The Integration of Architectural Design and Energy Modelling Software

Thesis

How to cite:

Hetherington, Robina Elizabeth (2013). The Integration of Architectural Design and Energy Modelling Software. PhD thesis The Open University.

The Integration of Architectural Design and Energy Modelling Software

Robina Hetherington
BA (Hons), Dip Arch (Sheffield), MSc (Liverpool)

March 2013

Submitted for the degree of Doctor of Philosophy

Department of Computing
and
Department of Design, Development, Environment and Materials

Faculty of Mathematics, Computing and Technology
The Open University

Abstract

Intelligent and integrated architectural design can substantially reduce carbon dioxide emissions from energy used in buildings. However, architects need new tools to help them to design enjoyable, comfortable, attractive and yet technically rigorous, low energy buildings. This thesis investigates, by means of a Research Through Design approach, how architectural software could be better designed to fulfil this need by the integration of design, energy simulation and decision support systems.

The problem domain of the design of buildings with very low energy requirements was analysed. Two case studies were employed to investigate the limitations with current software. User and domain software requirements were recorded and analysed. Conflicting requirements were noted, in particular, dichotomous views of the building model. An investigation was carried out into the different interoperable standards that result in these views and rules on how to compose the building model as a series of Intelligent Spaces proposed. The Intelligent Spaces would be abstract volumes, enclosed by zero thickness surfaces, which have data and rules attached. Early prototyping of integrated software was carried out by means of a series of sketches and diagrammatic examples.

The novel feature of the proposal is that it maintains both an abstract and detailed version of the building model through all stages of the building design and use. Key features of the proposed software are: 1) the ability to move iteratively between sketch to detailed design to explore different approaches to the building form and construction, 2) the setting and monitoring of relevant energy targets throughout the different building design stages and 3) the integration of an advisory system linked to energy targets to support decision making. This space based approach to the software has the potential to provide a ‘designerly’ front to the sophisticated processes of a Building Information Modelling environment.

Acknowledgements

This work is dedicated to my parents who instilled a life-long belief in education and the pleasures of continuing to study, learn and grow.

I would like to thank my supervisors, Robin Laney and Stephen Peake, for initiating the PhD, for being there throughout the duration of the work, for reading the too many words, for the coffee and the chats, and their support when the going got tough.

Other people I would like to thank, who sat and listened and made useful and pertinent comments on my ramblings, include: David Oldham, Michael Jackson, Brain Farrimond, Robert Lowe, Simos Yannas, Marian Petre, Chris Earl, Helen Sharp, Derek Jones, Janet van der Linden and Paul Garthwaite

My thanks also to the Open University, and in particular the Computing Department, for the excellent support, student facilities, IT, the CRC student forum and financial support for attendance at international conferences.

My gratitude also to the other PhD students at the OU for their friendship, support, advice, hugs and laughter.

Finally, the support team at home, David, Joseph and Danny, who have all been there for me in their own special ways, many, many thanks.

Contents

Abstract 3

Acknowledgements 5

List of Figures 8

List of Tables 10

Acronyms 11

List of Publications 13

Chapter 1 Introduction 15

- 1.1 Climate change and energy 15
- 1.2 Buildings and energy 16
- 1.3 Research aims and objectives 18
- 1.4 Research approach 19
- 1.5 Structure of the thesis 22

Chapter 2 Influences on Software to Design Low Energy Buildings 27

- 2.1 Changing practices in the design of buildings 28
- 2.2 A review of software developments 36
- 2.3 Barriers to integrated building design and simulation software 46
- 2.4 Discussion 48

Chapter 3 The Problem Domain: Low Energy Buildings 51

- 3.1 Energy and buildings 51
- 3.2 Proposed legislation 53
- 3.3 Physical concepts related to low energy buildings 58
- 3.4 Approaches to the design of a low energy building 71
- 3.5 Discussion 77

Chapter 4 Empirical Studies into Software to Design Low Energy Buildings 79

- 4.1 Case study 1– Modelling a small building using BIM and BES software 80
- 4.2 Case study 2 – Student experience with modelling a building using BES software 86
- 4.3 Conclusion 118

Chapter 5 Domain Requirements for Software to Model and Simulate Low Energy Buildings 121

5.1 Existing software tools 124
5.2 Building design software 126
5.3 Building Information Modelling 127
5.4 Building performance simulation 136
5.5 Building energy simulation 137
5.6 Design Advisory Systems 152
5.7 Implications for new combined software 158
5.8 Conclusion 165

Chapter 6 The Building Model and Interoperability 167

6.1 Interoperability 168
6.2 Comparison of IFC and gbXML 187
6.3 Improved methods for building model information exchange 188
6.4 Concluding remarks 199

Chapter 7 The Integration of Architectural Design, Performance Simulation and Design Advice Software 205

7.1 Abstract spaces 206
7.2 Steps in the building design using an integrated approach 212
7.3 Overview of the Intelligent Spatial Entity approach to the design of buildings 214
7.4 Discussion 234
7.5 Conclusion 236

Chapter 8 Conclusions 239

8.1 The problem domain 239
8.2 Interoperability 242
8.3 Integrated software 243
8.4 Evaluation 243
8.5 Future work 245
8.6 Reflection 250

References 257

Appendix 1 – Nomenclature 279

Appendix 2 – The Student Project 281

Appendix 3 – Questions and Results from the Student Survey 284

Appendix 4 – IFC and gbXML Tables 312

List of Figures

Figure 2-1 The waterfall model of project development 31
Figure 2-2 The twin peaks model of software development 34
Figure 2-3 The ‘multi peak’ approach applied to the architectural design process. 35
Figure 2-4 The dichotomous view of the building model 36
Figure 2-5 The ”MacLeamy Curve” for the building design process 40
Figure 2-6 The dichotomous process of building modelling 42
Figure 3-1 Patterns of energy consumption for buildings in the UK and USA in 2011 52
Figure 3-2 Hierarchy of permissible methods to achieve ‘zero carbon’ 54
Figure 3-3 On-site and off-site technologies 55
Figure 3-4 The revised “Zero Carbon" policy triangle for domestic buildings 56
Figure 3-5 The dynamic interactions of the sub-systems in buildings 59
Figure 3-6 Diagram of the multiple factors that affect the indoor environment......................64
Figure 3-7 Heat transfer mechanisms through a wall section 65
Figure 3-8 The effect of mass on thermal inertia 67
Figure 3-9 A glazed building subject to incident solar radiation 70
Figure 3-10 Solar shading devices 71
Figure 3-11 Holistic building design...72
Figure 3-12 The optimization of a building design to maintain comfort conditions.................73
Figure 4-1 A model and plan of a small building employed in the first case study..................81
Figure 4-2 Transfer of data from BIM software to BES software 83
Figure 4-3 The current process of energy analysis – an obstacle to iterative design 84
Figure 4-4 A thermal zone model of the building used in the second case study 87
Figure 4-5 Mapping of the student survey with the earlier case study 90
Figure 4-6 An example of a five-point scales employed in the survey.....................................94
Figure 4-7 Survey results: information sources..99
Figure 4-8 Survey results: the usefulness of graphs in decision making 102
Figure 4-9 Survey results: items for inclusion in a dashboard 103
Figure 4-10 Survey results: the methods employed to solve problems.................................110
Figure 4-11 Survey results: Expert and Decision Support systems 111
Figure 4-12 Survey result: percentage of students finding tasks difficult..............................112
Figure 5-1 Venn diagram of BIM and BES processes 123
Figure 5-2 Relationship between BIM software and BES software..126
Figure 5-3 The creation of a wall in BIM...131
Figure 5-4 The EnergyPlus simulation engine 141

Figure 5-5 The factors that affect internal illuminance distribution 143
Figure 5-6 Showing a model of a small building with a curved wall. 147
Figure 5-7 Daylight simulation in a building 148
Figure 6-1 Part of the ifc2x4 hierarchy 178
Figure 6-2 Composition of a building model in IFC 180
Figure 6-3 Issues with wall thicknesses and space boundaries for thermal calculations 181
Figure 6-4 IFC building material layers.. 182
Figure 6-5 Part of the gbXML hierachy 185
Figure 6-6 A building model of a small building with a curved wall. 186
Figure 6-7 Part of the gbXML hierarchy showing the five children root node 187
Figure 6-8 Assembly of a building model as a series of Intelligent Spatial Entities 192
Figure 6-9 Initial proposal for a change in the IFC hierarchy 193
Figure 6-10 Depictions of materials as layers and a construction detail 197
Figure 7-1 The Intelligent Spatial Entity and iterative building design process. 210
Figure 7-2 The five operation phases for the proposed software 212
Figure 7-3 The RIBA Plan of Work and the five software phases 213
Figure 7-4 The differing approaches to modelling a building. 215
Figure 7-5 The different modelling stages in the building design process 216
Figure 7-6 Types of Space 219
Figure 7-7 The naming convention for a building project employed in this study 220
Figure 7-8 A matrix of building design, performance and design advisor activities 222
Figure 7-9 A Block model employed in a shadow prediction 224
Figure 7-10 The monthly heating/cooling load for a complete building. 227
Figure 7-11 Enclosing Building Objects and Thermal Spaces 229
Figure 7-12 A curved surface 230
Figure 7-13 The BuildingBlock, ThermalSpaces and BuildingObject models. 231
Figure 7-14 Profile required for lighting modelling. 232
Figure 8-1 The commercial development of the software. 247
Figure 8-2 Data flow between the three components of the proposed software. 249
Figure 8-3 A visualisation of the problem space. 251
Figure 8-4 The Twin Peaks model for software development. 252
Figure 8-5 An alternate version of the Twin Peaks model. 253

List of Tables

Table 1-1 Mapping of the thesis chapters against the phases of RtD......................................22
Table 4-1 Three themes identified from the results in the student survey 117
Table 5-1 Requirements for BIM, BES and DAS collected into a building modelling and simulation theme 159
Table 5-2 Requirements for BIM, BES and DAS collected into an information and design decision support theme 161
Table 5-3 Requirements for BIM, BES and DAS collected into a visualisation theme............164
Table 6-1 A comparison of elements of the IFC and gbXML standards relevant to the storage of data relating to building geometries and materials employed in building energy simulation 202
Table 7-1 Types of Intelligent Spatial Entities and Other Space types...................................218

Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
BES	Building Energy Simulation
BPM	Building Performance Modelling
BPS	Building Performance Simulation
BPO	Building Performance Optimisation
BRE	Building Research Establishment
CAD	Computer-Aided Design
CAAD	Computer-Aided Architectural Design
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
COBie	Construction Operations Building Information Exchange
DAS	Design Advisory System
DXF	Drawing eXchange Format
DWG	DraWinG
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IPCC	Intergovernmental Panel on Climate Change
IPD	Integrated Project Delivery
ISO	International Organization for Standardization
gbXML	Green Building eXtensible Markup Language
GUI	Graphical User Interface
GUID	Globally Unique Identifier
HCI	Human Computer Interaction
HVAC	Heating, Ventilation and Air-Conditioning
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical, Electrical and Plumbing
MVD	Model View Definitions
NBS	National Building Specification
NZEB	Net Zero Energy Buildings
POE	Post Occupancy Evaluation
RE	Requirements Engineering
RIBA	Royal Institute of British Architects
RtD	Research through Design
SE	Software Engineering
STEP	Standard for the Exchange of Product

List of Publications

Hetherington, R., Laney, R. & Peake, S. (2012) Zone Modelling and Visualisation: Keys to the Design of Low Carbon Buildings. In: *16th International Conference Information Visualisation*. July 2012 Montpellier, France: pp. 495–508.

Hetherington, R., Laney, R. & Peake, S. (2011) A software vision to enable the holistic design of low carbon buildings. In: *3rd International Workshop on Software Research and Climate Change*. July 2011 Lancaster, UK: .Available from: https://sites.google.com/site/wsrcc2011/submitted-papers.

Hetherington, R., Laney, R. & Peake, S. (2011) Integrated Building Design, Information and Simulation Modelling: The Need for a New Hierarchy. In: *Building Simulation 2011*. 14 November 2011 Sydney, Australia: pp. 1430–1450.

Hetherington, R., Laney, R. & Peake, S. (2010) Zero and Low Carbon Buildings: A Driver for Change in Working Practices and the Use of Computer Modelling and Visualization. In: *2010 14th International Conference Information Visualisation*. July 2010 London, United Kingdom: pp. 590–596.

Hetherington, R., Laney, R. & Peake, S. (2010) Software engineering challenges: Achieving zero carbon buildings by 2019. In: *ACM-BCS Visions of Computer Science 2010*. 13 April 2010 Edinburgh University, UK: .Available from: www.ukcrc.org.uk/grand-challenge/gccr10-sub-9.cfm.

Chapter 1

Introduction

Architects in the United Kingdom and the European Union will be expected to design buildings to rigorous low energy standards in the near future (Great Britain, 2008a; The European Parliament and the Council of the European Union, 2010). According to Oreszczyn & Lowe (2010) the changes in praxis facing the AEC [Architectural Engineering and Construction] industry and the magnitude of the technical challenges to decarbonize the built environment is unprecedented. Although technical solutions exist, the process of designing buildings to rigorous, high-efficiency standards is complex and multifaceted.

Digital design tools have changed the way that many architects practice in the last quarter of a century. Numerous modern iconic buildings have only been made possible because of the use of advanced modelling and engineering computational techniques. However, the majority of contemporary buildings considered as exemplars of good design, could not be built under regulations currently being planned in the UK aimed at reducing energy usage. Hartman (2012) states that sustainable building design is difficult to do; it is rare for energy conscious buildings to win the top prizes for architecture. A radical change in building design practice will be required to enable the design of buildings to rigorous new standards. Software has a major role to play in helping architects meet these challenges.

