterior wall thermal insulation, solar radiation absorbance of exterior wall, categories of glazing, and shading system. The results are mapped against each other. The actions that produce the most significant changes indicate that tweaking those attributes with realistic values in the base model will have the greatest effect. Finally, a integrated strategy was reached by combing the attributes together, and the results of this strategy were compared with the base case, and contribution percentage of each attributes were calculated and mapped to give the designer a great insight on where to focus their design efforts for energy reduction.

3.4 Summary

This chapter describes methodology of the study including the aim, processes and procedures of the tests. Three file formats involved, namely DXF, gbXML and IFC; Four programmes were applied including Revit Architecture2010, Ecotect2010, eQUEST3-5, GBS; analysis for thermal comfort, energy consumption of building envelope design were designed based on function of Ecotect and eQUEST.

CHAPTER 4: IMPLIMENTATION

4.1 Test I – Product Model Delivery

Based on the literature review, product model delivery paths were established as shown in Figure 4.1. Test programmes included Revit Architecture 2010, Ecotect Analysis 2010, eQUEST 3-5 and Green Building Studio (GBS); three models with different detailed levels were established in Revit: Model A is a detail- designed house with furniture inside and topography outside (Figure 4.2), Model B is a less-detailed seven-storey Y-shaped residential building with only walls, floors, windows and rooms (Figure 4.3), Model C is a 33-storey Y-shape residential building with same detail level with B (Figure 4.4). They were exported from Revit Architecture as DXF, gbXML and IFC file formats and were imported into Ecotect separately. Then, the INP file format was generated by Green Building Studio (GBS)/ Ecotect with gbXML, this file was imported into eQUEST. Information losses during the delivery process were identified. Moreover, significance and barriers of product model sharing among those programmes were concluded.

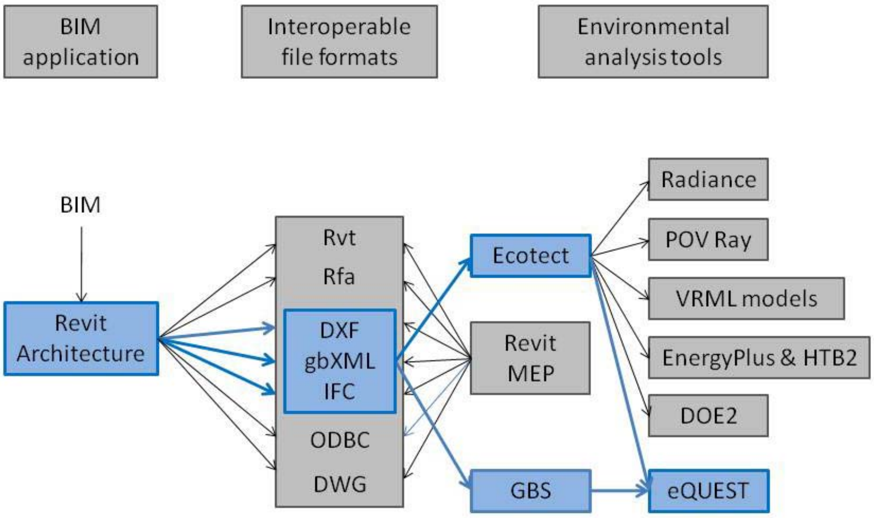
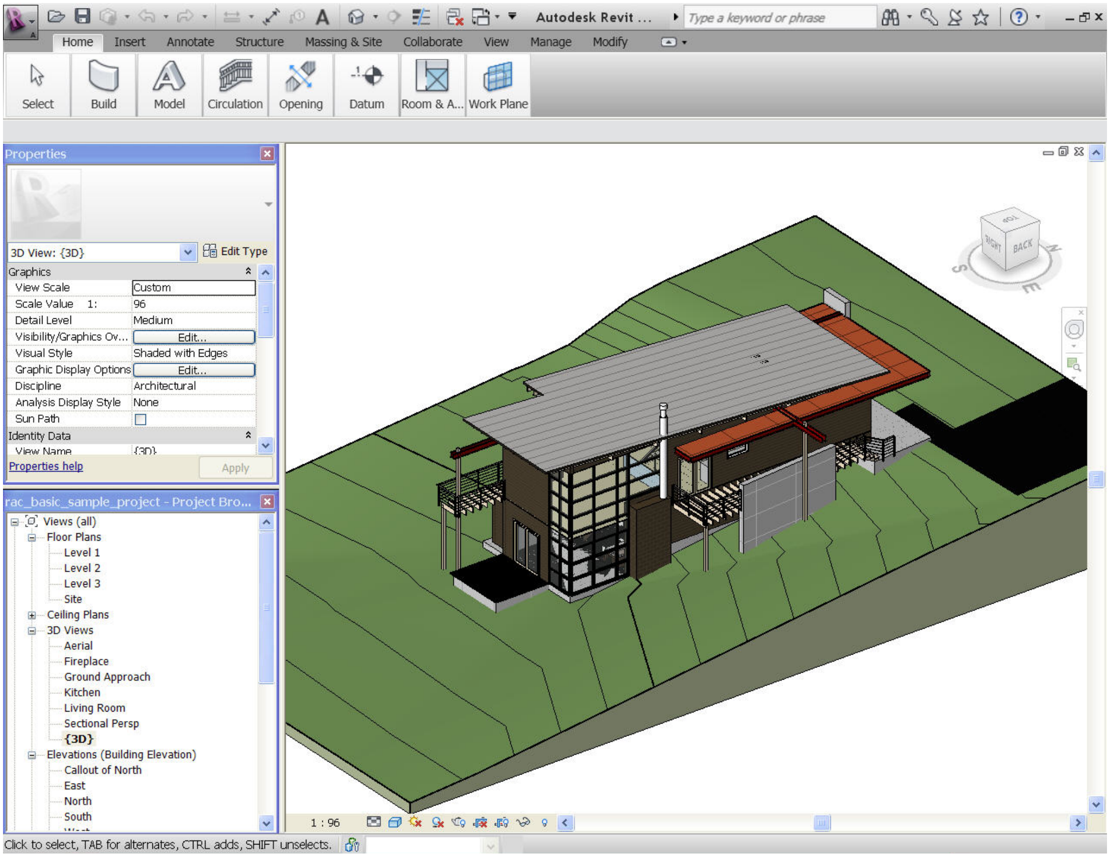


Figure 4.1: Data transfer steps based on literature reviews

4.1.1 Tested Models

Based on the research of Kumar, different interoperable file formats can only deliver limited information of BIM models. DWG is widely used format for data interoperability such as solids, regions and blocks; gbXML (Green Building XML schema) targets to exchange information to engineering analysis; and IFC (Industry Foundation Classes) has wider scope to support whole building and facility industry through the whole life cycle of a building. To figure out how the information can be delivered among the four programmes based on those three file formats, three models were built based on BIM standards and library components of The Housing Authority (HA) HK.

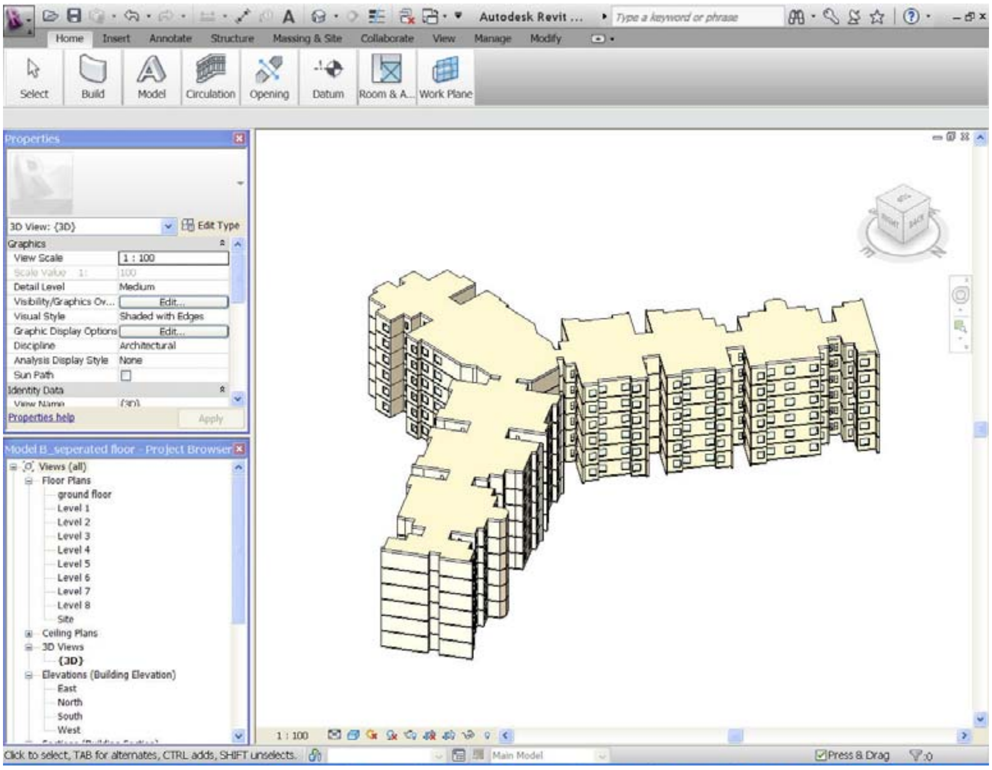


3D View: {3D} Edit Type

Graphics	
View Scale	Custom
Scale Value 1:	96
Detail Level	Medium
Visibility/Graphics Ov...	Edit...
Visual Style	Shaded with Edges
Graphic Display Options	Edit...
Discipline	Architectural
Analysis Display Style	None
Sun Path	☐
Identity Data	
View Name	{3D}

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure4.2. Model A: single room in Revit Architecture.

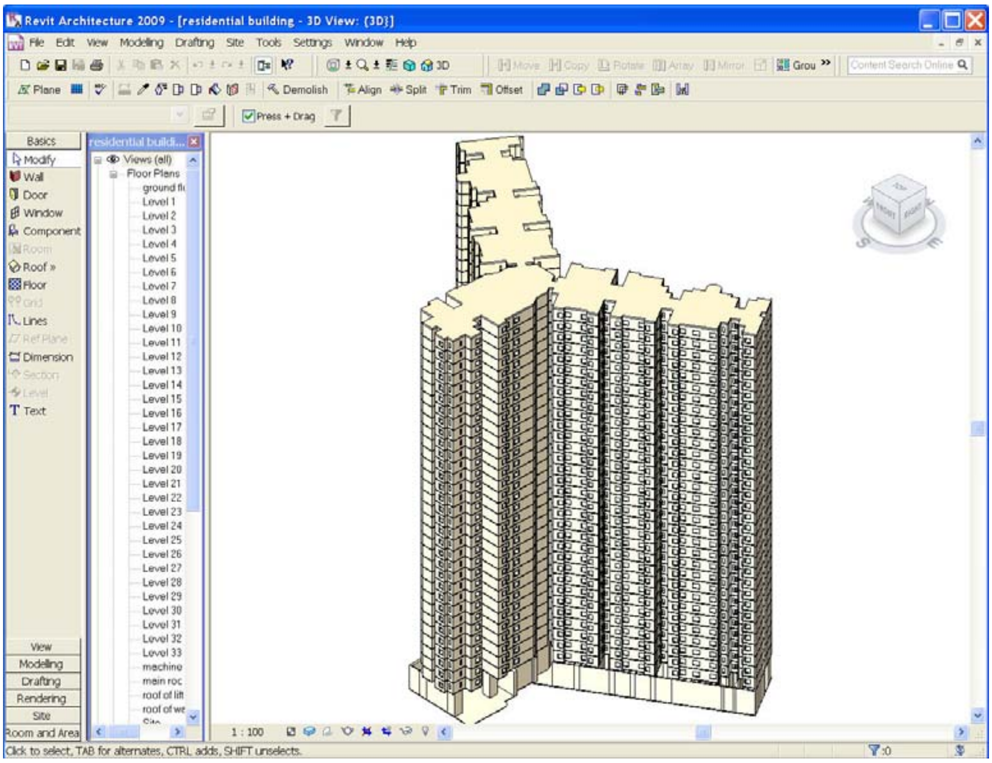


3D View: {3D} Edit Type

Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Medium
Visibility/Graphics Ov...	Edit...
Visual Style	Shaded with Edges
Graphic Display Options	Edit...
Discipline	Architectural
Analysis Display Style	None
Sun Path	☐
Identity Data	
View Name	{3D}

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure 4.3. model B: 7-storey Residential building model in Revit Architecture.



Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure 4.4. Model C: 33-storey high-rising Residential building model in

Revit Architecture.

4.1.2 Mode Preparation and Export

The re-organisation of information in receiving software application is largely depends on the specific environments and interfaces of the software itself. In Ecotect, bounding elements, e.g., wall, floor, ceiling, and roof, are converted to 2D surfaces, openings such as windows, doors and skylights are converted to sub-elements of those bounding elements, and overhangs and balconies that do not directly connect to rooms are considered as layer of shading surfaces. The volume of zone is essential for thermal and energy calculations. In Revit, rooms are the equivalent of zones and need to be defined for exporting a gbXML or IFC file. It is important to make sure that the rooms are correctly defined in Revit. Overlapping or non-fulfill of the rooms should cause errors when export a gbXML or IFC file. To make sure that all the rooms are bounded to floor, wall and roof, several steps need to be taken: 1) setting the upper limit of a room as the same as the upper limit of space in the model; 2) setting enough slitting lines to cover the whole plan, and displaying room 'interior fill' color in every section, then adjusting blue space to the bounding of roof and floor. Whether the rooms are properly set can be also checked in the export dialogue box (Figure 4.5).