1.1 Climate change and energy

Atmospheric concentrations of the main greenhouse gases, carbon dioxide, methane and nitrous oxide, are known to have increased significantly over the last two and a half centuries (IPCC, 2007b). Carbon dioxide is responsible for more global warming than the other two gases (even though they are more potent) because it is emitted in much greater quantities. The majority of the carbon dioxide emissions come from fossil fuel burning, and the main reason fossil fuels are burnt is for energy. Thus the problem of climate change mitigation, through the implementation of policies to reduce greenhouse gas emissions, is mainly one of the reduction of energy consumption (MacKay, 2009).

The UK Government is taking the issue extremely seriously. The Climate Change Act of 2008 sets legally binding targets to reduce the emission of greenhouse gases by 80% from 1990 levels by 2050 (Great Britain, 2008b). As buildings account for almost 50% of UK carbon dioxide emissions, the alteration of practices related to the construction and use of buildings will have a significant role in achieving these targets (Department for Communities and Local Government, 2007).

Due to global and regional warming, energy demands of buildings in the UK are changing and will continue to change. There is already increased demand for cooling of buildings and a decrease in heating energy consumption. Adaption strategies, implemented to reduce the vulnerability of natural and human systems to the effects of climate change, also need to be considered and balanced with mitigation solutions (IPCC, 2007a).

1.2 Buildings and energy

A key conclusion of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change is that substantial reductions in carbon dioxide emissions can be achieved over the coming years from reduced energy use in buildings. It is estimated that there could be energy savings of over 75% for new buildings, through designing and operating buildings as *complete systems.* However, they conclude that realising low carbon buildings will require significant changes in practice and policy to improve current praxis. “An integrated design approach is required to ensure that the architectural elements and the engineering systems work effectively together” (IPCC, 2007a, p.394).

The majority of energy consumed in the running of buildings is required to maintain comfort conditions. For the year 2011 the aggregate of energy used to provide space heating, space cooling, ventilation and water heating accounted for: UK housing 78%, USA residential 72%, UK services 50% and USA commercial 50%[1]. Significant savings can be made in CO_2 emissions if the energy required to run a building can be substantially reduced. These figures are for

---

[1] These statistics are taken from raw data obtained at:
https://www.gov.uk/government/publications/energy-consumption-in-the-uk and
http://buildingsdatabook.eren.doe.gov/default.aspx. More detail on energy usage is given in Chapter 3.

energy in use and exclude embodied energy (that used to extract, manufacture and transport building products to site). The building form also affects the energy used for lighting, if daylight can be used it can dramatically reduce the demand for electricity.

The proposed UK policy is for new buildings in England[2] to be 'zero carbon' in use, with the objective of zero net emissions of carbon dioxide from all the energy from buildings over the course of a year (Department for Communities and Local Government, 2008)(Great Britain, 2009, p.1) However, there is concern that there is a perception that achieving energy efficiency in the built environment is economical and straightforward. Oreszczyn & Lowe (2010) argue that this is because researchers have oversold the performance of available technologies. They believe that 'zero carbon' targets have been influenced by successful policies in the past. For instance, the use of legislation achieved reductions of car emissions in the 1990s. However, they argue that this demonstrates a lack of understanding of the complexity of the built environment sector in comparison with the car industry.

The IPCC [Intergovernmental Panel on Climate Change] conclude that a major impediment to the construction of low energy buildings is the lack of awareness amongst construction personnel, including architects and engineers, of energy-saving methods (IPCC, 2007a). The urgent need for further education and training in building physics is set out by The Royal Academy of Engineering in *Engineering a low carbon built environment : the discipline of building engineering physics* (King & Royal Academy of Engineering (Great Britain), 2010).

The design of a building or group of buildings is a complex process. In general, new building projects are individual and unique, responding to the particular needs of the client and the site. When designing a building the architect will consider aesthetics, technology, sociology, geography, history, philosophy, law and psychology, often moving iteratively between the disciplines. There is always a balance between *Art* and *Science*. Traditionally Art has led the process with the Science following. Currently the majority of the technical design process occurs after the client has 'signed off' the design and planning permission has been granted for the project. Historically, energy intensive technological solutions would be used to 'solve' problems arising from lack of environmental considerations at the design stage, for

---

[2] The UK Government has devolved responsibility for Building Regulations to Scotland and Northern Ireland and is currently considering transferring responsibility to Wales (Department for Communities and Local Government, 2008)

instance over/under heating or lack of day lighting. With low energy design, the consideration of significant technical detail will be required at a very early stage to avoid these energy penalties. Traditionally rules of thumb and simplified calculations have been used to design environmentally friendly buildings. The implementation of rigorous new standards, such as those proposed for ‘zero carbon’ new buildings (Great Britain, 2008a) and ‘nearly zero-energy’ new buildings in Europe (The European Parliament and the Council of the European Union, 2010) will require a different approach. Frequent, quantitative analysis, to support the testing of options, as the design progresses, will be required to determine if the design has a sufficiently low energy consumption.

There are many ways that software and communication technologies can be, and are being used, to help mitigate against the threat of climate change by helping to reduce greenhouse gases generated by the built environment. They will have a significant part to play in how designers assimilate, handle, visualize and design buildings to achieve the proposed standards (Hetherington *et al.*, 2010b).

The architectural profession includes a number of large architectural practices with excellent IT resources and their own in house energy analysts who can afford to employ a wide selection of software. However, there are a significant number of smaller firms in the profession. It is estimated that in the UK over half of all architects work in practices with less than 10 employees (Chappell, 2010) and about one in ten working as sole practitioners (The Fees Bureau, 2009). It is a similar situation in the USA, with sole practitioners making up just over one-quarter of firms and about three-quarters of firms having 2 to 49 employees (The American Institute of Architects, 2012). In the UK there is concern as to how smaller practices will struggle with both the knowledge and data demands of designing to low and zero carbon standards (Technology Strategy Board, 2009). Thus, there is a need for the development of new software tools that are inexpensive and easy to use by architects who, at present, may not necessarily be skilled in energy efficient design.

1.3 Research aims and objectives

The aim of this research is to investigate how software could be better designed to support architects in the design of low energy buildings and thus help in the mitigation of climate change. The software is primarily concerned with the design of new, non-domestic, buildings; however, it could be used for both existing and domestic buildings. The software, as proposed, would constitute a valuable tool to enable architects to experiment with building form and construction, test alternatives, optimise their building for energy use and monitor actual final energy use and occupant satisfaction. The principal objective in this process is not to produce completely 'green' or 'sustainable' buildings; it is about fine-tuning designs to use as little energy as possible whilst maintaining high aesthetics standards.

The research question this thesis aims to answer is:

How could software be better designed with the integration of design, energy simulation and knowledge systems to support architects in the design of low energy buildings?

This has been broken down into a number of related questions:

- What are the problems with existing building design and simulation methods with respect to supporting the iterative and holistic design of low energy buildings?
- What are the interoperable languages currently in use and could they be modified to better support the reliable transfer of data between design and simulation environments?
- Could an approach based upon intelligent spatial entities be employed to enable the integration of building modelling, energy simulation processes and a design advisory system into one software tool?

1.4 Research approach

The approach adopted for the work as a whole is RtD [Research Through Design], a methodology employed the field of HCI [Human Computer Interaction] research. The method is concerned with making the 'right thing', that is a design that can transform the world from its current state to a preferred state. With RtD the research contribution is a novel integration of theory, technology and user need (Zimmerman et al., 2007). Cross, in citing Alexander (1964), compares a design approach with that of a scientific one. The designerly method aims to shape the components of a new structure, unlike an empirical scientific approach that will aim to identify the mechanisms of existing structures (Cross, 2001).

The design of integrated software has elements of attempting to solve a ‘wicked problem’. There is no true or false answer, just the exploration of ways in which the software could be made better. Although presented as a linear discourse in the thesis, the development of the method has been iterative, with the framing and resolution of the problem concomitant to each other (Rittel & Webber, 1973). The investigation of the problem domain and the solutions structures have been detailed and enriched concurrently as part of an iterative process (Hall *et al.*, 2002). Although a vision for the software is presented the eventual development of such software would require a large and skilled team and is beyond the scope of this thesis.

The RtD approach can produce a number of beneficial contributions (Zimmerman et al., 2007). Firstly it can be employed to identify opportunities for the advancement of current technology that will have significant impact on the world. As discussed earlier, the energy used by buildings has a significant role to play in mitigation against the threat of climate change. Secondly, this work is concerned with developing a vision of a preferred state with that knowledge transferred to the research, practice, and education communities (Fallman, 2003). This has been achieved through both presentation and discussion at conferences and peer review publications during the course of the development of the thesis. Finally the novelty of the research lies in the integration of technical contributions from more than one discipline.

This is transdisciplinary research carried out by an architect, with a computing qualification and knowledge of building and energy modelling. A definition of transdisciplinary is given by Stein (2007, p.99) - the individual should “demonstrate at least two disciplinary competences, neither of which is primary. They work and contribute to both and generate unique findings, conceptions and artefacts”. Dykes et al. discuss (2009, p.105) how a transdisciplinary project is focused and frequently concerned with a “real-world problem”. According to Rittel & Webber (1973, p.166), the researcher’s “world view” is the strongest influence in the resolution of a wicked problem.

This thesis is written from the perspective of an architect, but draws upon techniques from the field of software engineering, such as requirements engineering, to assist in framing and analysing the problem domain. This thesis gazes into the future for architects and how the software tools that they employ could evolve to support the design of low energy buildings. The software engineering profession has borrowed a number of terms from architecture, with new interpretations evolving. A list of terms employed in this thesis and the meaning in the various disciplines is given in the Nomenclature found Appendix 1. The three key terms employed in this thesis are defined as:

> *Sketch design*: A drawing, model or description illustrating the key concepts, functions and relationships of a design: applicable to both architectural and software engineering.
>
> *Abstract space*: A space or volume representing the essence of part, or whole of a building. It is a simplified three-dimensional form without detail, employed to illustrate proportions of spaces and relationships between spaces.
>
> *Intelligent Spatial Entity*: a building volume that can have variable dimensions, assigned rules, complex geometric and functional relationships with other building elements. The entities would be the vehicle for linkage between architectural design, building energy simulation and design decision support systems with intelligence incorporated by means of algorithms governing the interaction between these three elements.

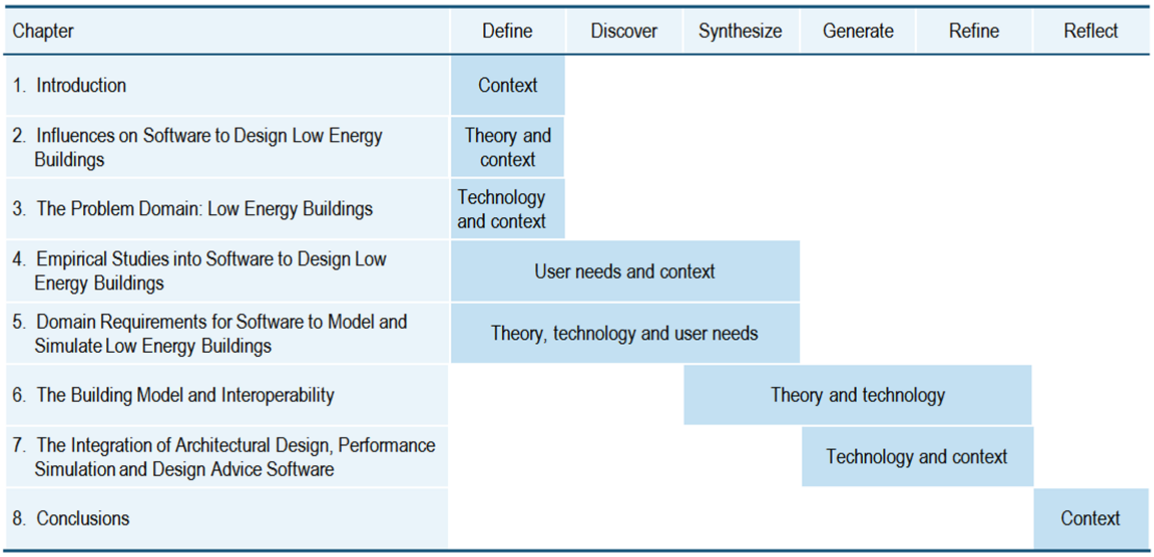
Although the overarching research approach is RtD, each individual chapter employs a research method appropriate for that element of the work. Empirical work, involving two case studies, was employed to investigate current software. Software requirements have been utilised in two chapters as a means to synthesize data from two viewpoints; user and domain (Sommerville & Sawyer, 1997). A systematic investigation (Génova, 2010) was carried out as part of a theoretical study into data structures. Early prototyping of the integrated software was carried out with a series of sketching and diagrammatic examples (Rogers *et al.*, 2011). Evaluation of the research process, the framing of the problem, the strategies for action, the modelling of the solution and articulation of the contribution to knowledge, including unintended findings, is achieved through reflection (Schön, 1983). Each method is discussed in more detail at the beginning of the relevant chapter.

1.5 Structure of the thesis

According to Zimmerman et al the RtD model results in designs or artefacts; in this thesis a sketch design for software is presented. The design should make an holistic research contribution that demonstrate novel integrations of “theory, technology, user need, and context” (2007, p.7). All of these features are included in this work as indicated in

Table 1-1. The phases commonly employed with RtD are given as: define, discover, synthesize, generate, refine and reflect (Zimmerman & Forlizzi, 2008).

Table 1-1 shows how these phases correspond with the content of the chapters in the thesis. The process has been iterative, with the phases, especially those of definition, discovery and synthesis overlapping and developed concurrently as shown in the table.



Chapter	Define	Discover	Synthesize	Generate	Refine	Reflect
1. Introduction	Context					
2. Influences on Software to Design Low Energy Buildings	Theory and context					
3. The Problem Domain: Low Energy Buildings	Technology and context					
4. Empirical Studies into Software to Design Low Energy Buildings	User needs and context					
5. Domain Requirements for Software to Model and Simulate Low Energy Buildings	Theory, technology and user needs					
6. The Building Model and Interoperability			Theory and technology			
7. The Integration of Architectural Design, Performance Simulation and Design Advice Software				Technology and context		
8. Conclusions						Context

Table 1-1 Mapping of the thesis chapters against the phases of RtD

The criteria for evaluating RtD given by Zimmerman et al (2007) are: process, invention, relevance and extensibility. These are achieved in this thesis as follows:

1. *Process*, where the rationale for the specific method used is given. This is outlined in this chapter (Introduction) with further detail provided at the beginning of each of the following chapters.

2. Invention, where design researchers must demonstrate that they have produced a novel integration of various technological approaches to address a specific situation. This is provided in Chapter 7 (The Integration of Architectural Design, Performance Simulation and Design Advice Software) where a sketch design for the software is given.

3. The *relevance* of the work within the real world is outlined in Chapter 1 (Introduction), Chapter 2 (Influences on Software to Design Low Energy Buildings) and Chapter 8 (Conclusions).

4. The *extensibility* of the work is outlined in the *Future work* section in Chapter 8 (Conclusions).

The research has involved the following: confirmation of the gap in knowledge through a review of the literature, the discovery and definition of the problem through empirical work in the application of software to model buildings and predict energy consumption, generation of the concept of working with Intelligent Spatial Entities as the basis for improved software, the refinement of the concept of combined software, reflection on the implications of the software and the possible future development of the software. The research contribution is demonstrated through the recording of the process in this thesis and the generation of a sketch design for the integrated software in Chapter 7. The structure of the thesis is outlined below.

Chapter 2, *Influences on Software to Design Low Energy Buildings,* is a review of the literature on modelling for design and energy performance simulation and provides confirmation of the limitations of existing software implementations. In addition to academic research the problem space is influenced by: governmental policy, professional processes and proprietary software development. A number of strands relevant to the proposed software are covered: the need for the combined software, approaches to the design of buildings, methods for building performance simulation, implementation of design advisory systems and issues of limited data interoperability.

Chapter 3, *The Problem Domain: Low Energy Buildings,* provides background information on the problem. It discusses what low energy building design means for the architect in the context of proposed ‘zero carbon’ legislation. A depiction of building behaviour is given by describing the interactions of the separate aspects of heating/cooling, lighting and ventilation. The need for iterative design practices and optimisation of the building design for energy usage along with the knowledge required by the architect to work to new rigorous standards is discussed.

Chapter 4, *Empirical Studies into Software to Design Low Energy Buildings,* reports empirical work employed to frame and define the problem. Limitations associated with typical current software for the prediction of building energy usage and to support iterative design processes are described. An initial explorative case study was employed to gain insights into how BIM [Building Information Modelling] and BES [Building Energy Simulation] software works. A further, confirmatory, case study involving a group of architectural students set a task to model a low energy building is outlined. The results of a survey completed by the students are employed to compile an initial set of user requirements for new software.

Chapter 5, *Domain Requirements for Software to Model and Simulate Low Energy Buildings,* continues with a more detailed definition of the varying requirements of the software intended to enable design to develop whilst concurrently simulating the energy performance of buildings. The aim is to develop a rich picture and understanding of the application domain (Offen, 2002; Jackson, 2001). The different approaches of design and energy simulation, to the modelling of buildings and recording of information are discussed and analysed. Domain software requirements for integrated building design, performance simulation and design advisory systems are then established.

Chapter 6, *The Building Model and Interoperability,* provides an investigation into interoperable standards developed in the AEC industry that relate to energy performance modelling. Existing interoperable languages, employed to move data both to and from building design software and building energy performance software, are analysed. A possible change to the hierarchy of one of the most widely employed languages is discussed and an approach to the composition of the building model as a series of Intelligent Spaces is proposed. The use of exemplars is recommended to better support energy performance modelling as part of iterative building design.

Chapter 7, *Integration of Building Design and Simulation Software* outlines a new approach to building modelling through the use of Intelligent Spatial Entities. This approach employs spaces, enclosed by zero-thick coplanar surfaces, as a basis for the design and construction of a building model. The method involves the integration of two existing software types -

building design modelling and building performance simulation, along with the development of a third component - a design advisor integrated into one software tool. The use of Intelligent Spaces throughout the design stages is illustrated with the anticipated operation and interaction of the three components outlined.

Chapter 8, *Conclusions*, ends the thesis. It discusses and concludes how the research questions are answered. It evaluates and discusses the contributions and the limitations of the research. Future work is outlined in terms of both the development of the proposed software and research directions. The thesis concludes with a personal reflection on the transdisciplinary design and research process.

Chapter 2

Influences on Software to Design Low Energy Buildings

As discussed in the previous chapter the burning of fossil fuels to provide energy for buildings account for significant amounts of CO_2 emissions which contribute to climate change. Computerised practices have an important part to play in how buildings can be designed to dramatically reduce their energy requirements and thus reduce the CO_2 emissions. The aim of this chapter is to review the contemporary influences on the development of software to support the design of low energy buildings.

The objectives for this chapter are:

1. To establish the reasons why building design practices and software tools will need to change to cope with planned legislative practices.
2. To discuss the software currently employed in the design of buildings, simulation of energy performance and to support decision making.
3. To identify the current barriers to integrated design and simulation software.

The development of software employed by the AEC industry is influenced by a number of groups: government bodies (these set the rules that affect the end product), the professions involved in the design of buildings (as users of the software), software companies and academia. There is significant overlap and shared work between these groups. The literature covered in this chapter is therefore wide ranging, incorporating government policy statements, publications from professional bodies, academic research outputs and commercial software.

This chapter is the first of three that contribute to the framing and focusing of the problem. The relevance of the work within the ‘real world’ is described and opportunities for new approaches for tools to both support and enable the design of low energy buildings are identified. This review forms part of the *definition* and *discovery* of the problem in the Research Through Design approach of this thesis (Zimmerman & Forlizzi, 2008).

2.1 Changing practices in the design of buildings

This section sets the scene for the AEC industry in the UK which is likely to change radically as a result of proposed legislative changes. It discusses the changes and the need for the architectural profession to adapt to them.

2.1.1 Legislative drivers

The UK is at the forefront in setting ambitious standards for low energy buildings. In 2007 the Government announced the intention that all new domestic buildings in England should be 'zero carbon' by 2016 in the "Building a Greener Future: policy statement". It was proposed to be achieved by progressive tightening of Building Regulations legislation over a number of years (Department for Communities and Local Government, 2007). With the Budget of 2008 the Government announced an ambition that all new non-domestic buildings should also be 'zero carbon' by 2019 (Great Britain, 2008a). Scotland and Wales are also legislating for significant reduction in carbon emissions from the built environment and construction processes (Construction Skills, 2011). For more information on proposed dates see the *Arup*[3] *Legislative Timeline* (Arup, 2012). In addition the EU has set a target for all new buildings to be 'nearly zero-energy' by 2021[4], including existing buildings undergoing major renovation (The European Parliament and the Council of the European Union, 2010).

The rate of change in the Building Regulations in the UK is unprecedented. For instance in England, 2002, 2006 and 2010 saw tightening of the existing regulations, and the new low and zero carbon standards will require even more changes with proposals for revisions in 2013, 2016 and 2019. This proposed legislation will be outlined in greater detail in

---

[3] Arups are an independent firm of designers, planners, engineers, consultants and technical specialists offering a broad range of professional services, for more information see http://www.arup.com/

[4] 31 December 2020, transcribed to 'by 2021'

Chapter 3. Keeping up to date with these changes is a major issue for building professionals. The IPCC [Intergovernmental Panel on Climate Change] concluded that a major impediment to the construction of low carbon buildings is the lack of awareness amongst construction personnel, including architects and engineers, of energy-saving methods (IPCC, 2007a).

Another challenge to the AEC industry arose in 2011 when the UK Government announced the intention to legislate for the use of collaborative 3D BIM for all publically funded projects by 2016 (Department for Business, Innovation and Skills, 2011). The goal is for all project and asset information, documentation and data to be stored in an electronic format. The BIS document acknowledges that there is a lack of compatible systems, standards and protocols. The use of unifying standards should facilitate the comparison of design alternatives, eliminate costly coordination errors, create a link between design and manufacture and serve as a basis for asset management subsequent to construction.

During the course of the thesis the context of BIM in the UK has altered significantly. Pre 2010 BIM was regarded by many as simply another type of software, comparable to existing CAD packages (Harty & Laing, 2011a). At the beginning of 2010 BIM, because of the high cost, both in terms of initial set up cost and training, usage was relatively limited (Hamil, 2011). The first announcement by the UK government in March 2011 was that intention that BIM would be a requirement on publically funded construction projects over a certain size (Department for Business, Innovation and Skills, 2011). However, by June 2011 the government confirmed that the policy would be for *all* publically funded projects (Department for Business, Innovation and Skills, 2011). The following year, in July the Cabinet Office (2012) published an update on this procurement policy that modified the implementation timetable and elements of the proposal. Of particular interest to this work was the inclusion of policies from the Low Carbon Construction Action Plan (HM Government, 2011). The UK government, in an effort to reduce greenhouse gases and the cost of operating buildings, is to move towards the consideration of whole life values rather than initial construction costs of building projects (Cabinet Office, 2012). The pace of adoption is in the UK is now exceeding government expectations with many public sector clients requesting BIM in advance of the 2016 deadline, and interestingly, an increase of interest from private sector clients (Malone, 2013).

Although there is now pressure from government for the AEC industry to adopt BIM it is not universally liked or adopted by the architectural profession. The use of digital tools is limited in the architectural profession. In the 2012 National BIM Report, it was estimated that 35% of architectural practices do not use CAD [Computer-Aided Design], only 31% are 'aware of or using' BIM and only 4% work solely in 3D (National Building Specification, 2012, p.10).

The proposed targets for 'zero carbon' buildings and the application of BIM have raised concerns from academia, government and practice. The concerns relate to the sheer scale of changes in praxis facing the construction industry in the next 20-30 years regarding the reduction of CO_2 emissions relating to the construction and operation of buildings. The proposed acceleration of regulatory change towards low energy buildings is predicted to create "tremendous problems" for the construction industry (King & Royal Academy of Engineering (Great Britain), 2010). Oreszczyn and Lowe (2010, p.108) highlight the "magnitude of the challenge", "the sheer scale of the undertaking" is outlined in a report, Low Carbon Construction by the Department for Business, Innovation and Skills (2010, p.2). The more recent announcement by Department for Business, Innovation and Skills that the UK Government intends to legislate for collaborative 3D BIM has been described as "game-changing" concerning both ICT and cultural processes in the construction sector (Department for Business, Innovation and Skills, 2012, p.3).

2.1.2 Design practices for low energy buildings

The design of a building or group of buildings is a multifarious process. When designing a building the architect will consider aesthetics, technology, sociology, geography, history, philosophy, law and psychology, often moving iteratively between the disciplines. There is always a need for a balance between the *Art* and *Science*. Traditionally Art has led the process with the Science following. This approach is implicit in the stages of a project as set out by the RIBA [Royal Institute of British Architects]. The RIBA Plan of Work was first published in the 1960's and although it has undergone a number of iterations is still in use. This approach is comparable with the 'waterfall' model of software development as shown in Figure 2-1 (Royce, 1987).

As indicated in Figure 2-1, in the RIBA *Plan of Work* the technical design occurs after the client has "signed off" the design and planning permission has been granted for the project. Historically, energy intensive technological solutions would then be used to "solve" problems arising from lack of environmental considerations at the design stage, for instance, over/under heating or lack of day lighting. In 2011 the RIBA published a *Green Overlay to the Plan of Work* (Gething, 2011). In this document Gething expands on how the stage approach can be made 'greener'. The document has a strong emphasis on sustainability with the aim of setting out what should happen and at what stage. In the following year the RIBA published a *BIM Overlay to the Plan of Work* that aims to assist design and construction teams in using BIM to provide a more efficient, intelligent and cost effective design process (Sinclair, 2012). Both documents use the sequential stages of the existing plan of work, and are intended as the basis for professional engagement rather than guides to design processes.

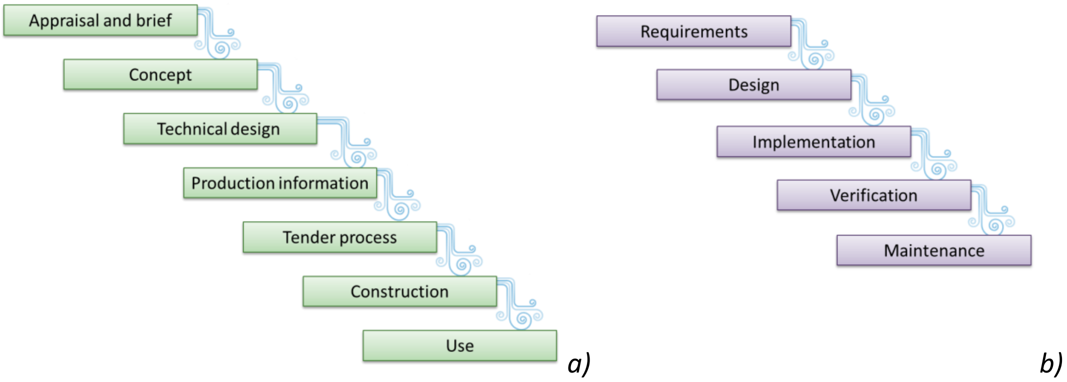


Figure 2-1 The waterfall model of project development

The waterfall model as found in the a) the stages of a building project (after Royal Institute of British Architects, 2008) b) software development (after Royce, 1987) which implies that one process has to be completed before the next can be started.

Other publications deal more specifically with the process of designing green or sustainable buildings. There is generally an emphasis on working with the climate, site and building type. For instance Krygiel & Nies in their book, *Green BIM*, suggest the following design sequence (2008):

1. Understand the climate, culture and place,
2. Understand the building type,
3. Reduce the resource consumption needed,

4. Use local resources and natural systems,
5. Use efficient technology,
6. Apply renewable energy generation systems,
7. Offset remaining negative impacts.