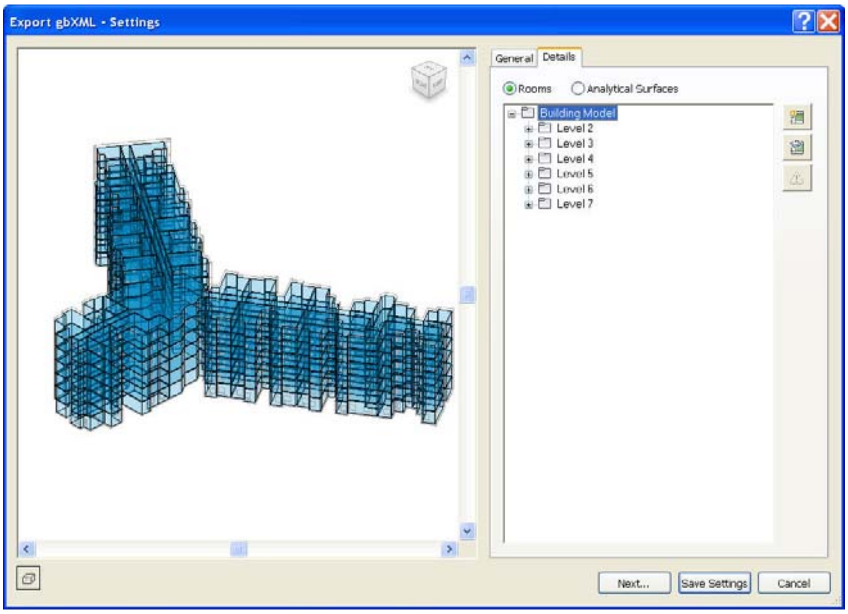


Figure 4.5. Export gbXML from Revit Architecture.

4.1.3 Model Import

4.1.3.1 ECOTECT

Model A, B, C were successfully imported into ECOTECT with DXF and gbXML file formats, while there seems to be still some problems with the exterior wall and roof placement, especially for Model A (single room). This could be partly caused by model organisation of gbXML file in Ecotect. Usually components which bound or shade the space can be correctly transferred, while other components such as column, overhang, tile, curtain wall were assigned to the layer of external shading, and mistakes like dislocation, overlap and loss of those components may happen. Windows and walls were separated, therefore extra works like opening windows and adding roofs need to be done before building performance analysis. To acquire a correct imported model, it's essential to keep the model for importing as simple as possible to avoid mistakes after importing.

Information delivered by DXF and gbXML are different. Based on Figure 4.7, it is clear to see that furniture and typography were not included in the gbXML/ IFC file in Ecotect. This information is not essential for the particular simulation of this research, while it might have been vital for running an acoustic simulation. However, DXF cannot deliver “rooms” to Ecotect which is essential to environmental analysis. Moreover, the elements in DXF files are recognized as independent lines or triangular meshes, which are recognized as complete walls, floors windows by gbXML and IFC file. That’s because of data structure of interoperability file formats themselves, DXF is a CAD file formats developed for geometry information delivery, while gbXML /IFC are developed to facilitate the transfer of building information among compatible software applications

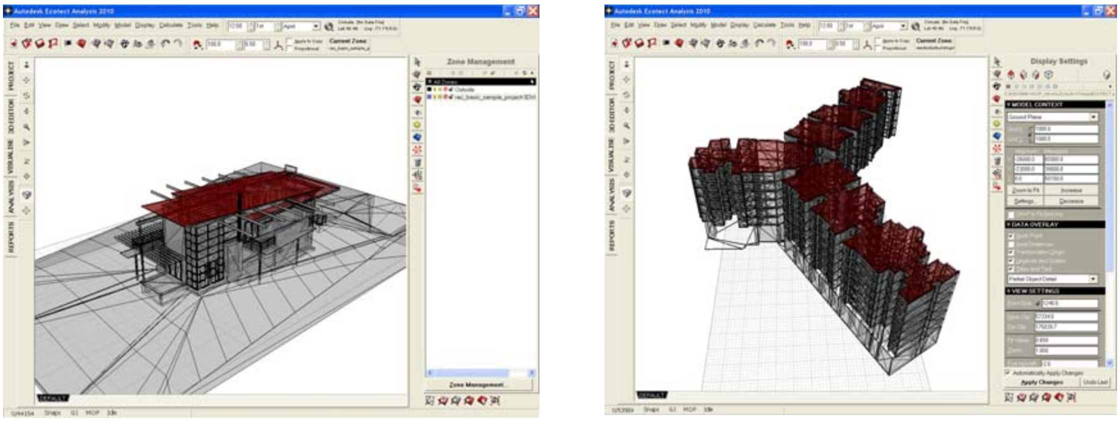


Figure 4.6. Model AB, DXF to ECOTECT.

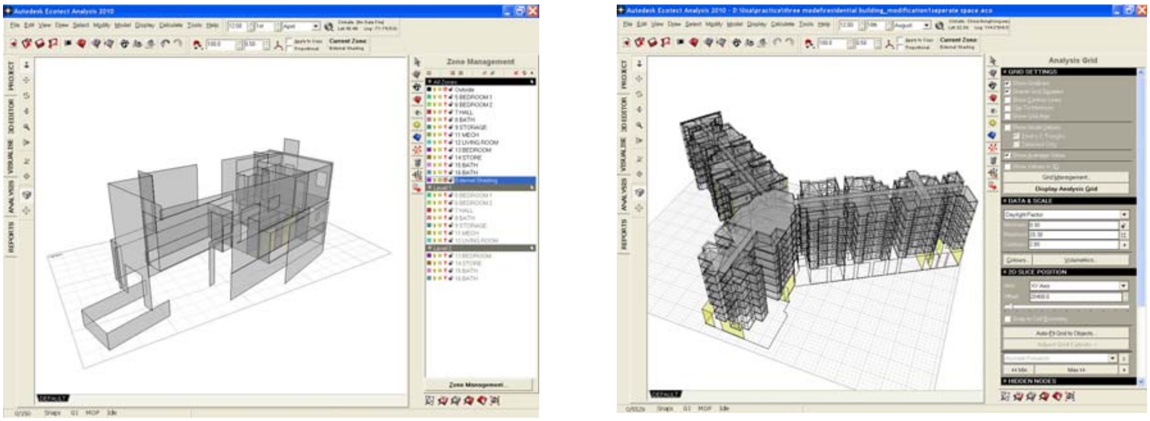


Figure 4.7. Model AB, gbXML to ECOTECT.

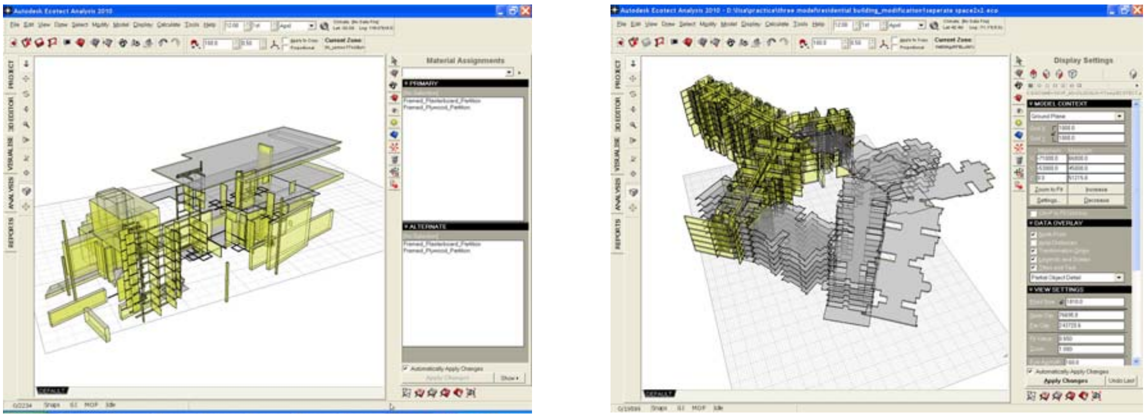


Figure 4.8. Model AB, IFC to ECOTECT.

The imported IFC file produced faulty models in Ecotect, the floor and roofs were dislocated (Figure 4.8). Part of the reason is because IFC support is only at beta stage in this release of Ecotect, therefore ifcSpace data and complex curves may not transform correctly.

4.1.3.2 eQUEST

eQUEST does not provide any BIM interface directly. The only way to import 3D-geometry information from a CAD programme is using third party programmes. Green Building Studio (GBS) and Ecotect which can transfer gbXML file into DOE-2 input file were used in this test.

The delivery of Model B from ECOTECT to eQUEST last over 24 hours, and the INP produced a false model in eQUEST, with only windows shown in a wrong spatial relationship. The wall, roof and floor were not successfully transferred because of certain mistakes. With the same gbXML model exported from Revit, a INP file was successfully generated for eQUEST, this process lasted for half an hour and produced a model in eQUEST with right geometry and material information (Figure 4.9). While it was found that the import of the model hinders the actions in the programme itself. Provided that the model is imported, eQUEST will disable the wizard functions.

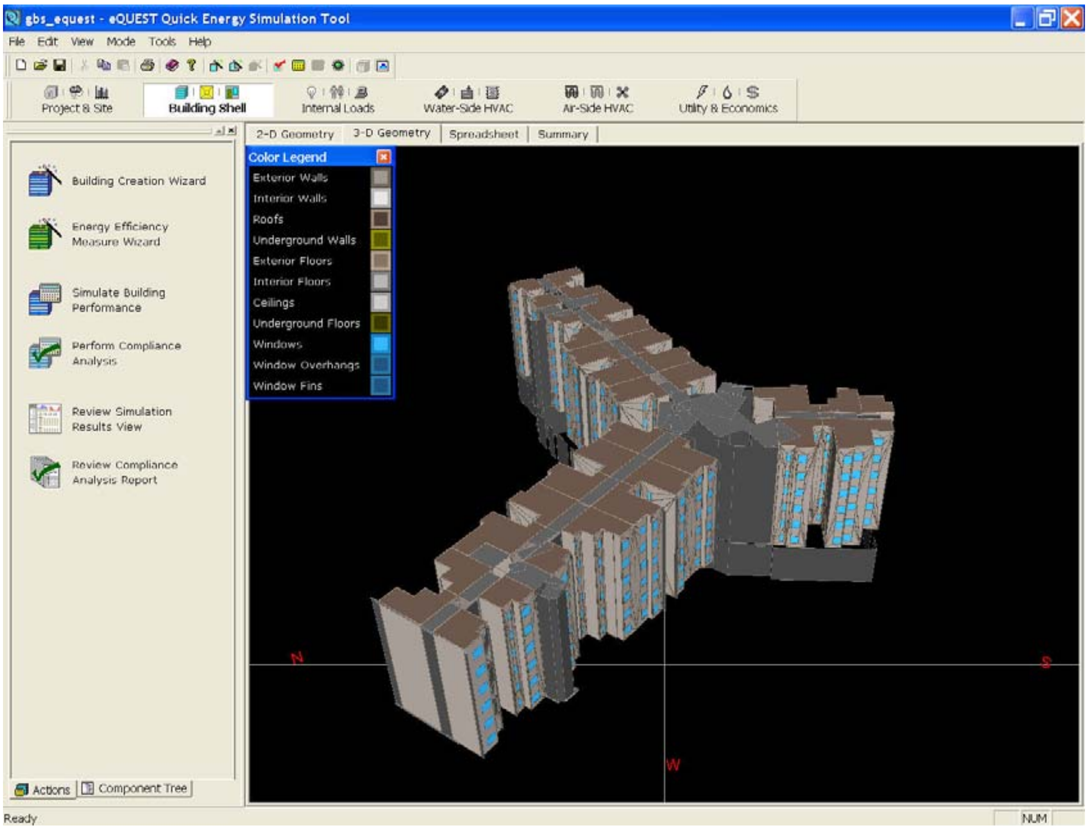


Figure 4.9. Model B, inp to eQUEST from GBS.

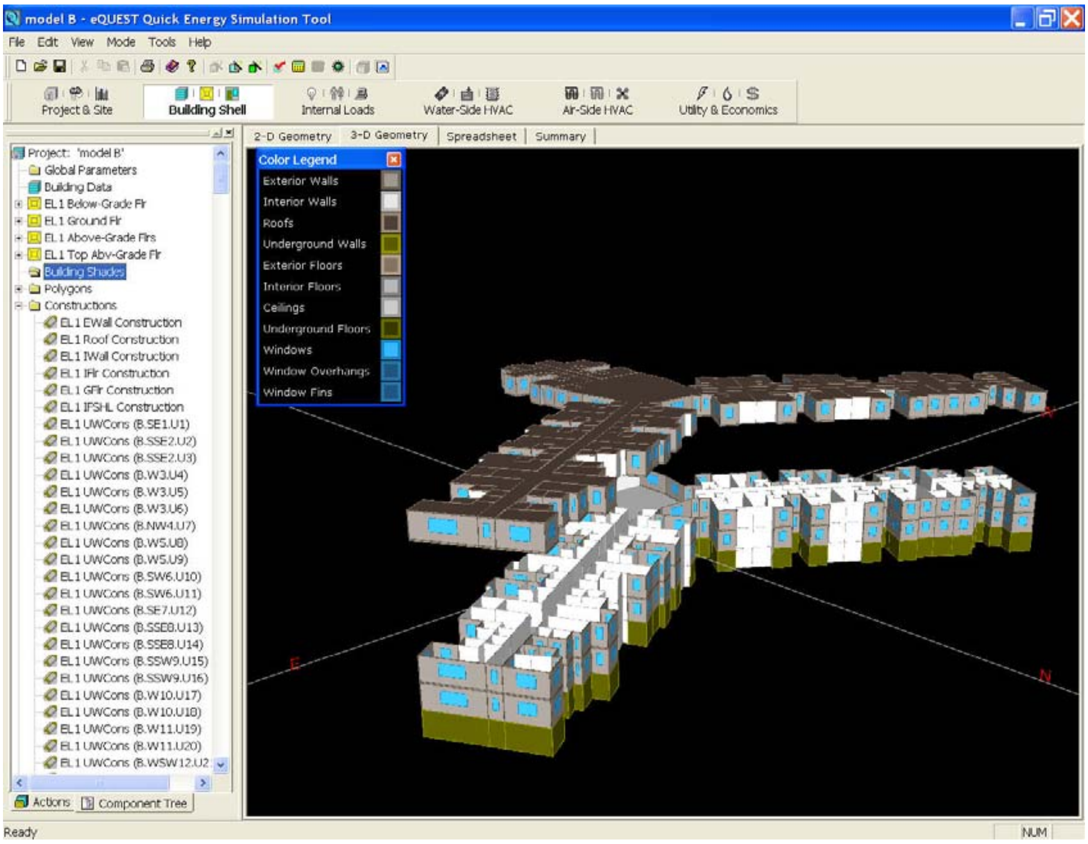


Figure 4.10. Model B, established in eQUEST with the floor plan from AutoCAD.