Lévy, in her book, *BIM in Small-Scale Sustainable Design* (2012) discusses the following steps in the creation of high-performance architecture:

1. Site indexing where building envelopes, slope analysis and views are modelled,
2. Climate indexing to consider solar geometry (sun studies and daylight factors) and prevailing winds that will determine the effectiveness of passive strategies,
3. Energy efficiency through consideration of the building envelopes ability to gain or lose heat through: passive cooling (ventilation, thermal mass) and passive heating (solar orientation, net glazing area and thermal mass),
4. Effective building hydrology,
5. Waste reduction.

There are a growing number of ‘sustainable’ or ‘green’ projects now built or being built around the world using such principles, for examples see *Footprint* website published by the Architect’s Journal[5]. However, labels such as ‘sustainable’ or ‘green’ may be merely a veneer. To tackle the issue of climate change requires the rigorous reduction of the energy consumption of a building. For instance, the adoption of sustainable strategies such as waste reduction or the use of natural materials may not result in any reduction of energy usage.

The proposed low energy requirements in the UK will necessitate regular quantitative analysis to predict the energy demands of the proposal as the design is developed. Most

---

[5] http://www.architectsjournal.co.uk/footprint/

texts on building energy simulation deal mainly with the algorithms or techniques involved, however, in *Designing Zero Carbon Buildings* Jankovic (2012) outlines the stages in employed in a simulation model as:

1. The definition of the building in three-dimensions,
2. Setting the site location and associated weather files,
3. The definition of the construction, such as walls, floors, ceilings, windows and doors,
4. Setting the building use, such as patterns of occupancy, including room conditions, internal gains, air infiltration and ventilation requirements,
5. The definition of the heating and/or cooling systems,
6. The specification of renewable energy systems.

This reflects the current general practice of post design validation, where the building is defined first and simulation is employed afterwards to specify the HVAC [Heating, Ventilating, and Air Conditioning] equipment and confirm compliance with regulatory codes. He discusses optimization of the design only in terms of optimisation of the construction of the building. However, this is a relatively conservative view of optimisation and misses the opportunity to manipulate the building form in conjunction with the other parameters.

Iterative, holistic and collaborative approaches are required to realise buildings that are aesthetically pleasing with low energy requirements. Iterative means to repeat a process with the aim of improving and refining the building design. Holistic means that the building design should be viewed as a whole, integrating all of the factors into one. Collaboration means a number of people, working in a team, towards a common goal on a building design. In the USA the Rocky Mountain Institute have called for more integrated processes to support the comparison of design options (Franconi, 2011) and collaborative practices (Tupper *et al.*, 2011). The process of architectural design has always been iterative and reflective (Schön, 1983).

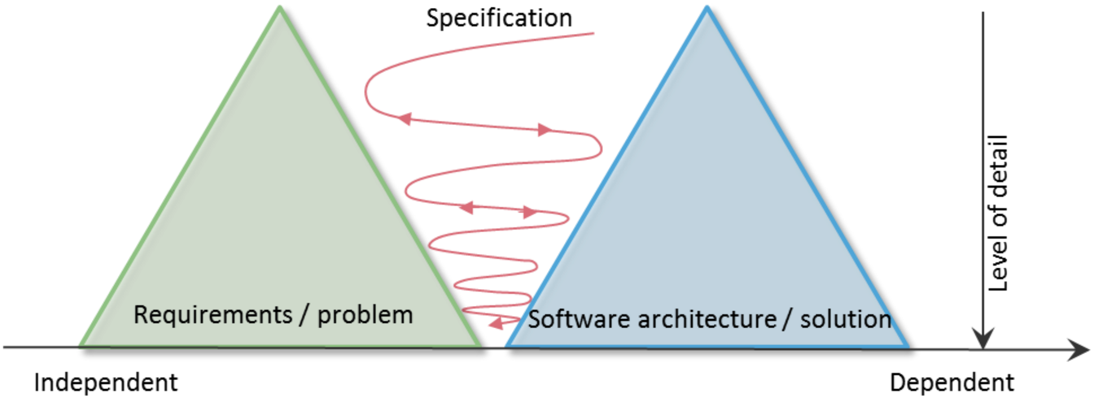


Figure 2-2 The twin peaks model of software development

The twin peaks model illustrates how problem structures can be developed and enriched as part of an iterative process with the solution domain (after Hall et al., 2002; Nuseibeh, 2001)

Comparisons can be drawn with the 'twin peaks' concept in the field of software engineering. The *twin peaks* model in Figure 2-2 shows how problem (or requirements) structures are developed and enriched as part of an iterative process with the solution (software architectures) domain (Hall *et al.*, 2002, Nuseibeh, 2001). The process of architectural design could be considered to have more parameters than the *twin peaks* model: the client's requirements (or the brief), the aesthetics, the buildability of the proposal and the predicted performance as shown in Figure 2-2. Buildability includes structural design, predicted costs and materials.

Building performance simulation can be part of this iterative process, with, for instance, acoustics informing and generating design solutions in auditoria. However, the rigorous prediction of energy usage is generally not considered early in the design process, instead reliance has been placed on post design, high energy consuming solutions. Examples being air-conditioning used to moderate internal temperatures and electricity to provide adequate task lighting.

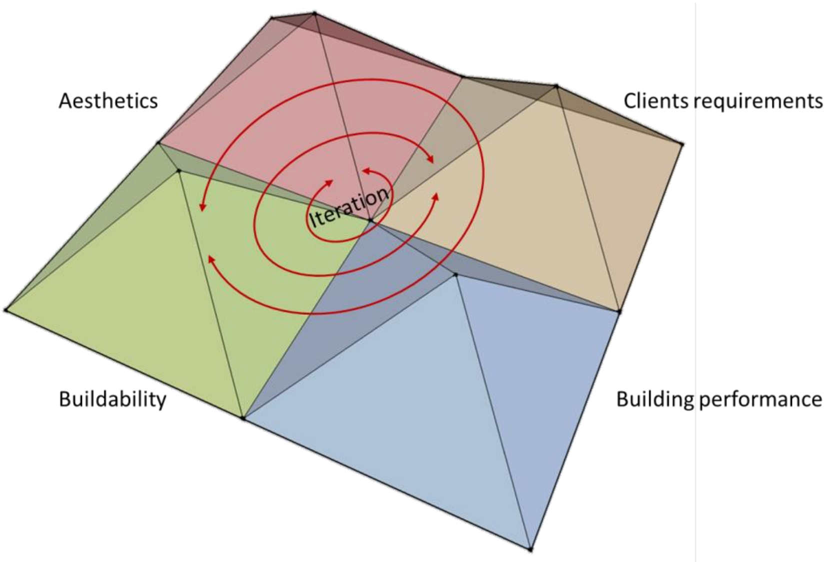


Figure 2-3 The 'multi peak' approach applied to the architectural design process.

Iterative design involves the designer taking into account all four processes: aesthetics, client's requirements, builability and building performance, as building detail is added and enriched.

Extensive knowledge is required to perform building energy modelling and interpret simulation results (Schlueter & Thesseling, 2009). It is at present rare for the building designer to carry out this type of analysis, due to the expertise required to run the software. Often external energy consultants are employed. There is a recognised need to provide access to detailed simulation tools at all stages in the design process to support freedom to explore options and improve the design accordingly (Donn *et al.*, 2012). However, there is concern about the lack of experienced and skilled energy modellers with adequate building physics knowledge (Tupper *et al.*, 2011). Although there are now multiple professional certification programs none have gained real traction in the industry. The majority of energy modellers are self-taught and have learnt from doing.

Large or prestigious projects are generally designed by major design firms with either their own in-house energy analysts or the ability to afford to employ external consultants. However, concern has been expressed as to how smaller practices will cope with limited access to tools and expertise (Technology Strategy Board, 2009). Access to simulation software to model rigorously physical processes by architects is seen to be empowering by Sullivan (2012). She outlines the benefits of a better understanding of environmental analysis software and their results; that there will be an improvement in the design process, better cost planning and enabling of a dialogue with engineers. Tupper et al. (2011) conjecture that in the future building energy modelling could be used by a wide range of end-users, especially architects, to inform a broader array of decisions.

In order to predict the energy used by a building design it is necessary to simulate the physical interactions of that building over time. To do this in detail, especially for non-domestic buildings, will require 3D modelling as will be discussed in further detail in the next chapter. This will represent a major challenge to the profession given the limited adoption of 3D modelling processes discussed above. CAD, BIM, BES and visualization software require a significant amount of time to learn and to achieve proficiency (Krygiel & Nies, 2008). This thesis is concerned with how these types of software might be better designed to support the design of low energy buildings.

2.2 A review of software developments

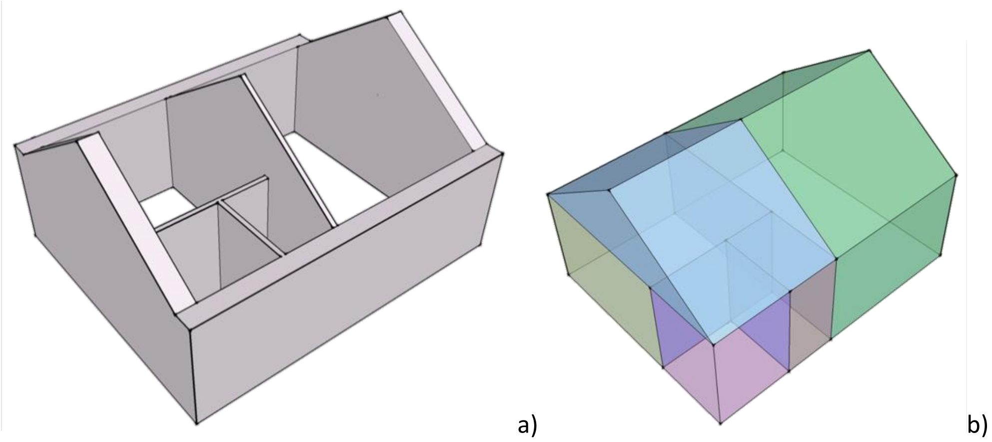


Figure 2-4 The dichotomous view of the building model

The two figures illustrate a) the architectural view of the building composed of objects and b) the thermal view of the building composed of spaces

There has been a traditional separation of architectural design and energy simulation processes and software tools. Standalone software, such as BIM or BES programs, have been developed for very different purposes and this results in a dichotomous view of the building model (Hitchcock & Wong, 2011). The separate approaches are illustrated in Figure 2-4; the architectural view, when BIM is employed, is of a building composed of objects such as walls, floors and roofs. The energy simulation view is that of a building comprised of thermal zones, these are volumes of thermally consistent air. As will be discussed, at present interoperability of data between the different types of software is limited and imperfect. The next two sections discuss the evolution and current research directions of building design and simulation software.

2.2.1 Software to design buildings

Architecture has gone through significant changes since the 1980s when CAD was introduced. The use of software has significantly altered working practices and enabled imaginative and inspiring designs, sometimes using complex geometries, only achieved through the use of advanced modelling and engineering computational techniques (Lawson, 2005). However, advances in digital design media have created a complex web of multiple types of software, interfaces, scripting languages and complex data models (Oxman, 2008). More than one package is often used in any one project (National Building Specification, 2012).

CAD has been employed by the architectural profession predominantly to replicate drafting and visualisation processes that were previously carried out manually. CAD can provide higher speed, accuracy and photo-realistic visualisations compared with the production of drawings by hand. BIM, although still regarded as an emerging technology within the AEC industry (Eastman *et al.*, 2011; Succar, 2009), has now reached a level of maturity, and hence usefulness, for the UK government to require its use in public projects, as discussed earlier.

BIM has been the subject of research and development in computational design over the past 20-30 years and has often been misconceived as being a new version of CAD (Holzer, 2011). Unlike CAD, BIM software contains not only the building geometry and spatial relationship of building elements in 3D; it can also hold geographic information, quantities and properties of building components. Each component is an ‘object’ that is recorded in a backend database. Most BIM software contains extensive libraries of building components. They also provide sophisticated rendering and visualisation functions. There are high expectations in the AEC industry for efficiency gains and for more integrated collaboration with the adoption of BIM (Holzer, 2011). BIM is seen as a driver to facilitate collaboration between the various fragmented sectors in the AEC industry (Harty & Laing, 2011b). The use of BIM can reduce wastage on site through using techniques such as collision detection and exchange of 3D data by contractors. Cloud computing technologies are now being employed to provide integrated building design models through the use of BIM servers.

BIM is described as a “methodology to manage the essential building design and project data in digital format throughout the building's life-cycle” (Penttilä, 2006, p.403) A number of ‘frameworks’ or ‘methodologies’ have been developed in recent years for the development and implementation of BIM (Arayici *et al.*, 2011; Jung & Joo, 2011; Singh *et al.*, 2011; Gu & London, 2010; Succar, 2009). In addition there are a growing number of texts on the impact of BIM and the predicted changes in working practices, for example: *Handbook of Research on Building Information Modeling and Construction Informatics* (Underwood & Isikdag, 2009); *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors* (Eastman *et al.*, 2011) and the *Government Construction Strategy* (Cabinet Office, 2011).

A framework to describe the relationship between BIM based sustainability analyses and the LEED [Leadership in Energy and Environmental Design] certification process has been developed (Azhar *et al.*, 2011). However, this reflects the current practice of post design performance simulation, and not simulation integrated into design decision-making. Schlueter and Thesseling (2009) argue, in their description of a prototypical tool, that in order to evaluate the dependencies of performance criteria on form, material and technical systems, building performance assessment needs to be seamlessly integrated into the design process. Their approach, however, uses a relatively simple statistical method to perform energy calculations and is only suitable for early design decisions.