To figure out the information lost during the model delivery from Revit to eQUEST, a INP file was produced in Equest with the floor plan from AutoCAD (Figure 4.10). With the Schematic Design Wizard in eQUEST, foot print of typical floor was created based on DWG file imported from AutoCAD; and with the help of customized dialogue, building envelope constructions , daylight zone, activity area, HVAC system, etc., were set in a short time. Comparing the components tree of the two models, it is clear to see that imported model losing general project information like building location and type; walls, roof, window can be read while walls were all assigned to be exterior wall; material were reassigned while can be modified easily in properties; thermal zones were correctly delivered; while the information for layer and floors was completely lost (Table 4.1). In eQUEST, floors were recognized as Below-Grade Flr, Ground Flr, Above-Grade Flrs, Top Abv-Grade Flr, therefore, no matter how many floors there are, it displays as four floors by representing Above-Grade Flrs as one. For models imported, it only recognizes as one floor which result in difficulties in analysis for specific floor.

4.2 Test II – Building Performance Analysis with Imported Product Model

4.2.1 Thermal Comfort

To conduct thermal comfort analysis, building material need to be resigned and zone properties need to be assumed based on different seasons. Therefore, walls were assigned as ConcBlockPlaster, windows were assigned as SingleGlazed_AlumFrame, Plaster_Insulation_Suspended ceilings, ConcSlab floors and Concrete Asphalt roof. And after loading the weather file of Hong Kong to Ecotect, three typical day in summer, winter and mid-season were identified as 18Aug, 24Dec and 13Oct, and corresponding input parameters and assumption for PMV calculations were set in the programme (Table 4.1)

Typical day		Air Velocity	Relative Humidity	Clothing	No. of People and Activity
Summer	18-Aug	1m/s	70%	0.4 (Short and Tshirts)	3 and sedentary 70 W
Winter	24-Dec	0.1m/s	85%	1.5 (Business suits and	3 and sedentary 70 W

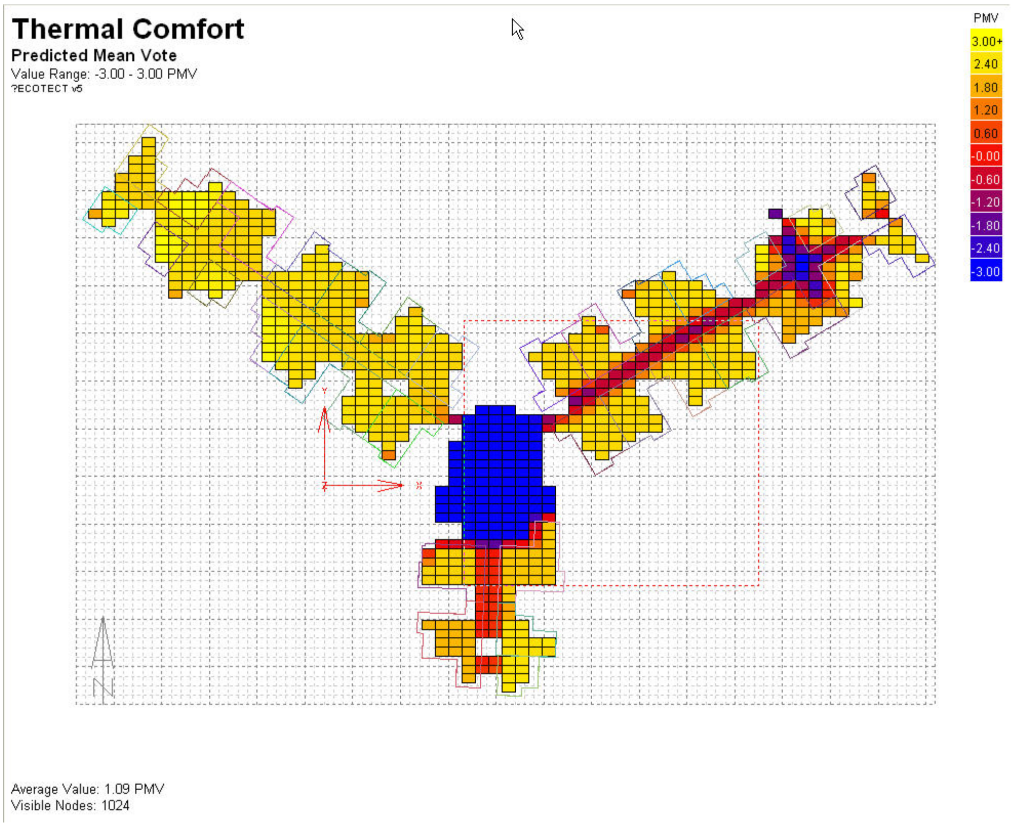
				thermals)	
Mid-season	13-Oct	0.25m/s	70%	0.6 (Trousers and shirts)	3 and sedentary 70 W

Table4.1. Input parameter and assumption for PMV calculation.

The PMV average values of each flat are given in Table 4.2 for the three typical floors. Given the thermal sensation scale of PMV in Table 4.1, it can be seen that the thermal comfort in typical seasons are acceptable for those three floors. In summer, the PMV in all three floors are close to +1, indicating slightly warm condition; in winter the PMV are close to -1 which indicates slightly cool condition and finally the thermal comfort level is of neutral in mid-season according to its sensation standard.

Flat PMV			
	Summer W	inter	Mid-season
6/F 1.18		-0.79	0.89
19/F 1.21		-1.70	0.01
32/F 1.27		-1.01	-0.01

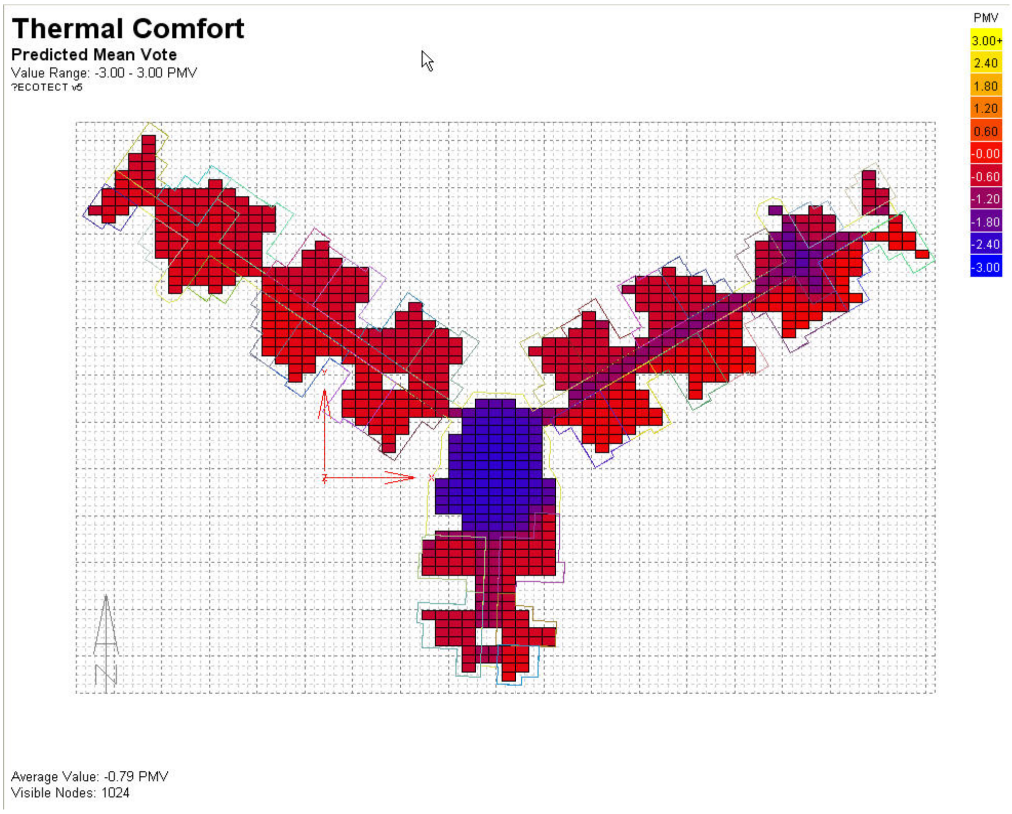
Table4.2. PMV for three typical floors.



Value Range: -3.00 - 3.00 PMV

Average Value: 1.09 PMV
Visible Nodes: 1024

Figure 4.11. PMV distribution in summer.



Value Range: -3.00 - 3.00 PMV

Average Value: -0.79 PMV
Visible Nodes: 1024

Figure 4.12. PMV distribution winter.

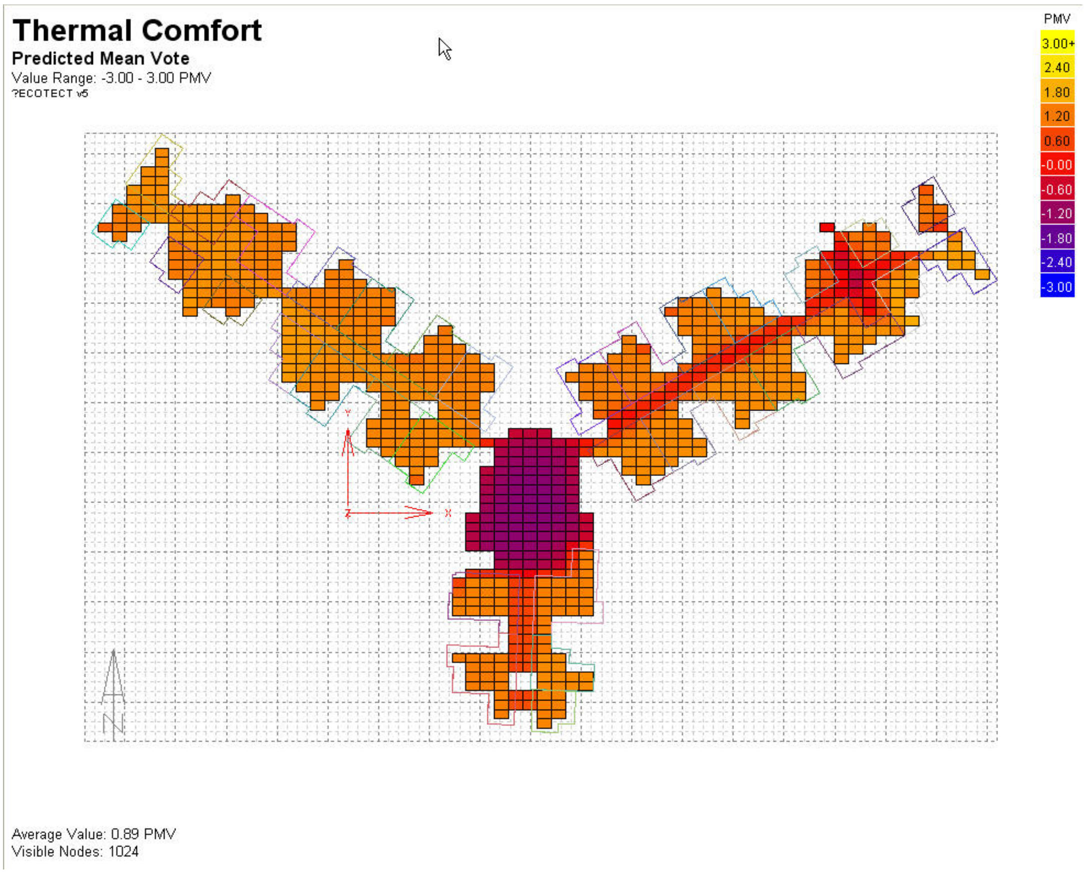


Figure 4.13. PMV distribution mid-season.

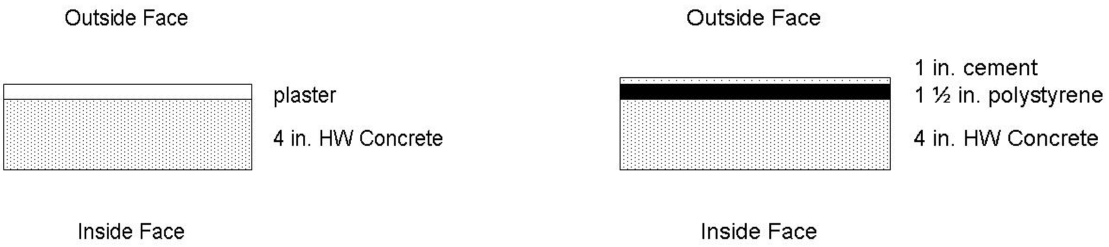
4.2.2 Optimized Strategy for Energy Saving

In eQUEST, the effects of five single energy saving strategies were analyzed with imported product model. The five strategies involved exterior wall thermal insulation, exterior wall solar radiation absorbance, area ratio of window to wall and categories of glazing and shading system, their effects on energy saving were represented by annual AC system electric consumption. Finally an optimized energy saving strategy were developed, and a comparison study between the BASECAS and optimized was conducted.

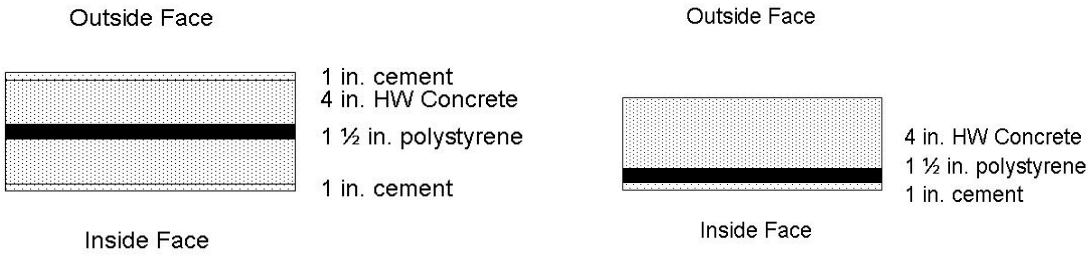
4.2.2.1 Exterior Wall Thermal Insulation

To further explore the relationship between energy consumption and wall structure, eQUEST was used in this study. DOE-2 file can be exported through Ecotect and imported into eQUEST as follows.