Opinions are mixed as to the usefulness or appropriateness of BIM to the design process. There are concerns regarding possible inhibition of creativity through the use of high precision tools too early in the design stage that can give the illusion of more precision than is intended (Kalay, 2006). Kalay (2004) discussed how early computer-aided design approached the problem from an intuitive, architectural design viewpoint. He observed that this approach was lost as software was developed primarily to support drafting and rendering requirements through the development of CAD. Holzer discussed the need for architect, in their design practice, to be aware of the need to differentiate between the “divergent, open-ended, and often erratic processes of design exploration” and the more “convergent processes of assembling and sharing intelligent geometrical objects in 3D” (2011, p.468). Both the perceived negative and positive impact of BIM tools on creativity have been reviewed by Ahmad et al. (2012). There are calls for more research into the application of BIM software during the early and conceptual design stages (Leon & Laing, 2012).

In May 2012 the RIBA published *BIM Overlay to the RIBA Plan of Work* in response to the UK Government’s commitment to the application of BIM to all its projects. This guide gives a clear description of the maturity levels that match to the Government’s aspirations for collaborative BIM. Part of the vision is for Level 3 with the perceived “holy grail” of a *single project model* that, along with other goals, will facilitate environmental performance by reducing the time required to prepare building models to enable iterative design (Sinclair, 2012, p.6). This thesis explores how this might be achieved for energy performance simulation.

2.2.2 Software to simulate building performance

BPS [Building Performance Simulation] applies science to predict how a building will function once it is built. The main purpose is to model as closely as possible a real-world physical process. Examples are heating/cooling, lighting (daylight and artificial), air-movement, noise and acoustics. BES is a type of BPS, it is the prediction of the energy used by a building and can include heating/cooling, lighting (daylight and artificial) and air movement.

The need for creating buildings with very low energy demands may tend to compromise architectural creativity (Hetherington *et al.*, 2011). However, the ability to make easy use of BPS could enable the architect to explore a range of aesthetically pleasing design options whilst monitoring their implications on the predicted energy performance.

Getting the design ‘right’ at an early stage on all projects has important cost benefits. This is illustrated by the *”MacLeamy Curve”* in Figure 2-5 showing qualitatively how an architectural project becomes more difficult to change the more developed it becomes (Construction Users Roundtable (CURT), 2004). The red line shows how the ability to impact on cost and functional capabilities reduces as the project develops. The green line shows how the cost of making changes dramatically increases as the design progresses. MacLeamy suggests that moving more of the design effort into the schematic design stage (blue solid line) from the technical design stage (red dashed line) can minimise the cost of design changes. Although this diagram was developed to support the concept of IPD [Integrated Project Delivery] the concept is applicable to building energy modelling. The use of BPS at the present time is limited (Hensen & Lamberts, 2011), it is usually carried out after the design has become fixed and applied on one solution rather than used to test alternative approaches. It is often restricted to iconic projects where the budget is sufficiently large to enable the employment of specialist energy consultants.

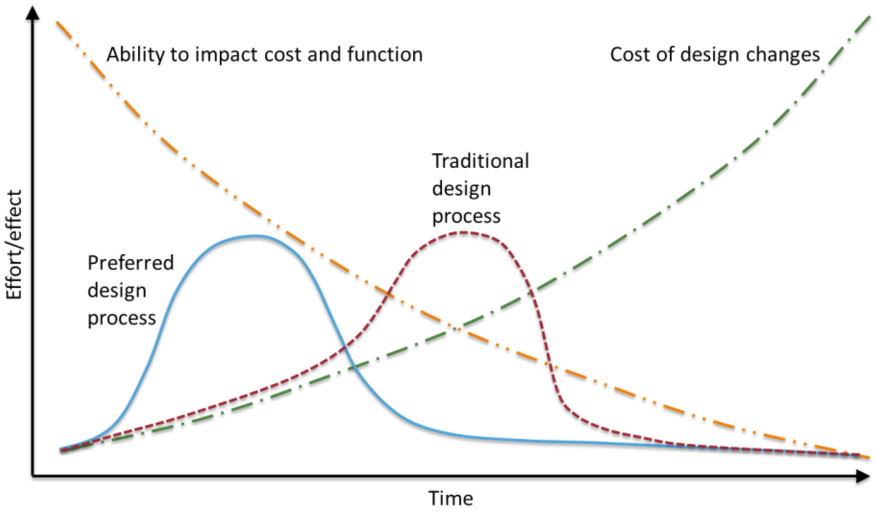


Figure 2-5 The "MacLeamy Curve" for the building design process

The figure illustrates the four important concepts about the relationship between design/cost and the traditional phases of design and construction. The position of the blue, solid line under the orange, dashed line is meant to illustrate that design changes are better made earlier in the process. The green line shows how the cost of making changes dramatically increases as the design progresses (after Construction Users Roundtable (CURT), 2004)

Thermal analysis tools have been developed for use primarily by energy experts to assess designs against standards/codes or to size mechanical plant. The Digital Lab at Georgia Tech list just 4 main BIM design software tools (Digital Building Lab, 2012), in comparison there are many BES tool available (at least 406 at the time of writing) with a wide range of analysis parameters such as building envelope, solar gain, day lighting, infiltration, ventilation, electrical systems and equipment, and HVAC (U.S. Department of Energy, 2011). Most of these tools have been developed by academics, researchers or HVAC engineers (Attia *et al.*, 2009; Papamichael & Pal, 2002). In a comparison of 20 major programs it was found that there was no common language to describe what the tools could do (Crawley *et al.*, 2008).

Dynamic energy modelling, because it typically simulates the response of a building to climate at hourly intervals over a year, is computationally demanding. The more complex the model mesh, the more time-consuming the simulation, with little improvement in the uncertainty of the simulation results (Hensen & Lamberts, 2011). Therefore BES and similar simulation and analysis tools require a ‘simplified’ or ‘reduced’ building geometry (Bazjanac, 2010). The basic concept employed in thermal calculations is the thermal zone for which internal temperatures and heating and cooling loads can be calculated. Each zone should consist of an enclosed volume of relatively homogeneous air, this might typically be a single room. However, for a large space, with windows on more than one side, it may be appropriate to sub-divide the volume into multiple zones to allow for differences between the north, south, east and west sides. Equally, two or more small inter-connecting rooms may be grouped into a single zone, as they are subject to the same thermal effects and can be treated as a single volume. Each thermal zone requires an envelope of enclosing surfaces to enable the calculation of inter-zonal heat flow paths and incident radiation. All thermal analysis algorithms calculate a single temperature for each zone which is the average over the whole space. Data entry and the display of results vary widely according to the software used.

Traditionally, thermal analysis has been carried out by external consultants. The different methods of data entry to simulation software is shown in Figure 2-6. Information regarding the building geometry is often passed from the building designer in the form of 2D drawings, and then entered into the simulation software as numerical/ text data. Recently software has been developed with ‘user-friendly’ interfaces, however again the consultant will often create a 3D zone mesh based on 2D data. Only recently has BIM software, such as Autodesk’s Revit, facilitated conversion of a 3D mesh, created in a design environment, into zone data for use in thermal analysis. However, often the mesh requires manual correction and semantic data is not transferred (Hitchcock & Wong, 2011; Krygiel & Nies, 2008). Any changes made to the building design in the simulation software have to be entered manually into the BIM tool giving rise to potential errors.

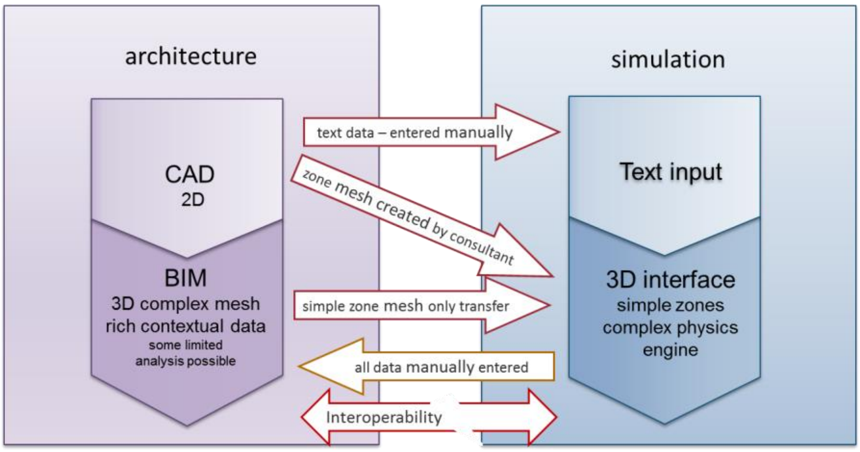


Figure 2-6 The dichotomous process of building modelling

The figure illustrates the data flow between architectural and simulation software. Data entry to simulation software can be: text entry; a zone mesh created by the consultant or a zone mesh from BIM software. Any changes made to the building design in the simulation software have to be entered manually into the BIM tool.

There is a lack of confidence in the tools; both in terms of functionality (Crawley *et al.*, 2008) and the results (Tupper *et al.*, 2011). Predictive inconsistencies between accredited tools have been reported with different pass/fail outcomes with regard to compliance for the same building using a variety of tools (Raslan & Davies, 2010). There is also concern in the building research/academic community as to how well the design predictions compare with actual energy use; it is believed that there may be significant under-estimation (Oreszczyn & Lowe, 2010). This is now being shown by *CarbonBuzz,* a collaboration between CIBSE [Chartered Institution of Building Services Engineers] and the RIBA, which is already reporting significant gaps between the predictions given by energy models and actual consumption[6].

Papamichael and Pal (2002) cite the main barriers to the development and use of BPS tools to be the low market interest and high time-cost of applying them. Clarke (2001) also lists

---

[6] http://www.carbonbuzz.org/index.jsp

barriers to the uptake of the application of simulation to the design of the built environment. One software issue he outlines is the need for the development of suitable user interfaces to provide access to the considerable power of simulation. A survey comparing tools for the design of low energy buildings has been carried out by Attia and De Herde (2011). The feedback from the building design community was that most tools were not accessible and current practice meant that multiple tools were required to design such buildings. They found that there is a lack of pre-decision and post-design informative support for building energy analysis and optimisation. They also suggest the need for tools to support the optimisation of geometry and envelope for renewable energy potential. They conclude that more investment in early design tools is required. For a comparison of tools for the design of Net Zero Energy Buildings see Attia and De Herde (2011). Tupper et al list: the lack of availability of tools to simulate and predict energy used in buildings, the range of features in existing tools and the reproducibility/quality of the results as barriers to the more widespread application of energy modelling. They conclude that “energy modelling processes need to be clarified and streamlined so practitioners can spend more of their time on the critical thinking required to make recommendations for improving actual building performance” (2011, p.742).

2.2.3 Design Advisory Systems

The need for better information to be made available to building designers when modelling building energy usage and implementing low energy strategies is discussed by Tupper et al. (2011), Bunker et al. (2011) and Attia et al. (2009). These papers involved consultations with building design professionals about the difficulties of performing in-depth analysis. Access to better knowledge and data resources is identified as key to the improvement of the quality of building energy analysis by practitioners (Tupper *et al.*, 2011). The urgent need for further education and training in building physics has been set out by King and the Royal Academy of Engineering in *Engineering a low carbon built environment: the discipline of building engineering physics* (2010).

The major issues recorded are the need for:

- Access to better knowledge on how to use energy modelling tools (Tupper *et al.*, 2011).

- The provision of the means for a practitioner to develop a solid understanding of building science/physics, (Tupper *et al.*, 2011; King & Royal Academy of Engineering (Great Britain), 2010). Specifically, help with developing strategies for understanding: thermal mass, natural ventilation, renewable energy and embodied energy (Bunker *et al.*, 2011). Tupper at al. note that most practitioners learn by doing.
- The appreciation of the variability of user behaviour and the resultant effect on energy modelling prediction (Donn *et al.*, 2012).
- The provision of a mixture of quantitative and qualitative information through:
    - A library of specifications, drawings, standard details, product data and CAD reusable data.
    - Design requirements such as energy targets (Bunker *et al.*, 2011).
- Methods to share data, possibly through the provision of a shared internet-aware library (Donn *et al.*, 2012; Bunker *et al.*, 2011).
- The provision of good practice knowledge relating to exemplar buildings (Bunker *et al.*, 2011) and compelling case studies (Tupper *et al.*, 2011).
- The provision of data relevant to the design stage, particularly the schematic stage (Bunker *et al.*, 2011).
- Access to POE [Post Occupancy Evaluation] data/past design data (Donn *et al.*, 2012; Bunker *et al.*, 2011).

CAD, BIM and energy analysis and visualization software require a significant amount of time to learn and to achieve proficiency (Krygiel & Nies, 2008). Tupper et al. (2011, p.740) observe that practitioners frequently “pass down knowledge from person to person” and rely on a few experts from within their professional networks for information on energy modelling procedures. Existing resources, such as research papers, training sessions and software documentation, are often under-utilized because they are hard to access. They suggest that some of these resources should be embedded within software tools to better integrate learning into the workflow.

A DAS [Design Advisory System] is a type of expert system that can be linked or embedded into software to provide the type of knowledge listed in the preceding section. Feigenbaum cited in Giarratano & Riley (1989, p.1) defines an expert system as "an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult and require significant human expertise for their solutions". Expert systems are designed to solve complex problems by reasoning about knowledge and emulating the decision-making ability of a domain expert. An expert has knowledge or special skills in a particular area beyond that of the normal person. Typically an expert system contains two components; a knowledge base that contains facts and an inference engine to draw conclusions (Giarratano & Riley, 1989).