Polystyrene was used as the exterior insulation layer (Polystyrene located between an outside layer of 20mm cement and a 200mm reinforcement), interior insulation layer (Polystyrene located between an inside layer 20mm cement and a 200 mm reinforcement concrete layer) and a middle insulation layer in this study (two 20mm cement and 100mm reinforced concrete layer symmetrically covered both sides of the polystyrene). The thickness of insulation layer increased from 25mm to 100mm. (Figure 4.14)



BASECASE Exterior insulation



Middle insulation Interior insulation

Figure 4.14. Structures of walls with exterior, middle, interior insulation separately.

The effects of thickness and position of the insulation layer on annual AC system electric consumption, cooling electric consumption and heat electric consumption are shown in Figure 4.15~Figure 4.17. From the results, the following deductions can be made: (1) Both the annual cooling and heating electric consumption were lowest when employing polystyrene as the exterior thermal insulation layer. The penultimate was employing polystyrene as the middle thermal insulation layer. When it was employed as the interior insulation layer consumed the most;

(2) The effects of thermal insulation on cooling consumption was slightly weaker than the effects on heating consumption;

(3) Increasing the thickness of the thermal insulation layer meant a much weaker reduction of annual cooling and heating electric consumption. The 100mm exterior polystyrene thermal insulation was the best, the annual AC system cooling and heating electric consumption were decreased by 4.07% and 73.2% separately compared with BASECASE

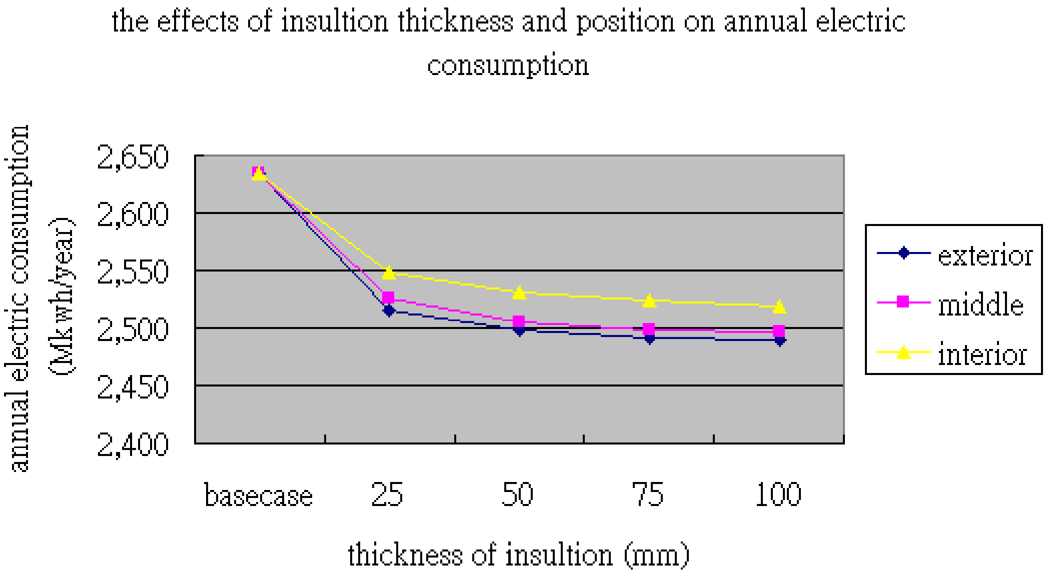


Figure 4.15. The effects of insulation thickness and position on annual AC electric consumption.

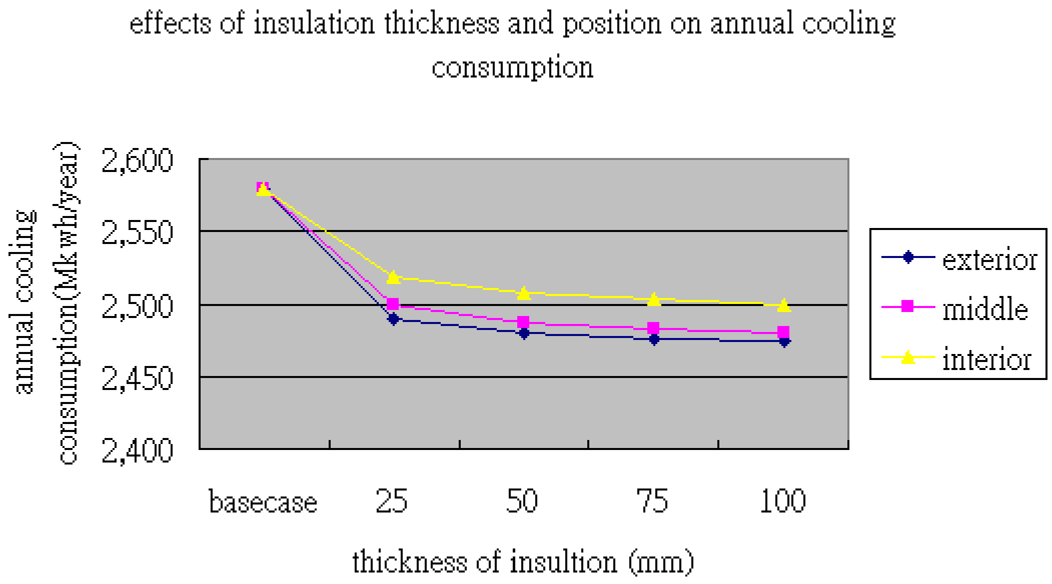


Figure 4.16. The effects of insulation thickness and position on annual cooling consumption.

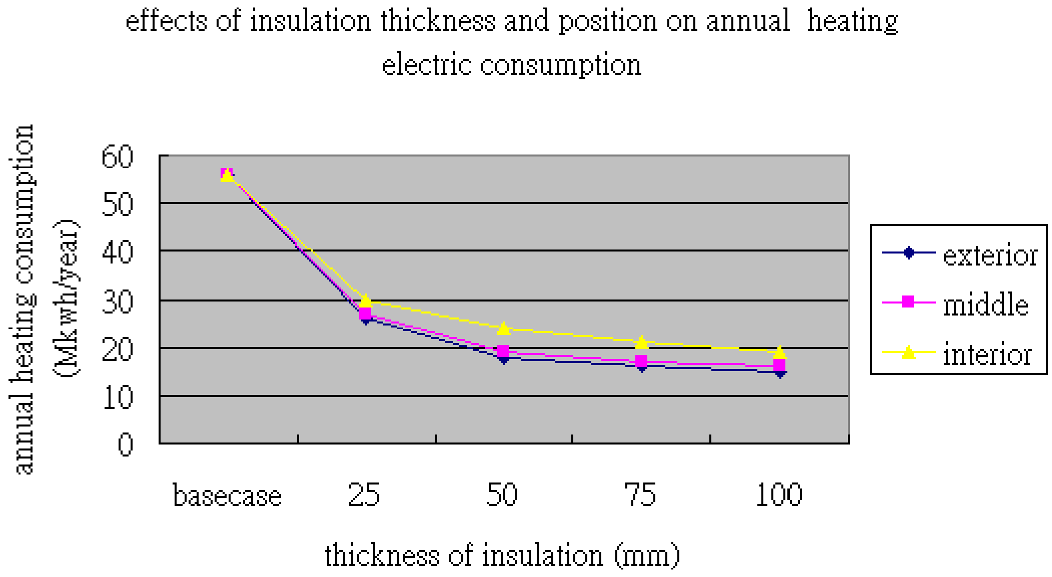


Figure 4.17. The effects of insulation thickness and position on annual heating consumption.

4.2.2.2 Solar Radiation Absorbance of Exterior Wall

Different building exterior surface materials have different solar radiation absorbance. The darker the color of the material is, the larger the solar radiation absorbance will be. With a changing rate of 0.2-0.9, the annual AC system electric consumption of a building with different exterior surface solar radiation absorbance is shown in Figure 4.18. Compared with BASECASE (solar radiation absorbance of 0.6), there was a decrease of 11.5% in cooling electric consumption, an increase of 6.8% in heating electric consumption, and a decrease of 11.2% in total annual electric consumption with a solar radiation absorbance of 0.2. Changing the solar radiation absorbance to 0.9, meant an increase of 9.48% in cooling electric consumption, a decrease of 7.39% in heating, and an increase of 9.15% in total annual electric consumption

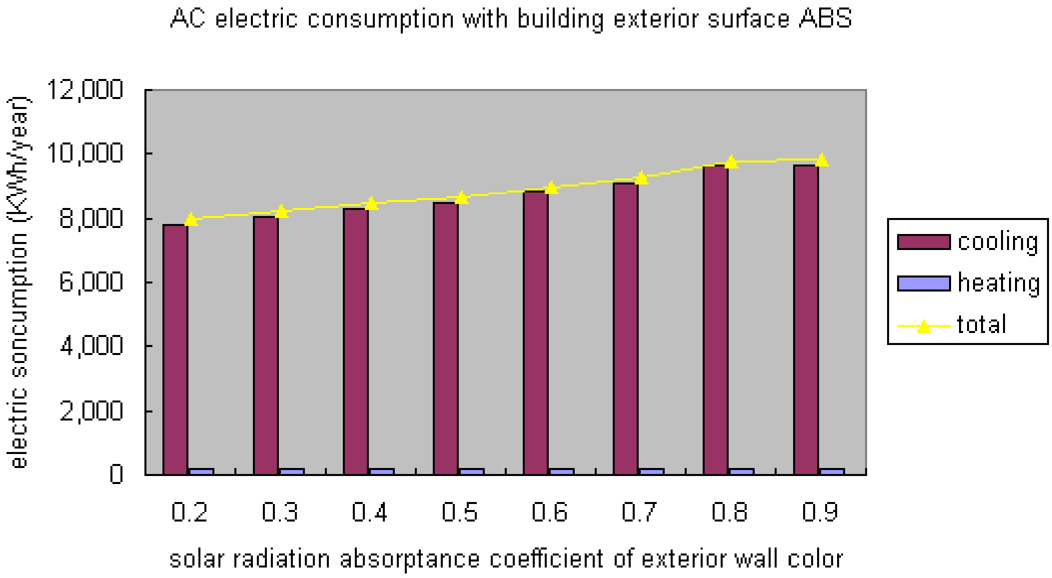


Figure 4.18. The AC electric consumption with building exterior surface ABS.

4.2.2.3 Area Ratio of Window to Wall (Floor to Ceiling)

Through changing the southwest area ratio of window to wall from 20% to 45% under a certain area ratio of window to wall (30%) of other sides and changing the southeast area ratio from 20 to 45% under a certain area ratio (30%) of other sides, the curves of annual cooling, heating and total electric consumption by end use are shown in Figure 5.19~5.21. The fitted regression lines were shown on the figures, x means the area ratio of window and wall and y means the electric consumption. R^2 means the goodness of fit, the nearer the R^2 is close to 1, the better the fitted regression lines are. With the increase of southwest and southeast area ratios of window to wall, the cooling electric consumption and annual electric consumption were increased linearly. The effect of southwest area ratio of window to wall was more obvious than that of the southeast one. The heating electric consumption was decreased linearly too when the southwest and southeast area ratio of window to wall increases. Because of the double effects of the temperature difference between indoor and outdoor and the solar radiation, the indoor heat gain and cooling electric consumption begun to sharply increases among April, and achieve the peak among July and August.

A saving of 1.20% in annual electric consumption was obtained by changing the southwest area ratio to 20%; which included a saving of 2.50% in cooling electric consumption and an increase of 6.67% in heat electric consumption. A saving of 0.32% in annual electric consumption was achieved by changing the southeast area ratio to 20% which includes a saving of 0.77% in cooling electric consumption and an increase of 0.09% in heating electric consumption. If all the area ratios of window to wall were 20% the annual electric consumption would be decreased by 2.81%. It is clear to see that adjusting the southwest area of window to wall, rather than southeast, can have greater effect on annual electric consumption.

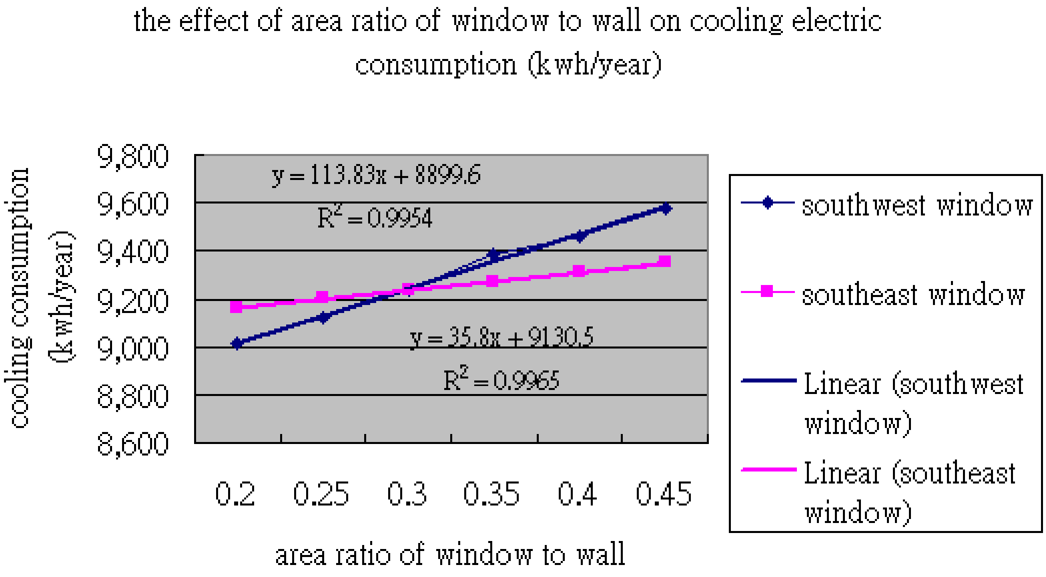


Figure 4.19. The effect of area ratio of window to wall on cooling electric consumption.