Advisory systems associated with building design have not, to date, become widely employed. An early attempt to develop a DAS for building design software, and possibly the most ambitious, was undertaken in the late 1980's by the CAD research unit at California Polytechnic State University. The ICADS [Intelligent Computer-Aided Design System] was intended to advise on a broad spectrum of building design activities; lighting, sound, structure, cost, climate and access. Conceived before the advent of BIM, it was an ambitious system that interpreted a drawing of a building as it was developed by the designer working in a CAD environment. The system combined a number of domain expert systems in the form of intelligent agent software applications to continuously evaluate the design for validity and to propose alternative strategies in real-time. The advice was to be delivered as if in 'a conversation' with the design assistant. Pohl et al. (1992) list the limitations of the system at that time. The weakest component was the Geometry Interpreter, a bridge between the CAD drawing environment and the expert systems. The other issues were the coordination/resolution of the results from the domain experts and the compilation of a knowledge base.

A desktop tool called the *Building Design Advisor* was developed at the Lawrence Berkeley National Laboratory in the late nineties. It is of interest to this work as it was intended to link to both a CAD-type design environment and external analysis tools. It consisted of a Schematic Graphics Editor, to enter the building design geometries, a Building Browser to record the building objects and their parameters and a Decision Desktop. For every building object created a "smart" default value was selected from a Prototypes Database for all non-geometric parameters required as input to the analysis tools linked to the DAS. The Decision Desktop allowed building designers to compare multiple design alternatives. The tool was only developed to a beta version with limited functionality (Papamichael, 1997). The use of 'smart' default values might not give the necessary control of parameters that would be required for the optimisation of low energy building designs.

More recently and specifically related to building energy analysis, is the MIT Design Advisor. This is an online tool to assist with early-stage design of energy efficient buildings. The tool relies on manual entry of zone dimensions, which are restricted to simple rectangular volumes and has limited heat transfer simulations (Urban & Glicksman, 2006). However, one interesting feature is the ability to compare four scenarios so that the designer can monitor any improvements to the performance as changes are made.

The first two tools discussed above were ambitious in nature, and were not completely realised, one of the reasons being the difficulty of linkage to the design environment whilst the last is standalone and does not attempt to link at all. With the advent of 3D building object modelling the opportunity to extract from, and feed data, into the design software may be more feasible, although the complexity of the system would remain challenging.

2.3 Barriers to integrated building design and simulation software

There is a growing consensus within the literature of the need for integrated design and building performance simulation software (Eastman *et al.*, 2011; Hensen, 2004; Papamichael & Pal, 2002; Augenbroe, 2002; Clarke, 2001). This is seen as a necessity to enable the replacement of traditional sequential processes with interactive concurrent design (Dong *et al.*, 2007). Integration could be achieved in two ways; by the provision of good interoperability to facilitate the movement of building data between design and simulation software or by integrating the software into one tool (or suite of tools).

With regard to energy modelling, interoperability relates to the transfer of models to and from Building Design software, typically BIM, and BPS software. Interoperability, enabling building professional software to exchange information, is seen as important by both industry (Young *et al.*, 2008; Khemlani, 2004), academia (Amor & Dimyadi, 2010; Eastman *et al.*, 2010; Howard & Bjork, 2008; Bazjanac, 2002) and government (Cabinet Office, 2011; Gallaher & Chapman, 2004). Interoperability in the AEC field has traditionally relied on file-based exchange formats limited to geometry such as DXF [Drawing eXchange Format].

However, the need to include semantic data led to the development of IFC [Industry Foundation Classes]. The IFC schema was developed in the mid-nineties as a product data model for the design and full lifecycle record of buildings, by industry-led buildingSmart (formerly the International Alliance for Interoperability). The current standard is ifc2x3, with the next version, ifc2x4, coming to the end of its development phase (at the time of writing it is ifc2x4 Release Candidate 3). The IFC model is both rich and highly redundant, offering different ways to define objects, relations and attributes (Venugopal et al., 2010). It has been developed to be generic, to meet the requirements of many factions in the AEC industry such as architects, engineers, contractors, suppliers, fabricators, government officials, etc. IFC is complex, reflecting the semantic richness of building systems. Ifc2x4 has over 800 entities, 358 property sets and 12 data types (BuildingSMART International Ltd, 2011c).

Although the aim of IFC is to “contribute to sustainable built environment through SMARTER information sharing and communication” (Rooth, 2010, p.3), exchange of thermal data is generally achieved by using a different language, gbXML [green building XML]. The gbXML schema was developed to transfer information needed for energy analysis (GbXML.org, 2010). The current version is 5.10 released in January 2013.

Poor interoperability necessitates the manual entry of data and the resulting possibility of discrepancies and errors. The time involved with this re-entry of data also discourages iterative, holistic design practices (Eastman *et al.*, 2011). Although IFC has broad support from the majority of software companies, the implementations are inconsistent (Eastman *et al.*, 2011; Grilo & Jardim-Goncalves, 2010). The current state-of-the-art software implementations supporting energy performance have been described by Hitchcock and Wong as “woefully inadequate” (2011, p.1089).

At the present time multiple software tools and building models are often required in the design of a low energy building (Tupper *et al.*, 2011; Attia & De Herde, 2011). Recently there have been significant developments towards integrated tools with the large software houses developing new, or adapting existing, software. However, the priorities of the dominant BIM vendors appear to be the development of energy analysis tools embedded within their flagship products with limited interoperability of data to external BPS software (Hitchcock &

Wong, 2011). Autodesk have developed Project Vasari[7] and ArchiCAD developed Eco Designer[8] for use in the early conceptual design phases by building designers. These tools use fairly simplified algorithms for thermal simulation calculations. However, Donn et al. (2012) argue that access to detailed simulation functions is necessary at a stage in design when the freedom to explore options is greatest. This requires the integration of much more powerful simulation engines than currently available within BIM environments.

2.4 Discussion

The research and publications reported in this review confirms that this work is timely. There is potentially a convergence between the legislative policies on BIM and low energy building design. BIM has reached a level of maturity in recent years such that it is now on the cusp of becoming mainstream, with some governments requiring its use on public projects. In parallel, the UK and the EU are planning to set rigorous energy targets for new buildings to help mitigate against the threat of climate change. In order to achieve aesthetically satisfactory buildings with very low energy demands, iterative design, with monitoring and checking against performance targets, from early conceptual studies through to the technical design, will be required (Gething, 2011).

The research reported in this chapter suggests that there is likely to be a transformational change in design practices and the tools used by the AEC industry. A number of strands have been highlighted in the literature: the need for improved building design and simulation tools, the need for the architect to develop a better understanding of building physics and the need for better interoperability of data to support iterative design.

The need for better tools was a theme of a number of presentations at *Building Simulation 2011*[9]. Tupper et al. (2011), Attia et al. (2009) and Bunker et al. (2011) reported on surveys and workshops with professions/practitioners and concluded with a recommendation for the development of new tools to design low energy buildings. At EcoBuild 2012, Gething (2012,

---

[7] http://usa.autodesk.com/

[8] http://www.graphisoft.com/products/ecodesigner/

[9] http://www.bs2011.org/

p.17), in introducing the Green Overlay to the RIBA Plan of Work, stated that design attitudes need to change to achieve low energy, sustainable buildings and he questioned if the right tools are available for “holistic iterative design”.

Increasing the understanding of the physics underlying the design of low energy buildings by the designer has been identified as important in the literature. Gething (2012, p.17) described it as a “game changer” for architects. Again the survey work with professionals by Tupper et al. (2011), Attia et al. (2009) and Bunker et al. (2011) confirmed this need for better understanding of the science to support low energy design.

Problems associated with the interoperability of data between design software and simulation software has also come to the fore during the course of this thesis. It again cropped up in a number of papers at *Building Simulation 2011.* The poor support of interoperability by current design and simulation software was highlighted by Hitchcock and Wong (2011). Tupper et al. (2011, p.741) reported on the difficulty of sharing data between the tools and the wasted time in translating and pre-processing of data rather than it being spent in “critical thinking required to make recommendations for improving actual building performance”.

In summary, there is evidence from academic, government and professional bodies that new tools, with improved integrated energy simulation and design decision support are required. The next three chapters form a practical framing and in-depth definition of the problems associated with designing low energy buildings. Chapter 3 describes the problem domain; what low energy means and the factors that need to be modelled and simulated. Chapter 4 reports on empirical work carried out in late 2010 and early 2011, before publication of much of the literature cited in the present chapter, into user experiences of modelling low energy buildings. Chapter 5 provides an analysis of current software methods to model buildings for both design and simulation purposes.

Chapter 3

The Problem Domain: Low Energy Buildings

The previous chapter reviewed the influences on the development of software related to the design of low energy buildings. This chapter aims to provide more detail on the technical aspects of the problem domain; the design of low energy buildings. It outlines why dynamic simulation of energy performance will be increasingly become important as part of the iterative and holistic design process of new buildings in the future. In order to achieve this it will:

1. Establish what low energy building design means for the architect.
2. Provide an overview of the physical parameters involved in relation to energy and buildings.
3. Outline an approach to the low energy design of buildings and identify the need for integrated simulation modelling and design decision support.

This chapter continues with the *definition* and *discovery* of the problem domain in the Research Through Design approach of this thesis (Zimmerman & Forlizzi, 2008). The energy currently used by buildings is discussed, proposed legislation to restrict this energy is outlined, the physics that underlie simulation techniques is described and the need for energy consumption prediction, integrated into the design process, is discussed. An understanding of the application domain and the constraints is an important part of the process of software development (Sommerville & Sawyer, 1997). As Jackson observes, “the problem is in the world outside the computer” (2001, p.1).

3.1 Energy and buildings

Buildings consume energy and the majority of that energy is used to keep the occupants comfortable. Space heating, space cooling, ventilation and water heating all contribute to that comfort. Figure 3-1 illustrates the energy consumed in buildings for 2011 for the UK and USA (DECC, 2012; U.S. Department of Energy, 2012).

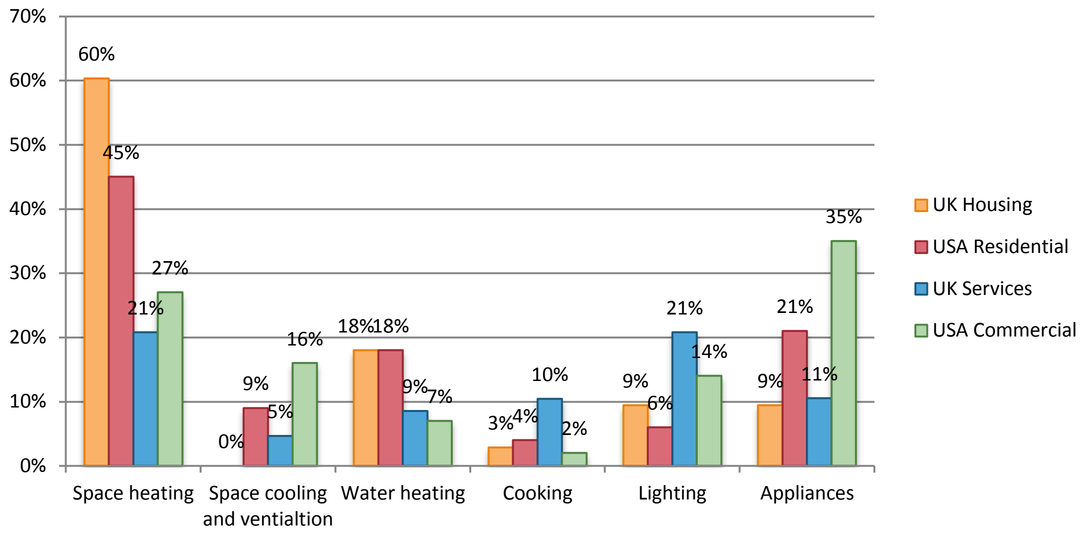


Figure 3-1 Patterns of energy consumption for buildings in the UK and USA in 2011

The numbers to generate this graph have been taken from UK and USA government publications for domestic and services (UK)/commercial (USA) buildings. It can be seen that space heating uses most energy.

Totalling the figures from Figure 3-1 that relate directly to maintaining occupant comfort gives the following: UK housing 78%, USA residential 72%, UK services 50% and USA commercial 50%. Thus the elements that relate to indoor occupant comfort account for at least 50% of energy use in each of these categories. If energy created by the burning of fossil fuels to provide heating, cooling and water heating can be reduced to near zero then significant savings can be made in CO_2 emissions. These statistics are for energy in use and exclude embodied energy (that used to extract, manufacture and transport building products to site). Lighting also accounts for energy use, more so in service or commercial buildings, 21% in the UK and 14% in the USA. The building form and construction affects the amount and quality of daylighting within the building. The electrical load of a building can be significantly reduced if daylight can be employed in lieu of electric lighting.

The following sections outlines the legislative context and describes the physical concepts of occupant comfort, response to external environment, the building fabric, ventilation, heat gains and building performance simulation techniques.

3.2 Proposed legislation

A wide assortment of terms exist for key concepts relating to buildings such as net-zero energy, renewable energy, low energy, and low-carbon buildings. Kibert & Fard (2012) attempt to provide a definition for these terms. Much of the confusion relates to the ability to generate electricity on site and export it to the grid and, as they note, this option does not exist for all sites. They recommend that there should be an international standard approach to reduce misunderstanding and support collaboration.

The UK is at the forefront in setting ambitious standards, with the objective that all new domestic buildings in England will be ‘zero carbon’ by 2016 and non-domestic buildings by 2019 (Great Britain, 2008a, p.87 and 89). The intention, in 2009, was for the energy from new buildings to have zero net emissions of carbon dioxide over the course of a year (Great Britain, 2009). However, the UK Government has struggled with a definition for ‘zero carbon’ for both domestic and non-domestic buildings, as will be discussed in this section.

The ‘zero carbon’ goal for housing was to be achieved in three steps by amending the Building Regulations: 2010, 2013 and 2016. Initially the concept for ‘zero carbon’ homes was that they must have zero net emissions from all energy use in the home over the course of a year (Department for Communities and Local Government, 2007). Arriving at a definition of zero carbon for non-domestic buildings has been even more difficult than that for housing. Consultation to add further detail on the definition of zero carbon and to extend it to non-domestic buildings was initiated at the beginning of 2010. Further research has been carried out with the publication of a report to establish an evidence base for energy and carbon emission performance (AECOM, 2011). The definition for non-domestic buildings is, at the time of writing (early 2013), still not agreed; see the Communities and Local Government website[10].