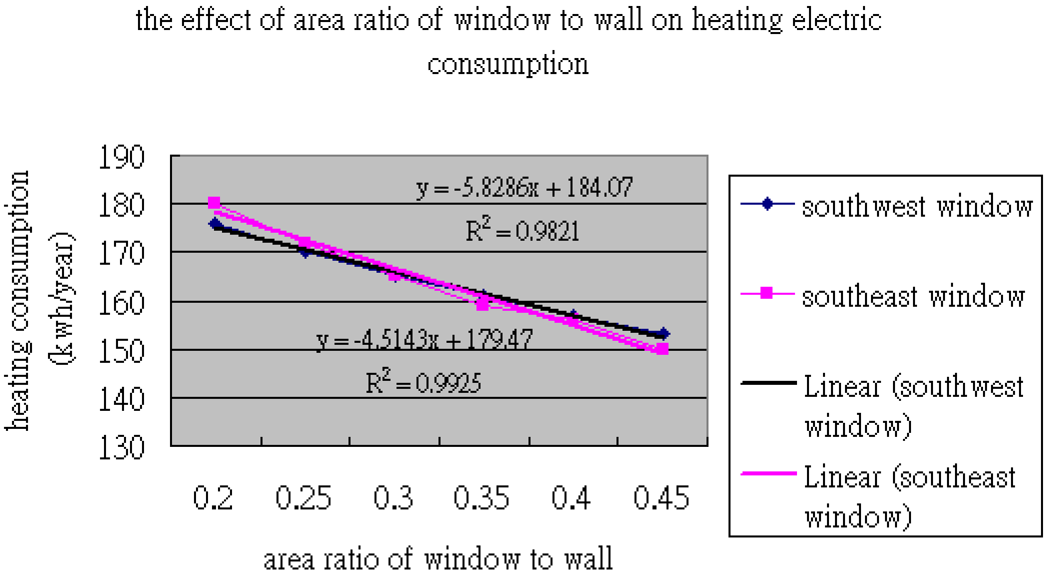


Figure 4.20. The effect of area ratio of window to wall on heating electric

consumption.

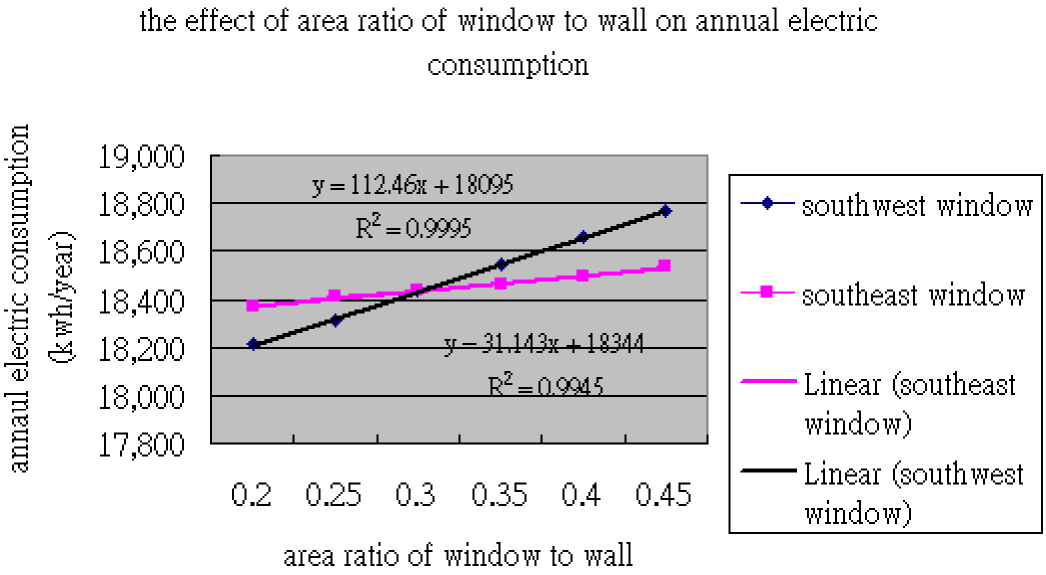


Figure 4.21. The effect of area ratio of window to wall on annual electric consumption,

4.2.2.4 Categories of Glazing

The area of glazing accounts for 70%~ 80% of the whole window, so the glazing capacity includes heat conduction coefficient and solar heat gain coefficient (SHGC) – which greatly influences the building's energy consumption. The glazing in the BASECASE model was 1/8 in. normal clear glass. The electric consumption of AC system with different kinds of double and single glazing windows are shown in Figure 4.22, the thickness of double glazing and single glazing windows are 1/8 in. and 1/4in. respectively. The double glazing one with low-e & electro & reflective has the best efficiency in energy saving of AC, with an annual electric consumption decrease of 15.42%, a decrease of 15.42% and 4.59% in cooling and heating electric consumption respectively (mainly the consumption was taken place in cooling).

Unlike the study recorded before, the difference between single and double glazing is weak. According to practices, the double glazing window, as a whole, can decrease the heat conduction coefficient and the electro glazing. Low-e glazing or reflective glazing can strengthen the reflection of solar radiation, so the AC system's annual electric consumption should be decreased (obviously which cannot be shown in Figure 4.22). To explore the essential factors affecting the quality of energy consumption of glazing, single glazing and double glazing with different SHGC were studied comparatively.

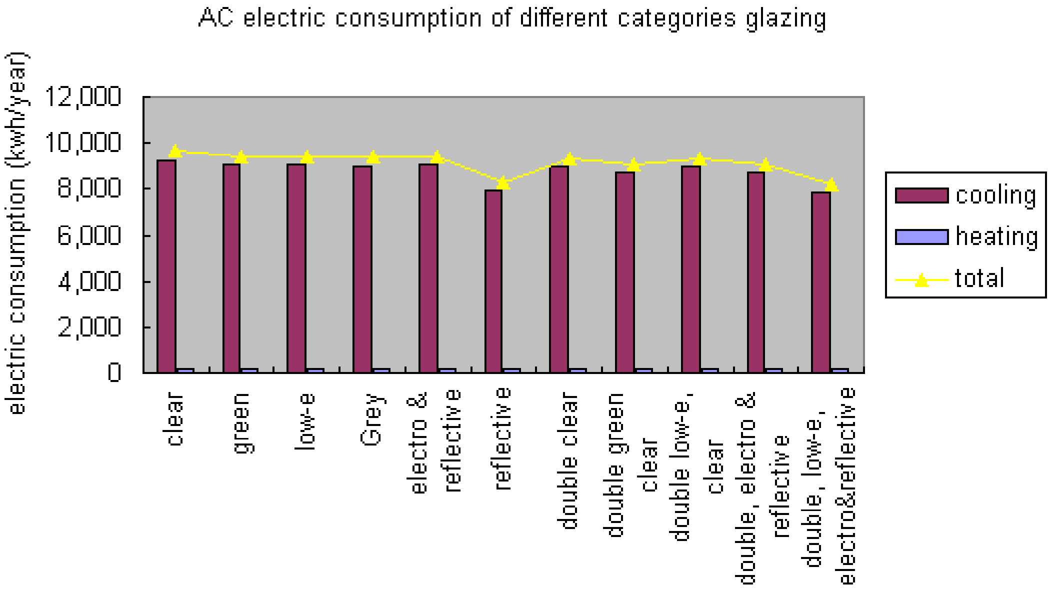


Figure 4.22. AC electric consumption of different categories glazing.

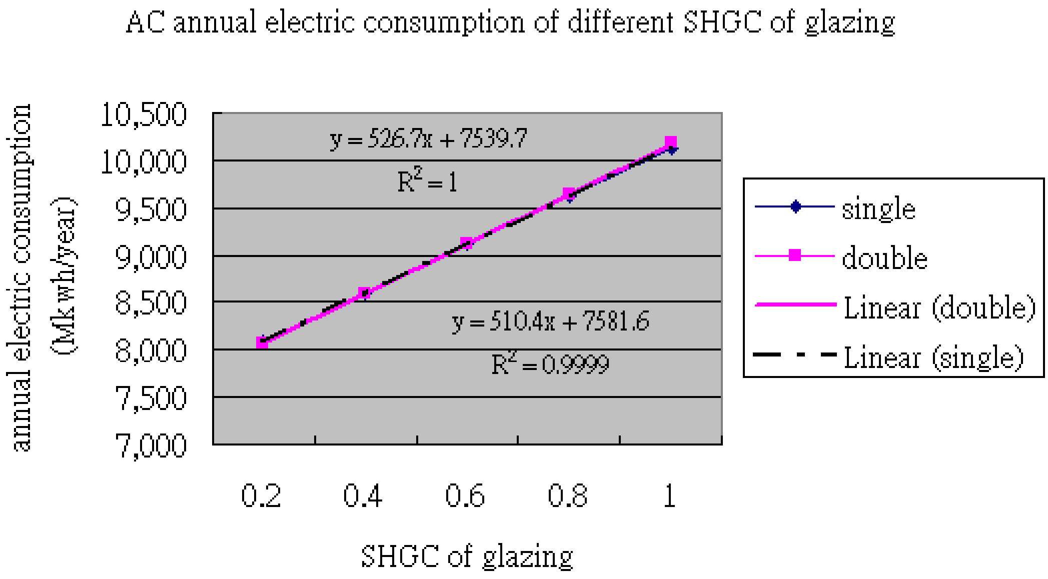


Figure 4.23. AC annual electric consumption of different SHGC of glazing.

Figure 4.23 shows the linear correlation of annual electric consumption with SHGC, x means the value of SHGC, and y means the annual electric consumption increased. The differences between single and double glazing windows are very weak, therefore the decrease of annual electric consumption of different categories glazing should be mainly caused by reflection capability of window strengthened by electro glazing, low-e glazing or reflective glazing. In other words, using a glazing with high reflection capability like reflective or low-e, electro which can strengthen reflective rather than double glazing would increase energy-saving in Hong Kong.

4.2.2.5 Shading System

Window outer fixed shading includes horizontal shading (with overhands only), vertical shading (with fins only) and integrative shading (with overhangs and fins). A maximum length of 1.5m of overhangs or fins was used. For overhangs or fins, the distance from the window edge were both 0.15m. The effects of window outer shading on annual cooling and heating electric consumption are shown in Figure 4.24~4.26.

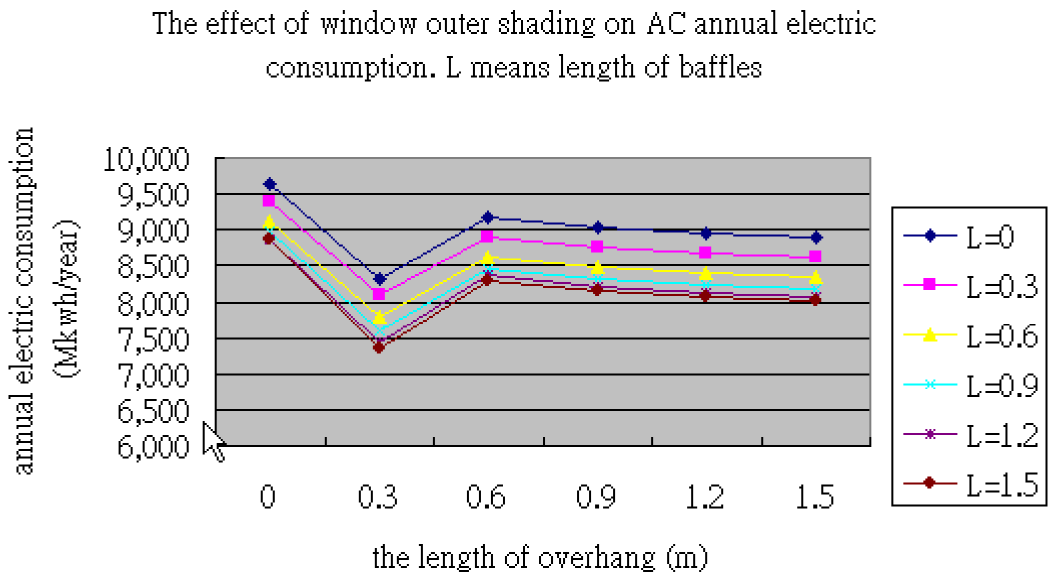

The effect of window outer shading on AC annual electric consumption. L means length of baffles

Figure 4.24. The effect of window outer shading on AC annual electric consumption (L means length of baffles).

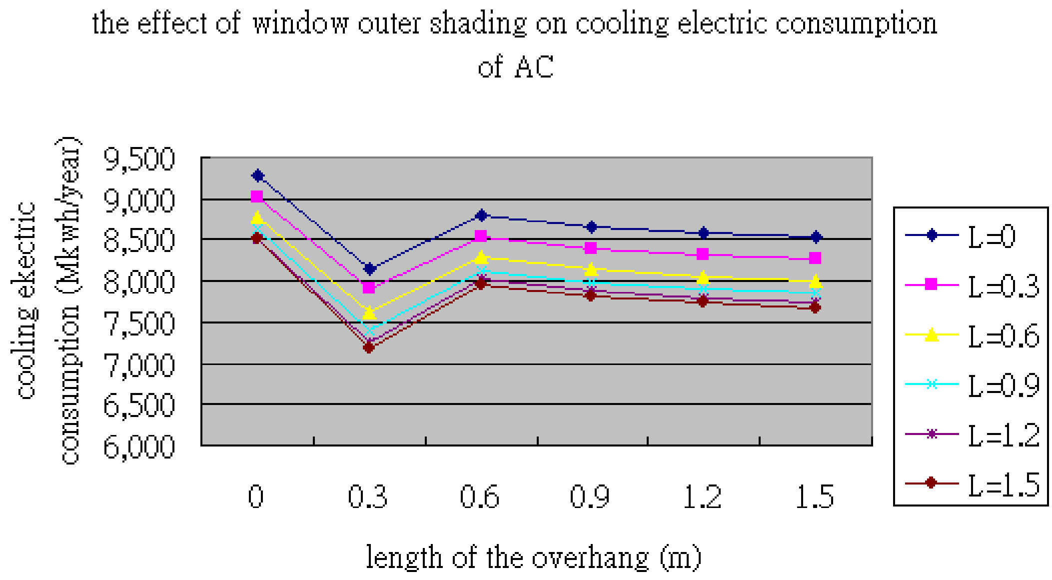

the effect of window outer shading on cooling electric consumption of AC

Figure 4.25. The effect of window outer shading on cooling electric consumption (L means length of baffles).

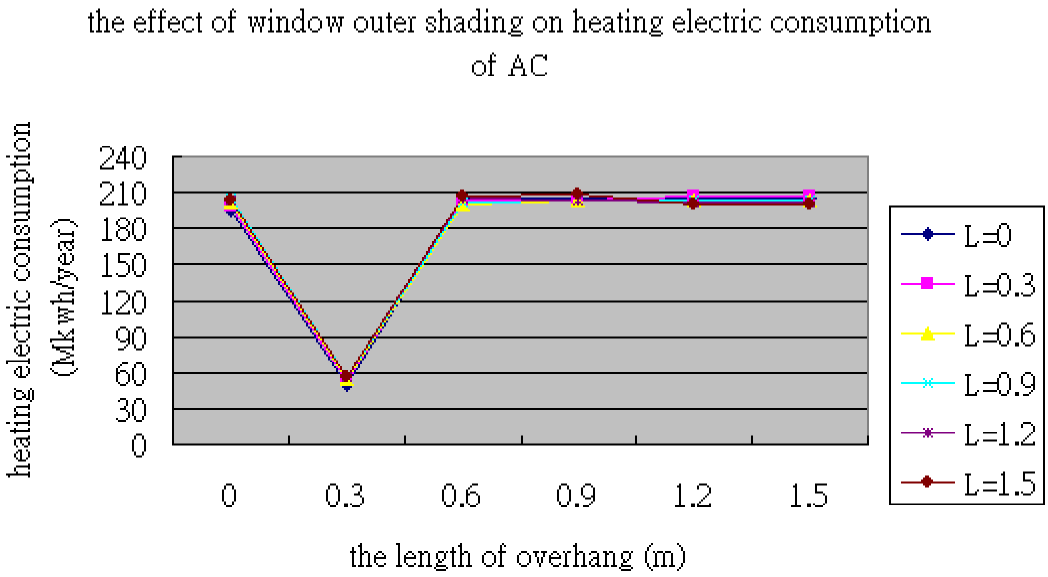


Figure 4.26. The effect of window outer shading on heating electric consumption (L means length of baffles).

The effects of vertical shading are inferior to that of horizontal shading on variation of cooling or heating electric consumption, but superior to horizontal shading on annual electric consumption. The horizontal shading of 1.5m overhangs can decrease 8.27% the cooling electric consumption when the vertical fins were 0.3m , increase 3.57% of the heating electric consumption, and finally achieve a saving of 8.19% in the total electric consumption. The vertical shading of 1.5m fins can decrease 8.08% of cooling electric consumption, increase 4.59% of the heating electric consumption, and reduce 7.89% of the annual electric consumption. When using the integrative shading of 1.5m overhands and fins, the cooling consumption was decreased by 17.30%, heating electric consumption was increased by 2.55%, and annual electric consumption was decreased by 17.05%

The influence degree increases quickly with the extending of the length of overhangs and fins. For example, the horizontal shading achieved a saving of 5.42% in annual electric consumption by the first overhangs extending to 0.6m, and achieved a saving of 6.98% with the last overhangs extending to 0.9m. For the sharp decrease caused by extending the overhangs to 0.3m (an unexpected result according to other similar studies), it requires further checking to decide whether it needs to be scrapped or adjusted.

The cooling electric consumption of the AC system decreased when using the window inner shading in summer and the heating electric consumption increased in winter. The effect of employing window inner shading in the BASECASE building was investigated only in the cooling period. This paper simulated four types of window inner shadings as shown in Figure 4.27.

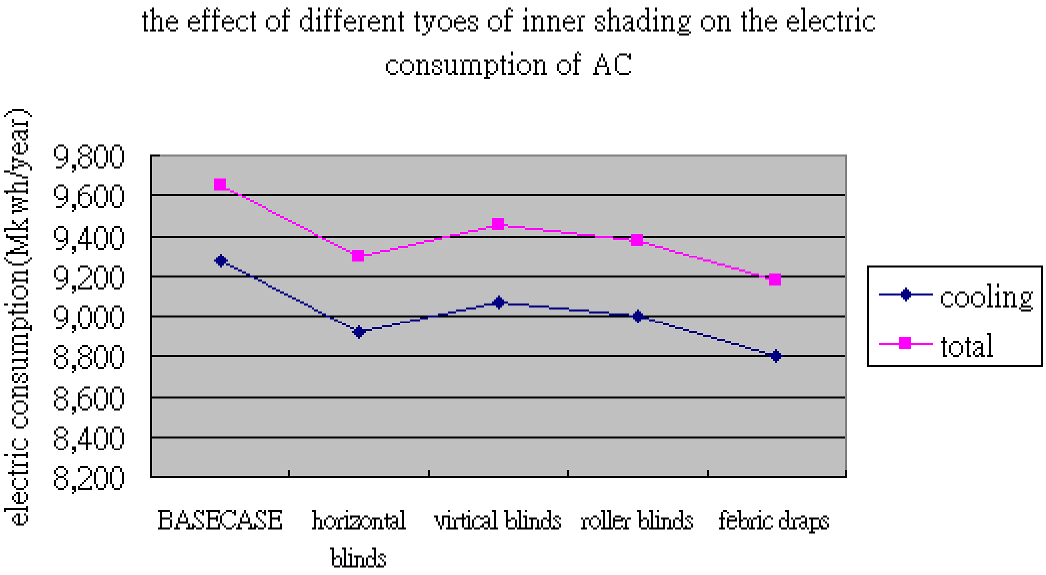


Figure 4.27. The effect of different types of inner shadings on the electric consumption of AC.

4.2.2.6 Optimised Strategy

The effects of five single energy saving strategies that include exterior wall thermal insulation, exterior wall solar radiation absorbance, area ratio of window to wall, categories of glazing and shading system and two combined energy saving strategies on the AC system electric consumption have all been developed for comparison study (Table 4.3). Choosing the best parameter of each strategy, the energy consumption and energy saved compared with BASECASE, are shown in Figure 4.28.

Component	BASECASE	CASE A
Exterior wall	No thermal insulation	Employing 4in. interior polystyrene thermal insulation
Area ratio of window to wall	30% 20%	
Glazing system	1/8 in. normal clear glazing	Double reflective glazing
Shading system	No shading system	dark roller blinds

Table 4.3. The developed designs.

The strategy RW/W 20%, changing the exterior insulation polystyrene into 75mm (II75) and using dark roller blinds (DRB), makes little affection on the AC system annual electric consumption. Using double glazing (DG) and employing integrative shading of 1500mm (LNV 1500) are the best strategies to decrease the AC system electric consumption. Case A which included II75,DRB,RW/W20%,white lacquer(ABS0.2),DG,LNV1500 can decrease 38.94% of the AC system electric consumption.

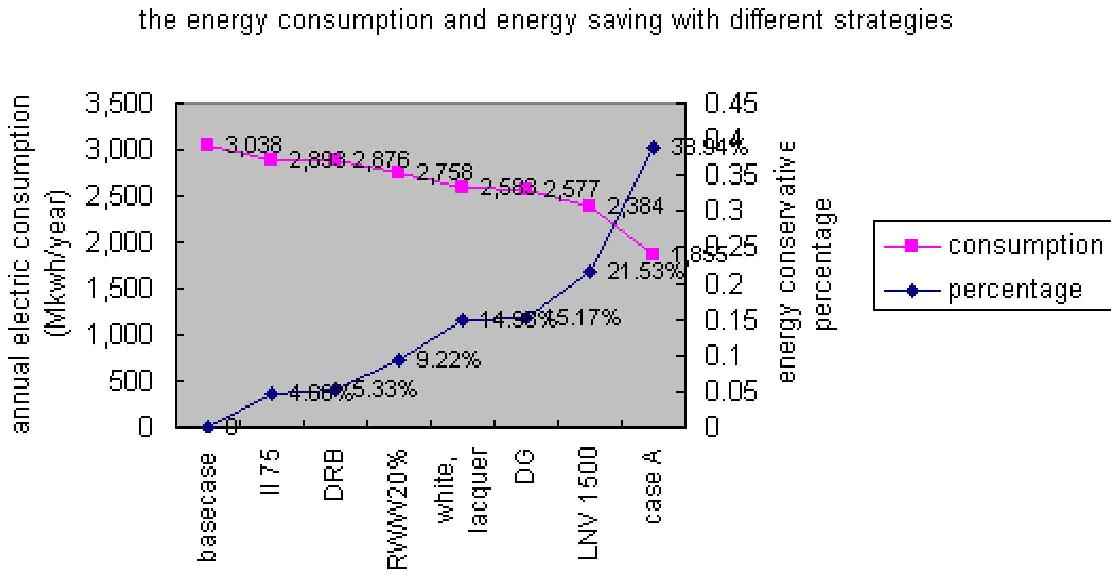


Figure 4.28. The energy consumption and energy saving with different strategies.

4.2.3 Summary

In this chapter, two tests were conducted. Information loss during delivery process through file formats DXF, gbXML, IFC and INP was recorded. Significance and barriers of product model sharing among Revit Architecture2010, Ecotect2010, eQUEST3-5, GBS were studied too. Analyses of thermal comfort and energy consumption of building envelope were conducted. PMV average values of three typical floors (6F/19F/32F) were calculated, and the result shows thermal comfort in typical seasons are acceptable for those three floors; five design strategies of building envelope were compared based on annual electric consumption o HVAC system.

CHAPTER 5: CONCLUSION

5.1 Introduction

This chapter presents the conclusions of this research study. The objectives of the study are first reviewed, supplemented by a summary of the main findings and the presentation of the contribution and significance of the research. The limitations of this study are indicated and recommendations for future research made.

5.2 Review of Research Objectives

The opening chapter outlines the current state of application of BIM in the AEC industry. This research aims at integrating BIM with Building Performance Analysis (BPA) tools for building sustainability analysis. The objectives are (1) Three file formats (DXF, gbXML, IFC): Information loss during delivery process; (2) Four programmes (Revit Architecture, Ecotect, eQUEST, GBS): significance and barriers of product model sharing among the programmes; (3) Two analyses (thermal comfort, energy consumption of building envelope design): application-specific input/ output for imported model

Regarding objectives, chapter 2 reviewed evolution of BIM technology and application. So far, major successes have been recorded using 3D building models for dynamic viewing, graphical animation, collision detection and process simulation - by linking to the construction schedule; some progress has also been made in the area of intelligent buildings modeling; Capturing the richness data of the intelligence and the data flows between the stakeholders are both critical variables of BIM maturity, therefore information deliverables has become another research hot spot of BIM globally, plenty of standards have been developed, released and implemented in commercial software for testing and application. Based on those accelerating emergence of guidelines and reports dedicated to exploring and defining the requirements and deliverables of BIM, a growing number of projects are carried out in relation to applying BIM in many fields. Emerging fields such as Facility Management, Sustainability Analysis are gradually bringing in BIM technology to form a more efficient workflow. And the success of the BIM concept within the building sector has made the major CAD vendors to promote the same concept within the civil structures area - such as bridges, earthwork, roads and highway design and construction space management.

For the second and third objectives, in chapter 2, a review of product delivery was described. Three interoperability file formats are described and compared, namely DXF, gbXML and IFC. For BPA tools, Ecotect, eQUEST, IES<VE>, Green Building Studio, etc., are described.

And for the same purpose, two tests are established in Chapter 3 and implemented in Chapter 4

5.3 Contribution to Knowledge

5.3.1 Developing a framework for applying BIM to building thermal comfort and energy consumption analysis

5.3.1.1 Model Preparation

Generally, two thing need to be concerned before conducting an integration design.

1. Determine the kind of analysis the project needs, then figure out if this will require zones or building geometry.

a) Geometry: For architectural sun or acoustic studies, geometry information of facility and topography is more important the zones. By developing workflow to track and import only the elements needed based in DXF file, analysis can be conducted in a more efficient way.

b) Zones: From Revit, a gbXML file can be quickly imported into Ecotect if the spaces are correctly set in Revit. And using Zones, Ecotect is a strong tool for architectural design studies related to sun, solar gains and thermal analysis. Moreover, as a base for model interoperability, Ecotect can import and export between BIM applications such as Revit Architecture and BPA tools such as IES, EnergyPlus, Radiance, and Daysim. While the delivery to eQUEST didn't work in this test.

2. Figure out the organisation of model in programmes for integration design, is it proper for the planned analysis, and whether the import of model will hinder its original function.

5.3.1.2 Product model delivery

Product model delivery from Revit to Ecotect, and then to eQUEST is time-consuming and unstable. While product model delivery from Revit to GBS, and the to eQUEST did work in the test, and with certain information loss, analysis can still be conducted (Figure 5.1).