---

[10] http://www.communities.gov.uk/publications/planningandbuilding/zerocarbonnondomreport

The principles employed by the government were based upon a three-tiered approach for reaching net zero emissions in use, shown as a hierarchical triangle in Figure 3-2 (Great Britain, 2009).

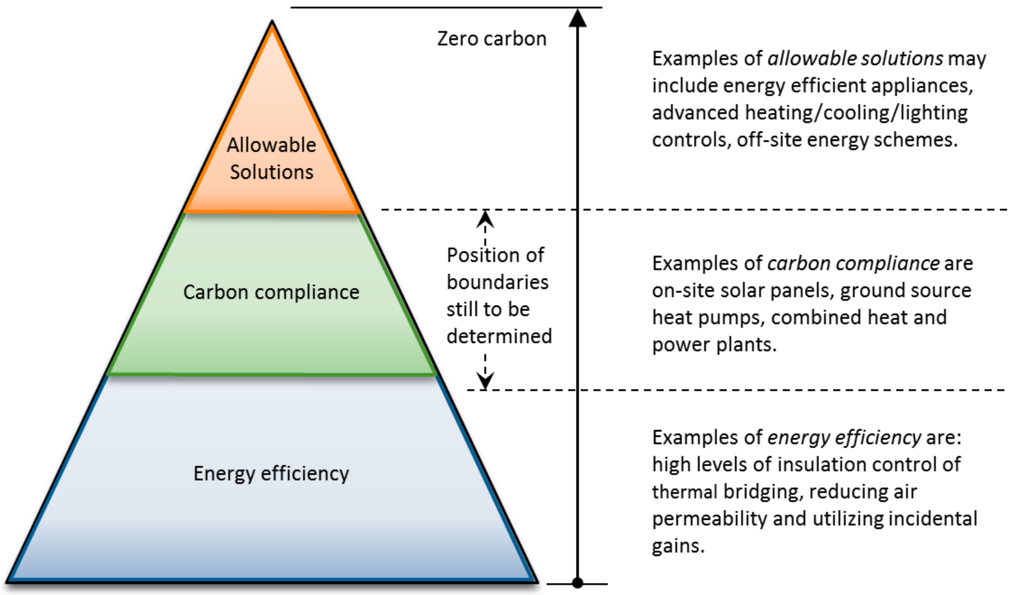


Figure 3-2 Hierarchy of permissible methods to achieve 'zero carbon'

The bottom tier of the triangle is 'energy efficiency', that is to construct building envelopes to very high standards so that little or no energy is required to heat or cool the building. The middle band of the triangle, 'carbon compliance', covers a number of measures including generation technologies located within, or closely connected, to the development. The top band of the triangle, 'allowable solutions' may include (predominantly) off-site measures developments (after Great Britain, 2009).

The priority, represented by the bottom tier of the triangle in Figure 3-2 is to construct building envelopes to very high standards of 'energy efficiency', so that little or no energy is required to heat or cool the building. This includes very high levels of insulation of the building fabric, the control of thermal bridging, significantly reducing air permeability, incorporating thermal mass and utilizing incidental gains, such as metabolic, lighting, solar and appliances. These are expected to be robust methods, entailing lower life-cycle costs than other, possibly higher maintenance, technologies which constitute the other two tiers.

There are limitations to the effectiveness of fabric and energy efficiency measures. 'Carbon compliance', the middle band of the triangle, covers a number of measures including on-site generation technologies, such as solar panels incorporated into the fabric, ground source heat pumps and combined heat and power plants located within, or closely connected, to the development as illustrated in Figure 3-3. However, some of these strategies rely on the site location and area. A reasonable land area is generally required for ground source heat, good, reliable, wind velocity for wind power and appropriate orientation and unobstructed sky to support solar power. Inner city sites in particular may lack such site generation potential. Thus to achieve net 'zero carbon' emissions through building energy efficiency and on site 'carbon compliance' measures may not be technically possible for many building types.

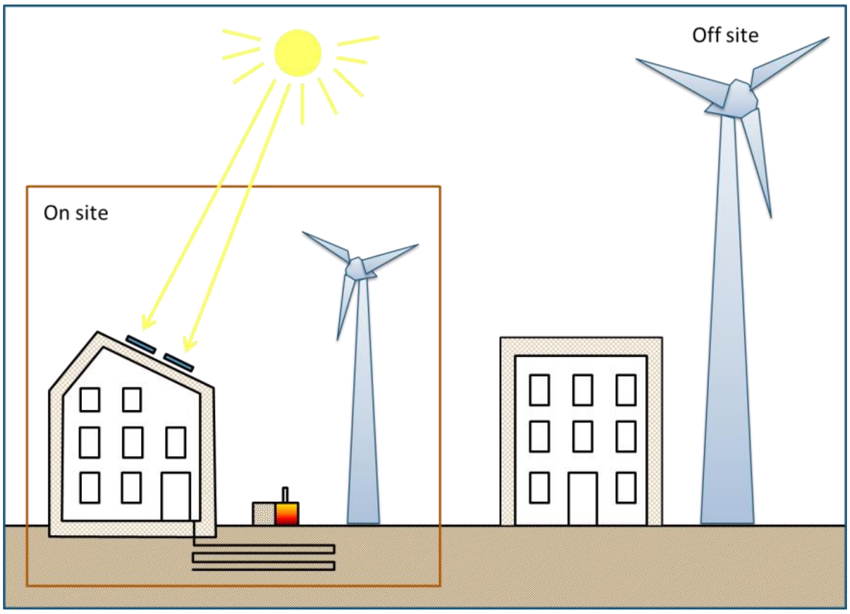


Figure 3-3 On-site and off-site technologies

On-site generation technologies include solar panels incorporated into the fabric of the building, ground source heat pumps and combined heat and power plants. Possible off-site technologies include local energy infrastructures and the improvement of the fabric of existing local buildings.

In order to meet the proposed standard there may be a need to apply (predominantly) off site measures, or 'allowable solutions'. Off-site solutions considered within the consultation are local energy schemes, credits for paying for local energy infrastructures, upgrading existing local buildings, etc., as illustrated in Figure 3-3. Other allowable solutions may include equipment within the building such as energy efficient appliances, for instance ultra low energy IT equipment, or advanced heating/cooling/lighting control systems (Great Britain, 2009).

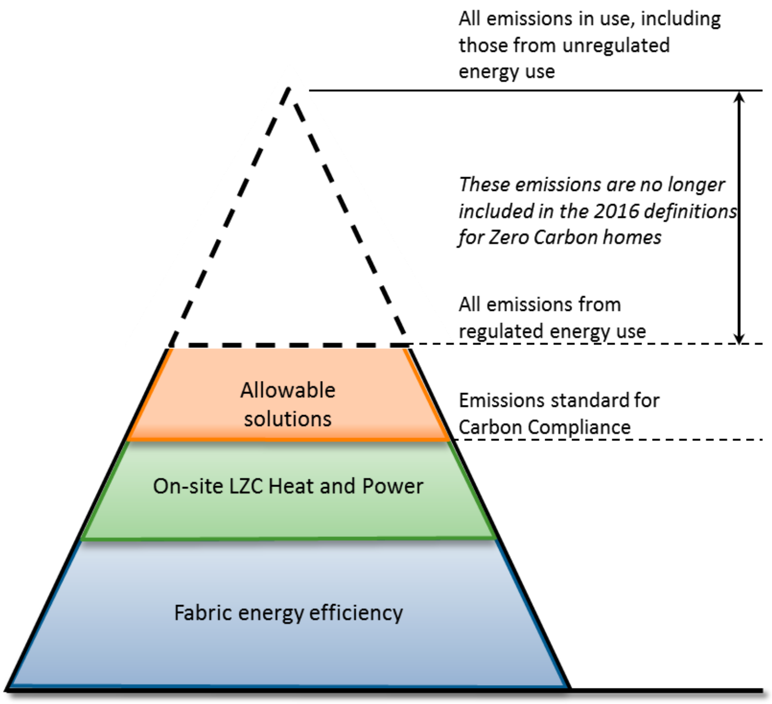


Figure 3-4 The revised "Zero Carbon" policy triangle for domestic buildings

The Budget of 2011 removed 'unregulated energy', that is energy used by appliances such as cookers, televisions and computers, from the previous total in the definition of "zero carbon" for domestic buildings (after Zero Carbon Hub, 2011).

Since the early announcements and round of consultations between 2008 and 2010, and changes in the Building Regulations, due to come into force in 2013, there has been little substance added to the proposals, although there has been a weakening in the policy on housing. The proposed standard for housing was reduced as shown in Figure 3-4 to reflect changes brought in by the Plan for Growth and the removal of 'unregulated' energy from the calculations for the total. Emissions, deemed to be 'unregulated', produced by cooking and electrical appliances such as televisions were excluded from the definition. The definition for 'zero carbon' homes is now currently restricted to the carbon dioxide emissions relating to regulated energy, i.e. covered by the Building Regulations. (HM Treasury & Department for Business Innovation and Skills, 2011). As a result of these changes the government has been heavily criticised as this is seen to be caving in to pressure from the housebuilding lobby (Webb & Harvey, 2011). Although consultations were carried out during 2009-2010 on the meaning of 'zero carbon' for non-domestic buildings[11], a definition of both the meaning and proportion of carbon compliance and allowable solutions has yet to be made, some three years later.

The European Union is also legislating for minimum energy performance requirements for new and existing buildings. In 2010, the EU adopted the *Energy Performance of Buildings Directive 2010/31/EU* to reduce the energy consumption of buildings and is currently consulting on a methodology and role for a framework for minimum energy performance requirements for buildings and building elements. The Directive requires that all new buildings are to be 'nearly zero-energy buildings' by 2021. For more information see the European Commission website[12].

There is much controversy regarding the government plans, especially with regard to the concept of allowing off-site generation, reliance on relatively expensive renewable energy solutions and the non-inclusion of unregulated energy consumption. However, although the UK government has to date (early 2013), failed to give a conclusive definition of a 'zero carbon' building, it is probable that at some point in the near future there will be legislation that will require that the majority of new buildings to be designed to have little or no reliance on the burning of fossil fuels. Few building owners will have the land or financial resources to provide off site solutions and the majority of new buildings will need to balance energy requirements with limited on site solutions. This will mean a significant improvement will be needed in the performance of the fabric and envelope of the majority of buildings. This thesis concentrates on software to design very low energy buildings. It proposes new accessible tools that use established modelling and simulation principles to support good, informed, low energy building design. It is not about the design of buildings to a particular set of laws or rules.

---

[11] See https://www.gov.uk/government/consultations/zero-carbon-for-new-non-domestic-buildings

[12] See http://ec.europa.eu/energy/efficiency/buildings/buildings_en.htm

3.3 Physical concepts related to low energy buildings

To understand how software may be expected to model building performance this section seeks to provide an overview of the concepts of physics that relate to energy use in buildings. A simulation allows the testing, comparison and evaluation of alternative design and technologies without the expense of creating a real prototype. Building performance simulation involves trying to predict and model real life and therefore requires a multi criterion approach (Augenbroe, 2011). Building simulation thus has a crucial role to play in the prediction of energy consumption and the optimization of building performance.

Historically humankind used their buildings to enable them to exist, with varying degrees of comfort, within potentially hostile natural environments. In architectural terms the aim of the building is to provide protection from the negative effects of climate and take advantage of the positive ones to provide as high a level of comfort and pleasure as possible. The increased use of technology and relatively cheap carbon based fuel have led to raised expectations of comfort and a move away from reliance on the fabric of the building to ameliorate the extremes of climate. This will now change with technology employed to assist in the reduction of energy demand. This can be achieved by controlling heat loss or gain via the fabric of the building and more efficient heating, cooling and ventilation systems. Highly engineered and managed solutions are needed to provide modern buildings that meet the demands of society.

A complete understanding of building behaviour can be obtained by taking into account the dynamic interactions of the building through: the occupancy, equipment and appliances, the building form and construction, the HVAC systems and the external environment (Hensen & Lamberts, 2011) as shown in Figure 3-5. All of the factors that create these interactions form the input values for energy performance simulation algorithms. The following sections discuss these parameters in greater detail.

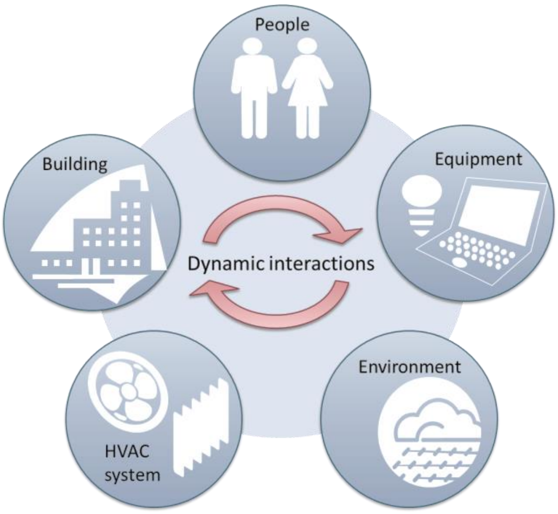


Figure 3-5 The dynamic interactions of the sub-systems in buildings

A complete understanding of building behaviour can be obtained by taking into account the dynamic interactions of people, equipment, the building, the HVAC systems and the environment (after Hensen & Lamberts, 2011).