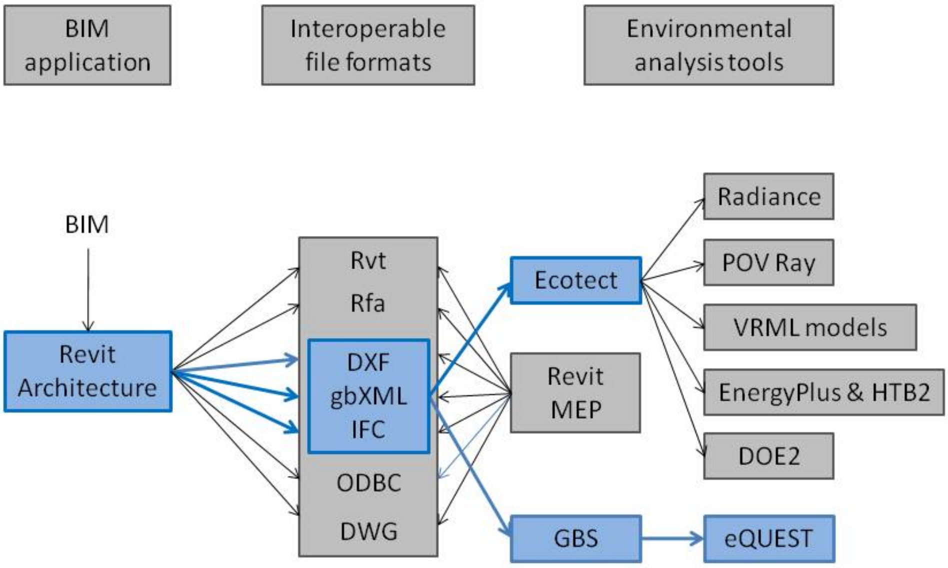
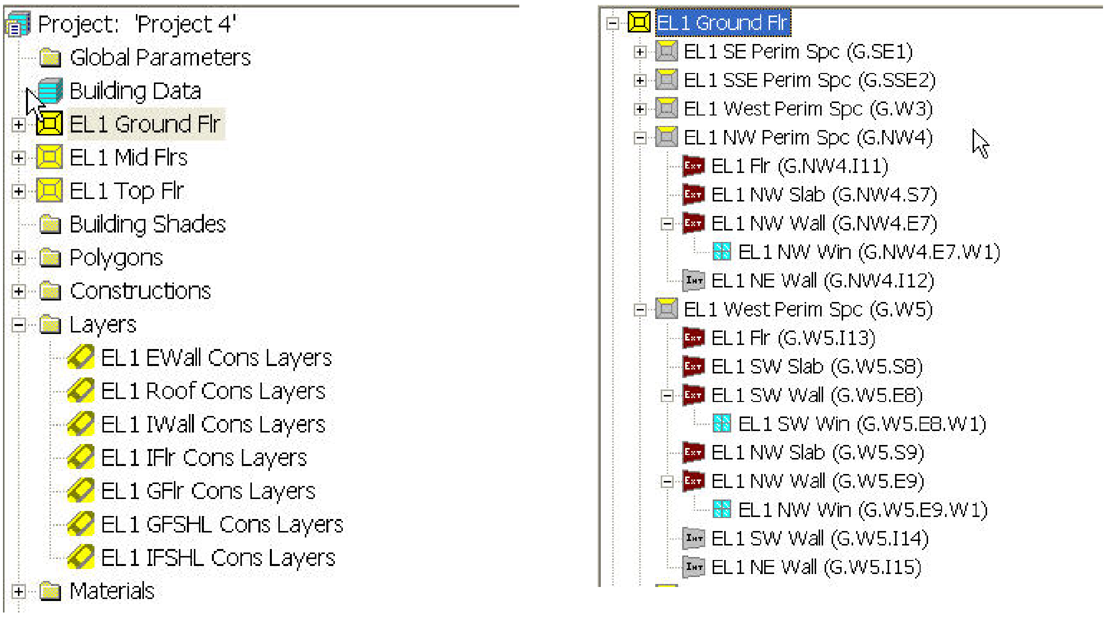


Figure 5.1. Modified data transfer steps.

Information loss during the delivery process was caused by data structure of the interoperability file formats and the model organisation method of the software applications (e.x. Revit Architecture separates object by floors).

Ecotect organizes model based on space when gbXML/ IFC file was imported, and layers were named after space automatically. For DXF file, as only geometry information of model was imported, Ecotect assign the whole model in one layer and read it as independent lines or triangular meshes. While DXF is the only file format that can transfer geometry information of facility and topography into Ecotect, this information is not essential for the particular simulation of this research, while it might have been vital for running an acoustic simulation.

eQUEST separates INP model by several ways. In the component tree, several sub-components file are listed under the project file, they are floors, building shades, polygons, constructions, layers, materials, etc. Models are separated into four layers Below-Grade Flr, Ground Flr, Above-Grade Flrs, Top Abv-Grade Flr, for imported model, as function of Building Creation Wizard is hindered, and the model can only be read as one floor which results in difficulties for analysis of specific floor . Each floor is organized as Exterior components and interiors components which are further divided into wall, slab, floor, etc. (Figure 5.2). And Under the sub-file of space polygon, spaces which are set in Revit can be correctly delivered, while they are also renamed which makes analysis for specific room very inconvenient. Under the sub-file of Construction, model are organized by construction of Exterior wall, interior wall, roof, ground floor , interior floor , etc., while for imported model eQUEST cannot differentiate interior and exterior wall, so all the wall are assigned as same materials for imported models.


- Project: 'Project 4'
  - Global Parameters
  - Building Data
  - EL1 Ground Flr
  - EL1 Mid Flrs
  - EL1 Top Flr
  - Building Shades
  - Polygons
  - Constructions
  - Layers
    - EL1 EWall Cons Layers
    - EL1 Roof Cons Layers
    - EL1 IWall Cons Layers
    - EL1 IFlr Cons Layers
    - EL1 GFlr Cons Layers
    - EL1 GFSHL Cons Layers
    - EL1 IFSHL Cons Layers
  - Materials

- EL1 Ground Flr
  - EL1 SE Perim Spc (G.SE1)
  - EL1 SSE Perim Spc (G.SSE2)
  - EL1 West Perim Spc (G.W3)
  - EL1 NW Perim Spc (G.NW4)
    - EL1 Flr (G.NW4.I11)
    - EL1 NW Slab (G.NW4.S7)
    - EL1 NW Wall (G.NW4.E7)
      - EL1 NW Win (G.NW4.E7.W1)
    - EL1 NE Wall (G.NW4.I12)
  - EL1 West Perim Spc (G.W5)
    - EL1 Flr (G.W5.I13)
    - EL1 SW Slab (G.W5.S8)
    - EL1 SW Wall (G.W5.E8)
      - EL1 SW Win (G.W5.E8.W1)
    - EL1 NW Slab (G.W5.S9)
    - EL1 NW Wall (G.W5.E9)
      - EL1 NW Win (G.W5.E9.W1)
    - EL1 SW Wall (G.W5.I14)
    - EL1 NE Wall (G.W5.I15)

Figure 5.2. Components tree of model in eQUEST.

Although varying model organisation and model creation practices were acceptable in intra-disciplinary 3D applications, they created challenges and rework for the architectural designers in the project. Therefore it is important to determine the kind of analysis the project needs, and choose the proper programmes accordingly, or on the opposite design the analysis fit for the programme. For example, as eQUEST cannot read floors of imported model and re-assign the same material to all the walls, an analysis for optimizing building envelop design is designed. As it does not concerns the exact place of the floors of the building, and does not ask for an exact value for annual HVAC electric consumption (the calculated results of Optimized CASE are used as a control group to BASECASE, then designers can choose the better strategy based on this value).

5.3.1.3 Re-Input for Specific Sustainability Analysis

Test II shows that BIM can facilitate complex processes of sustainable design such as thermal comfort analysis and building envelope design optimisation. And in order to sharing a product model among applications from different disciplines, interventions and specific customisations of the model organisations are necessary. Various input/output requirements happened after importing the product model into the receiving software applications. Both Ecotect and eQUEST required manual re-definition of data to perform environment assessment. Thermal comfort analysis in Ecotect required a re-assignment of material of building components, and a more detailed set for rooms such as schedule, velocity, and weather data. For building envelop optimisation design analysis in eQUEST, a more detailed identification of elements of building envelop were required than the architect's specification of the 3D objects in Revit Architecture (Table4.1, Table 4.3).

Therefore, it is clear that various requirements for re-input is unavoidable as different analysis have specific demanding for the model. Take function of Ecotect for example: LIGHTSCAPE, one choice for exporting in Ecotect, required a higher level of precision in all joints or connections, causing architects to modify joints and connections that not precisely meeting one another; and 4D applications required object breakdowns and groupings corresponding to the construction or installation sequence, rather than the architectural breakdowns.

Another problem of the conversions was that they are mainly one-way processes, as the type of data that can be actually transferred back to the BIM tools is of a much more limited nature, such as bitmapped files and spreadsheets which need to be interpreted, manually handled or inserted into the original BIM systems. Moreover, one-way conversions of product models are inflexible for subsequent modification and sharing.

5.3.2 Benefits and barriers of product model delivery

5.3.2.1 Benefits

Test I indicates that Building Performance Analysis (BPA) tools are capable of using BIM models based on commonly-used interoperability file formats. Base on Test I, a comparison about information delivery with file formats DXF, gbXML, IFC and INP was shown as following (Table 5.1).

Data		delivery from Revit Archi to Ecotect			Data transfer from GBS to eQUEST
		DXF	GbXML	IFC	INP
Project information	Drawing Units	Yes	Yes	No	Yes
	Location	No	Yes	No	No
	Building type	No	Yes	No	No
Geometry	Shape	Yes	Yes	Yes	Yes
	Area	Yes	Yes	Yes	Yes
	Volume	Yes	Yes	Yes	Yes
Topography	topography	Yes	No	No	No
Materials	Thickness	Yes	Yes	Yes	Yes
	Texture	No	No	No	No
	Properties	No	Yes	Yes	Yes

	Specification of new material	No	Yes	Yes	Yes
Elements	Constructive elements, window, wall, roof, etc.	No	Yes(but roof was lost in the test)	Yes (but roof was lost in the test)	Yes (cannot differentiate interior and exterior wall)
	Other elements, Furniture, plant, etc.	Yes	No	No	No
	Spatial relations	Yes	Yes	Yes (but dislocation happened in the test)	Yes (but dislocation happened in the test)
Data (the way it recognizes the elements)	Independent lines	Yes	No	No	Yes
	Surface	No	Yes	Yes	No
	Layer	No	No	No	No
zone	Thermal zone	No	Yes	Yes	Yes

Table5.1. Below shows the assessment criteria and the information file formats from the test.

It is proved that Ecotect 2010 cannot read IFC file correctly, therefore the 33-storey Y-type residential building was imported into Ecotect with gbXML file. And as INP file exported from Ecotect cannot be interpreted correctly in eQUEST, model C were delivered to eQUEST through Green Building Studio (GBS) (Figure 5.1). Therefore, considering the software applications for integration design in this test are Ecotect and eQUEST , and also as following performance analysis is about thermal comfort and energy consumption which requires zones, gbXML is used as the interoperability file formats for integration design in this study.

Benefits of this process can be concluded as:

(1) To realize the process of building information model delivery
(2) To exchange project data with IFC and gbXML file formats
(3) To conduct thermal comfort and energy consumption analysis with imported model

5.3.2.2 Barriers

Experience in this study shows barriers for integration design based on BIM are caused by interoperability file formats, model organisation in receiving applications. Information loss and rework for model modification for specific analysis is unavoidable, it is important to make clear the analysis objective, the use of the model, then decide what kind of information it needs to deliver, and which level of detail it needs to have.

(1) IFC/gbXL Standard

Problem occurred in the study related to interoperability file formats can be concluded as misreading of model geometry, loss of object information and confusion in revision.

Besides data structure of the file formats, the misreading and loss of information are also due to the default setting of receiving applications. For example, model organisation in Ecotect bases on zones. Therefore building elements that are not bounding to zones such as column, curtain wall, structure layers, are assigned to the same layer, and model details like joints, connections cannot be correctly represented either which hinders the subsequent modification and sharing of the model. On the other hand, this study also showed that software generates different IFC/gbXML export files if they model two identical windows from different point. I also experienced import errors with geometry from gbXML file. In that case, the middleware that mapped between gbXML file and INP file was the source of the errors: GBS generates the right import file while Ecotect generate a wrong with the same gbXML file.

Both gbXML and IFC file ignored all non-geometric object parameters during the process of produce model delivery. For example, in export for thermal comfort analysis, building components' properties such as velocity, time schedule device identification were lost in their representation in Ecotect.

Last problem is the confused revision of the model. Whenever I revised the 3D model and exported an update file, the Revit Architecture regenerated a new set of space identification. Therefore, when a second design iteration occurs, I have to manually synchronized the new design data with previous analytical data, or regenerate simulation of the entire building.

(2) Model Sharing

The study shows that the various 3D model organisation standards, specific input for receiving software applications and time-consuming one-way conversion could potentially undermine future absorption of the product models sharing.

The model organisation largely depends on the specific environments and interfaces of the software application in use. Although there varying model organisation and model creation practices were acceptable in intra-disciplinary 3D applications, they created challenges and rework for the architectural designers in the project. Moreover, to effectively sharing a product model among applications from different disciplines, significant interventions and specific customisations of the model organisations are required. Experience shows that bridging in mapping the output organisation from one application to the input requirement of anther application is cumbersome, time-consuming, and irreversible; all of which might deter subsequent product model exchanges. And conversion processes in this study are one-way conversions which are inflexible for subsequent modification and sharing, manipulation can be conducted only by repeating the conversion process.

5.3.3 Recommendation for Future Work

The study demonstrates how integration design could be conducted by BIM model delivery. As it only concerns about builders and designers, further work needs to be done to figure out how a project team can cooperate together for the product model sharing and information reuse. At this part, recommendations are made for designers and builders towards problems for model building and sharing.

5.3.3.1 Tailoring models to fit the analysis purpose

When working with product model, the first thing should be evaluating the specific purposes of the model and thus, tailors their efforts and expectations accordingly.

As information loss and re-input are avoidable during the model delivery process, the designers should first evaluate what kind of analysis purpose this model is going to meet, and what kind of data it needs to contain. For model that needs to be shared during the whole design process, it should contain data that are relevant and sharable to many parties; whereas for domain-specific models which interest particular specially disciplines, proper interoperability file format and level of model should be chosen to meet the demanding of the analysis purpose.

Moreover, designer should also consider categorizing product models as rough, careful, and precise: rough models are quick and "keep it simple" models which are only meant for quick studies and are discarded afterwards; on the other hand, precise models need to meet the demands of specialized applications (e.g. thermal simulation, energy consumption calculation)

5.3.3.2 Partial Data Exchange and Intervention Strategy

Although the product model exchange in schematic phase is preferable and valuable, there is always a need for later inter-disciplinary exchange, and accordingly mapping intervention is unavoidable. Besides tailoring the model to fit for the analysis purpose, developing partial model exchanges and model server are also ways for more efficient model exchange and interventions. Moreover, more rigorous testing and debugging of software is also necessary as software instability could deter the use of interoperability file.

REFERENCES

Hardin, B. (2009) BIM and Construction Management: Proven Tools, Methods and Workflows (Wiley Publishing, Inc)

Laiserin, J. (2008). BIM hand book – a guide to building information modeling for owners, mangers, designers, engineers, and contractors (John Wiley & Sons, Inc)

Maver, T. W. and Mc Elroy. L. B. (1999). 'Information technology and building performance', Automation in Construction 8(4), 411-415.

Ozel, F. and Kohler, N. (2004). 'Data modeling issues in simulating the dynamic processes in life cycle analysis of buildings', Automation in Construction 13(2): 167-174.

S. Blanchard, P. R. (1998). Life Cycle Analysis of a Residential Home in Michigan. University of Michigan, School of Natural Resource and Environment.

James R. Watson, G. R. W., Mat Kroguleck i, MACTEC's Facility Life cycle Group (2009). Post Construction BIM Implementations and Facility Asset Management. Journal of Building Information Modeling: 34-35.

Harinder (Harry) Singh, W., Inc., Dana K. Smith, Information Consulting, LLC, and John M. Przybyla, PE. GISP, Woolpert, Inc (2009). Reducing Facility Management Costs Through Integration of COBIE and LEED - EB. Journal of Building Information Modeling: 21-23.

Ting, H. (2009). Virtual Prototyping Technologies Enhancing Construction. The Hong Kong Polytechnic University

Jasnoch, U. and S. Haas (1996). A collaborative environment based on distributed object-oriented databases. Computers in Industry 29(1-2): 51-61.

Heng Li, T. H., C.W. Kong, H.L. Guo, Andrew Baldwin, Neo Chan, Johnny Wong (2008). Integrating design and construction through virtual prototyping. Automation in Construction 17: 915-922.

James R and Russ Watson, MACTEC E&C. (2009). Computer Aided Facilities Management.
http://www.wbdg.org/om/cafm.php

Lin, F. C.-S. (2003). The integration between design and maintenance of office building automation: a design support approach. 5th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2003), 26-28 August 2003, Johor Baru, Malaysia.

El-Ammari, K. H. (2006). Visualization, data sharing and interoperability issues in model-based facilities management systems. Concordia University

Gaudes, A. J. (1998). Optimizing mobility to marginalize interruption: A framework for facility management professionals that integrates virtual officing as a component of business continuity planning. University of Manitoba

Chau, Anson et al. (2005). 4D dynamic construction management and visualization software: 1. Development, Automation in Construction 14(2005) 512-524

Jrade (2004). Integrated conceptual cost estimating and life cycle costing system for building projects. Concordia University

Mihindu. (2008). Digital construction through BIM systems will drive the Re-engineering of construction business practices. International Conference Visualisation, VIS 2008, Visualisation in Built and Rural Environments, July 9, 2008 - July 11, 2008

Vanlande, Nicolle et al. (2008). IFC and building life cycle management.

Automation in Construction vol18 issue1 70-78

BIM case studies.
http://dcom.arch.gatech.edu/class/BIMCaseStudies/casestudies.htm

BIM Resource @Georgia Tech
http://bim.arch.gatech.edu/content_view.asp?id=464

Zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften. (2008). Planning of Construction Projects: A Managerial Approach. Universität Siegen

Kristine K. Fallon, Mark E. Palmer in cooperation with FIATECH. (2008). General Buildings Information handover guide: principles, methodology and case studies. National Institute of Standards and Technology Interagency Report

Calvin Kam, Martin Fischer(2001). Product Model & 4D CAD-Final Report. CIFE(Center for Integrated Facility Engineering) Technical Report Number 143

Mickaityte, A., E. K. Zavadskas. (2008). The concept model of sustainable buildings refurbishment. International Journal of Strategic Property Management 12(1): 53-68.

Tom Fusssell, Scott Beazley , Guillermo Aranda-Mena. (2007). National BIM guidelines and case studies. CRC-CI Project 2007-002-EP

Mickaityte, A., E. K. Zavadskas (2008). The concept model of sustainable buildings refurbishment. International Journal of Strategic Property Management 12(1): 53-68.

Yan-chuen, L., M. Phil. (2000). Refurbishment of building services engineering systems under a collaborative design environment. Automation in Construction 9(2): 185-196.

Juan, Y.-K., J. H. Kim. (2009). GA-based decision support system for housing condition assessment and refurbishment strategies. Automation in Construction 18(4): 394-401.
Lee, Y.-c. and J. D. Gilleard (2002). Collaborative design: a process model for refurbishment. Automation in Construction 11(5): 535-544.

Li, S., J. Isele.(2008). Proposed Methodology for Generation of Building Information Model with Laserscanning. Tsinghua Science & Technology 13(Supplement 1): 138-144.

Flourentzou, F. and C. A. Roulet (2002). Elaboration of retrofit scenarios. Energy and Buildings 34(2): 185-192.

Arayici, Y., Hamilton, A. (2005). Modeling 3D scanned data to visualize the built environment. Information Visualisation, 2005. Proceedings. Ninth International Conference on 6-8 July 2005 Page(s):509 - 514

Casey, M. J. (2008). Work in progress: How building informational modeling may unify IT in the civil engineering curriculum. Saratoga Springs, NY, United states, Institute of Electrical and Electronics Engineers Inc.

Fauerbach, S. (2007). BIM and civil engineering. CENews.
http://www.cenews.com/magazine-article----bim_and_civil_engineering-5564.html

Drogemuller, R. (2009). Can B.I.M be civil?. Queensland Roads 7: pp. 47-55.
http://scholar.google.com.au/scholar?hl=en&q=bim+transportation&as_sdt=2000&as_ylo=&as_vis=0

Stumpf, A., H. Kim. (2009). Early design energy analysis using bims (building information models). Seattle, WA, United states, American Society of Civil Engineers.

Eddy Krygiel, B. N., Steve McDowell. (2008). Green BIM: Successful

Sustainable Design with Building Information Modeling.

Akinci, B., M. Fischen. (2002). Formalization and automation of time-space conflict analysis. Journal of Computing in Civil Engineering 16(2): 124-134.
Penttilä, H Marko, R Simo Freese, S. (2007). Building Information Modelling of Modern Historic Buildings Case study of HUT / Architectural Department by Alvar Aalto. ECAADE 2007 (education and research in computer aided architectural design in Europe Conference)
http://www.ecaade.org/organisation/cumincad.html

Morris, J Ballesty , S Ding, L Drogemuller, R Mitchell, J Schevers, H Leifer , D Schwede, D Wu, J Henrikson, J Akhurst , P Spink, G . (2006). An Integrated Collaborative Approach for FM - Sydney Opera House FM Exemplar. 2nd International Conference of the CRC for Construction Innovation, pages pp. 1-13, Australia
http://eprints.qut.edu.au/8126/

Li, S., J. Isele. (2008). Proposed Methodology for Generation of Building Information Model with Laserscanning. Tsinghua Science & Technology 13(Supplement 1): 138-144.

Barch, J. A. M. C., A. Gillard.(2009). The atlantic college case study - Measuring performance to evaluate building simulation and enhance student learning. Barcelona, Spain, IEEE Computer Society.

Barch, J. A. M. C., A. Gillard.(2008). The Atlantic College case study - exploring the use of BIM for the sustainable design and maintenance of property.

Akinci, B., M. Fischen.(2002). Formalization and automation of time-space conflict analysis. Journal of Computing in Civil Engineering

Casey, M. J. (2008). Work in progress: How building informational modeling may unify IT in the civil engineering curriculum. Saratoga Springs, NY, United states, Institute of Electrical and Electronics Engineers Inc.

Kam, C. and M. Fischer (2004). Capitalizing on early project decision-making opportunities to improve facility design, construction, and life-cycle performance - POP, PM4D, and decision dashboard approaches. Automation in Construction 13(1): 53-65.

Staub-French, S., M. Fischer .(2003). An ontology for relating features with activities to calculate costs. Journal of Computing in Civil Engineering 17(4): 243-254.

Succar, B. (2009). Building information modelling framework: a research and delivery foundation for industry stakeholders. Automation in Construction 18(3): 357-75.

Sumedha Kumar (2008). Interoperability between building information models (BIM) and energy analysis programmes. Faculty of the school of Architecture University of southern California. May 2008.

M.Pidd.(1996). Five simple principles of modeling. The 1996 winter simulation conference.

Spyros Stravoravdis, Dr. Andrew Marsh (2005). A proposed method for generating, storing and managing large amounts of modeling data using scripts and on-line databases. Ninth International Conference. Montreal, Canada.

A. Oikonomou (2005). Summer thermal comfort in traditional buildings of the 19th century in Florina, north-western Greece. International Conference Passive and Low Energy Cooling for the Built Environment. Santorini, Greece.

Drury B. Crawleya, Jon W. Hand, Michael Kummert, Brent T. Griffith.(2008). Contrasting the capabilities of building energy performance simulation programmes. Building and Environment 43 (2008) 661-673

Shady Attia, Liliana Beltrán, André De Herde, Jan Hensen (2009). Architect friendly: a comparison of ten different building performance simulation tools. Eleventh International IBPSA Conference. Glasgow, Scotland.

Salman Azhar, Justin Brown, Rizwan Farooqui. BIM-based sustainability analysis: an evaluation of building performance analysis software.

Olof Granlund Oy Matti Korhonen, Tuomas Laine (2008). Energy analysis software evaluation. BIM interface and interoperability

Lam, K.P., N.H. Wong, and F. Henry. (1999). A study of the use of performance-based simulation tools for building design and evaluation in Singapore. In IBPSA. Kyoto, Japan

Gratia, E. and A. De Herde. (2002). A simple design tool for the thermal study of an office building. Energy and Buildings, 34: p. 279-289

Elisabeth Gratia, Andre De Herde.(2002). A simple design tools for the thermal study of dwellings. Energy and Buildings, 2002.34: p.411-420

Tianzhen, H., Z. Jinqian, and J. Yi, IISABRE.(1997). An Integrated Building Simulation Environment Building & Environment 32(3): p. 219-224

Papamichael, K. and J. Protzen.(1993). The limits of Intelligence in Design. The 4th International Symposium on System Research, Informatics and Cybernetics. Baden, Germany.

Augenbroe, G..(2002). Trends in building simulation. Building & Environment, 37: p. 891 – 902

Ahmad, Q., S. Szokolay. (1993). Thermal Design Tools in Australia: A comparative study of TEMPER, CHEER AH, ARCHIPAK and QUICK. Building Simulation '99, pp351-357, Adelaide, South Australia, Australia, IBPSA

Bloomfield. D, (1989). Design tool evaluation benchmark test cases. IEA SHC

Task VIII passive and hybrid solar low energy building, report T.8.B.4. Garston: Building Research Establishment

P. Paxton Marshall, 2007. Modeling, simulation, monitoring and verification in a design-build residential housing project. American Society for Engineering Education

Thomas Bulter.(2008). Design in a simulation environment. Georgia Institute of Technology

Jacob Bolda. Rapid Prototyping: a sustainable design aid. Rapid Prototyping Center Milwaukee School of Engineering

Hazem Rashed-Ali, Irina Solovyova, Darryl Ohlenbusch, Michelle R(2010). Integration and interdisciplinarity in the design studio, and experimental approach. American Solar Energy Society

Patrick Villella. (2009). Green you design with Autodesk Ecotect and Revit. Autodesk University

Paola C. Ferrari, Neander F. Silva, Ecilamar M. Lima. (2010). Building Information Modeling and Interoperability with environmental simulation systems. Innovations and Advances in Computer Sciences and Engineering

Joseph C. Lam, Sam C.M. Hui.(1995). Outdoor design conditions for HVAC system design and energy estimation for buildings in Hong Kong. Energy and Buildings 22 (1995) 25-43

M.Bojic, F.Yik, P.Sat.(2001). Influence of thermal insulation position in building envelope on the space cooling of high-rise residential buildings in Hong Kong. Energy and buildings 33 (2001) 569-581

M.Bojic, F.Yik, P.Sat.(2002). Energy performance of windows in high-rise residential buildings in Hong Kong. Energy and Buildings 34, 71-82

Catarina Thormark (2002). A low energy building in a life cycle-its embodied energy, energy need for operation and recycling potential. Building and Environment 37(2002) 429-435

Clélia Mendonça de Moraes; Arlindo Tribess; Irving Montanar Franco;Marco Túlio Carvalho de Andrade; Margarida Marchetto; Gustavo Caminati Anders; Gustavo de Oliveira.(2004). Experimental study of human thermal comfort sensations in classrooms: complementary evaluation with methods of building envelope performance and questionary application. The 21th Conference on Passive and Low Energy Architecture. Eindhoven, the Netherlands, 19-22 September 2004

Jong-soo Cho.(2002). Design methodology for tall office buildings: design measurement and integration with regional character. The Illinois Institute of Technology.

Runming Yao, Koen Steemers.(2005). A method of formulating energy load profile for domestic buildings in the UK. Energy and Buildings 37(2005) 663-671

Fabrizio Chella, Paolo Zazzini, Graziano Carta (2006). Compared numerical and reduced scale experimental analysis on light pipes performance. SET2006-5th International Conference on Sustainable Energy Technologies. Vicenza, Italy.

Agya Utama, Shabbir H. Gheewala.(2008). Life cycle energy of single landed housed in Indonesia. Energy and Buildings 40(2008)1911-1916

Jinghua Yu, Changzhi Yang, Liwei Tian.(2008). Low-energy envelope design of residential building in hot summer and old winter zone in China. Energy and Buildings 40(2008)1536-1546

Jeffrey Boyer, Arvinder Dang.(2007). Design for performance: a case study n the applied science of an environmentally. PBuilding Simulation 2007

Weimin Wang.(2005). A simulation-based optimization system for green building design. Concordia University Montreal, Quebec, Canada