3.3.1 Comfort conditions: thermal, visual and respiratory

Most of the energy used in a building is for the maintenance of the thermal, visual and respiratory comfort of the occupants by mitigating against the extremes of the outside environment. Goulding et al. (1992) identify the following parameters as affecting thermal comfort:

- Metabolism: the chemical reactions within the body aimed at maintaining an internal temperature of 37^{o}C. If the body can maintain this internal temperature without physiological effort then comfort will be achieved. Physiological efforts to increase heat loss include sweating to enhance evaporative losses. Physiological efforts to enhance metabolic heat generation to combat cold conditions include shivering. Because the temperature of the room is generally lower than that of the body, the body loses heat to its surroundings, thus becoming itself a significant source of heat. The amount of heat will depend upon the level of activity of the occupant.

- Clothing: the thermal resistance of different materials and quantities worn, mean that different values should be considered for different seasons.
- Room temperature: measured by a dry bulb thermometer[13] which affects heat lost from an occupant by convection.
- Relative humidity: is the amount of moisture in the air compared to the maximum that the air can "hold" at that temperature expressed as a percentage. It affects heat loss from the body by evaporation (latent heat).
- Surface temperature of partitions, expressed as the mean radiant temperature which is the average surface temperature of the space enclosure. It influences heat lost by radiation from the body, and is thus difficult to quantify as it varies according to how close the individual is to a particular surface.
- Air velocity relative to the individual: this influences the heat lost both through convection and evaporation of perspiration.

The need to achieve conditions of comfort leads to the specification of a parameter, which is typically a combination of two or more of the latter four of the thermal parameters that is then entered into BPS algorithms.

The quality of any simulation is very dependent upon the correct understanding and quantifying of these parameters. Because of the differences between individuals it is often difficult to specify precise values for comfort. Also with increased awareness of energy issues boundaries for standards of comfort are being questioned and stretched. In comparison to the knowledge regarding geometric representation and fabric/boundary properties the methods and standards for modelling user presence and actions can be regarded as ‘simplistic’ (Mahdavi, 2011, p.57).

---

[13] The dry-bulb temperature is the temperature of air measured by a thermometer exposed to the air but shielded from radiation.

Goulding et al. (1992) define three parameters for visual comfort:

- Illuminance levels: the requirement for sufficient light to perform tasks.
- Contrast: a measure of the difference in visual properties that makes an object distinguishable from other objects and the background.
- Glare: difficulty seeing in the presence of bright light.

Light control involves modifying the penetration of natural light by determining the incident flow, the amount of contrast and the luminance of windows. This is affected by the size and direction of window openings, use of blinds and shading devices. Achieving good, effective, comfortable daylighting should, in principle, reduce the dependence on electrical lighting by occupants. The need for lighting comfort results in the definition of design parameters such as the level of illumination and the glare index.

Ventilation is necessary to achieve good indoor air quality. Ventilation is typically measured in air changes per hour; this is the number of times all of the air in a space is completely exchanged with fresh air in an hour. The recommended rate of air changes can vary significantly according to the activity in the space, for instance in a general domestic room the requirement is 1, for a non-domestic kitchen it is 20 (Szokolay, 2008).

3.3.2 External environmental conditions

A building acts as a filter to modify the external climate. The response of a building to climate involves coping with effects from the sun, temperature, humidity, wind, and rainfall. These factors need to be considered at all times of the year, with the building performance providing acceptable comfort levels in all seasons.

Climate can be contrasted to weather, which is the condition of these elements and their variations over shorter periods. Climatic data informs the early design decisions and rules of thumb that can influence building form and massing. Weather data, given at short-intervals, normally hourly, is used in building simulation.

Barnaby and Crawley (2011) list the following environmental input values employed in BPS algorithms:

- Dry-bulb air temperature which is important for exterior surface convection and ventilation heat transfer calculations. This measurement is available for many areas, but it can be affected by the presence of other buildings (heat islands) and local topography.

- Humidity which is important for latent heat transfer calculations involving air movement caused by infiltration or ventilation.

- Solar irradiance, the power of the sun on a surface, both from direct and diffuse sunlight, which is important for heat gain though windows, both in terms of beneficial gains and overheating. It also affects the exterior heat balance. These data are also used to assess the suitability and predict the output of solar thermal and photovoltaic systems.

- Solar illuminance, the brightness of the sunlight (direct and diffuse), which is employed in daylight modelling.

- Sky temperature which affects the exterior surface heat balance.

- Cloud cover/sky condition is relevant to daylighting modelling.

- Wind velocity and direction information which is used in modelling external surface convection, infiltration and natural ventilation. Care should be taken with these data, observations at exposed weather stations can be unreliable for nearby sheltered sites.

- Ground temperature which is used to consider heat transfer from building elements below ground. There are limited data available at present for building simulation.

- Ground surface albedo, the diffuse reflectivity or reflecting power of a surface, which is generally only used for irradiance and illumination calculations in areas affected by the presence of snow for significant periods of time.

- Weather conditions, in particular rain, which will result in exterior surface wetting.

There are a number of factors which need to be considered in using and applying weather data files. Although the number and scope of weather recording stations have improved in recent years, the information from the nearest station may not reflect the local conditions of any site. For instance weather stations are often located at airports which can be significantly different from areas in relatively close proximity; this can be more pronounced when considering heat islands. Furthermore it is recommended for very low energy design that multi-year studies should be run, as opposed to employing a typical year, to ensure the full range of possible scenarios are explored (Barnaby & Crawley, 2011).

Building designs may also need to be assessed as to how they may function in the future with a potentially changed climate. In the UK future weather data is now being developed with the aim of allowing building designers to develop adaptation policies (Eames *et al.*, 2010).

3.3.3 Interaction of Building and Climate

There are typical, distinct, responses to three different climates that have traditionally influenced the built form (Hellman, 2001):

Cold and wet (or temperate) climates are typified by small fluctuations in temperature all year round and rainfall that can fall throughout the year. The vernacular response is to build steeply pitched roofs to enable the runoff of rain and thick walls to keep out the cold and store heat. Windows tend to be large to compensate for limited available light, with shutters or curtains frequently used to reduce heat loss.

Hot and dry climates are typified by extreme heat and negligible rainfall. The vernacular response is for buildings to be closely situated together to provide mutual shade, have small windows to reduce solar penetration and to have light colours to reflect rays from the sun. Walls are thick to absorb heat during the day and release it at night.

Hot and humid climates are typified by consistently high temperatures and levels of humidity, with considerable precipitation during part of the year. The vernacular response is for buildings to be on stilts to avoid damage by floods. Shallow sloping roofs are used to shed rain. Walls and floors are permeable to let air pass through to provide the air motion required to achieve thermal comfort by sweating in the hot humid conditions.

These vernacular responses relate mostly to the design of smaller buildings, particularly dwellings. Smaller building designs tend to be envelope or ‘skin-load’ dominated, that is the building response is closely related to the climatic conditions as outlined above. However, large projects are typically ‘internally-load’, dominated and often the need is for cooling to remove heat generated by occupants and equipment (Lévy, 2012, p.10). Thus the building designer needs to understand the physical principles involved for a particular situation and to seek appropriate ways to utilise them.

The building should, as far as possible, balance requirements for ventilation and daylight while providing thermal and moisture protection appropriate to the climatic conditions of the site.

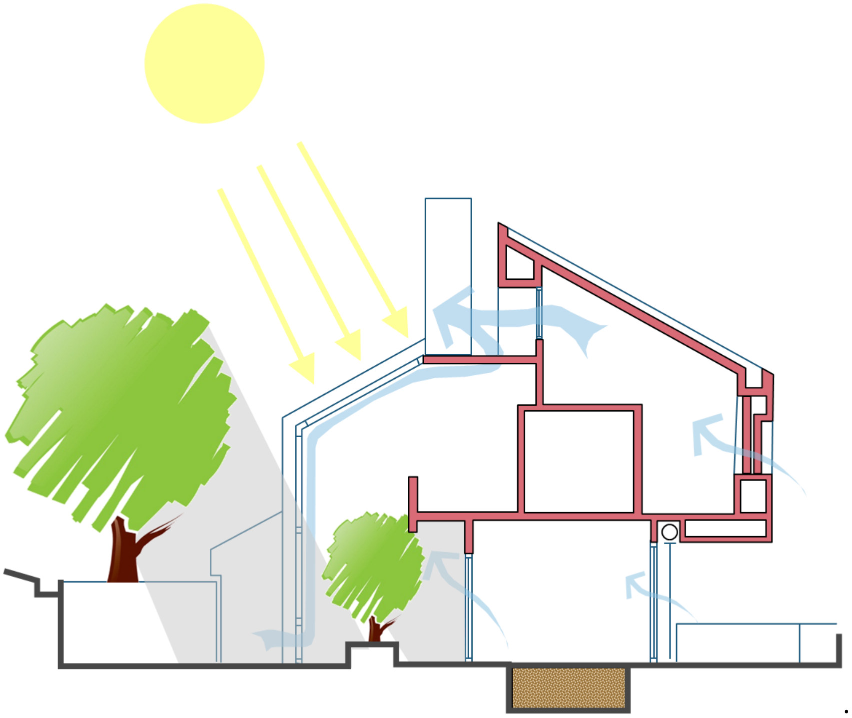


Figure 3-6 Diagram of the multiple factors that affect the indoor environment

Multiple factors, both inside and outside the building, will affect indoor comfort. They can include ventilation, daylight, solar gain, heat storage within the fabric and heat gain/loss through the building fabric and external features that can cause shadowing (after Goulding et al., 1992).

Figure 3-6 demonstrates some of the multiple factors to be considered in simulating the indoor conditions of a building. These factors include heat gains and losses through the fabric of the building, heat storage, solar gains, daylight, shadowing and ventilation. The following sections examine these factors from the viewpoint of creating a model of the building and the factors (or parameters) required for simulation software.

The fabric

The building fabric, or envelope, can be described by data relating to elements such as walls, roofs floors and windows. Such elements have properties, such as thickness, constituent materials, surface properties and appearance, all of which affect their contribution to a building, both in terms of aesthetics and performance.

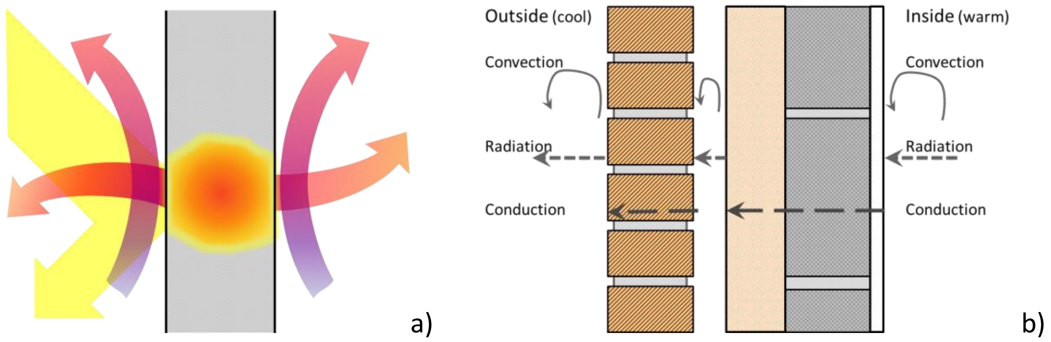


Figure 3-7 Heat transfer mechanisms through a wall section

(a) Shows a single leaf of a wall with incident solar radiation, some of which is absorbed and some reflected. The absorbed energy raises the temperature of the outside surface of the wall; some heat is lost from that surface by convection and long wave radiation and some is conducted into the wall were it is stored. The remainder of the heat is conducted through the wall to the inner surface and transmitted to the inner space by means of convection and long wave radiation.

(b) Shows the role of conduction, convection and radiation in a more complex wall with an insulated cavity (after Goulding et al., 1992).

Heat is transferred through building elements by three methods, conduction, convection and radiation, all acting simultaneously as shown in Figure 3-7 and discussed below.

Conduction is the transfer of heat through a solid via random atomic and molecular motion in response to a temperature difference. The thermal conductivity is defined as the quantity of heat passing at a steady flow through a one metre thickness of a square metre of the material in one second when the temperature difference between the faces is 1K (Kelvin). The reciprocal of thermal conductivity is thermal resistivity. The thermal resistance of a component, such as a leaf of brickwork, is the thickness of the material divided by the thermal conductivity.

Convection is the mechanism where heat is transferred to and from surfaces in contact with air, for instance in wall cavities and double glazed units. The convection heat transfer is the product of the area of the wall, the convection coefficient (also known as film coefficient) and the difference between the temperature of the air and the temperature of the surface. Convection can be affected by the roughness of the surface of the material.

Radiation is transfer of energy by electromagnetic waves. Any surface can absorb, reflect emit or transmit energy which will be dependent upon the direction in which the radiation is incident or emitted. External surfaces are exposed to solar radiation plus both long wave (infra-red) and short wave (visible) radiation exchange with surrounding surfaces. In enclosed spaces there will be radiation exchange between the different surfaces, wall to wall, wall to floor, ceiling to wall, etc. Radiation is also important in determining the heat flow across a cavity as illustrated in the wall section in Figure 3-7 b).

The thermal transmittance (also known as the U-value) is a measurement of the rate with which heat is lost through one square metre of the element with 1K temperature difference between the air temperature on each side. The U-value incorporates the thermal characteristics of each layer in the element plus the convective and radiation energy transfer at the surfaces and across any cavity. These latter are usually combined in the simplified form of standard surface and cavity resistance values. The U-value can be calculated directly from the appropriate values for surface resistance and the thickness of the various layers.

U-values can be used for a steady state calculation and this is usually adequate for heating load calculations (Spitler, 2011). With very low energy buildings the thermal storage effects are very important and more complex simulation techniques are generally required to describe the dynamic thermal behaviour of the building element. Daily variations in incident solar radiation and outdoor temperatures and the response of building elements need to be taken into account. Figure 3-8 illustrates the principles involved for opaque materials. When solar radiation strikes a material the exterior surface absorbs part of the radiation and converts it to heat. This heat is conducted through the material at a rate which depends upon the thermal diffusion characteristics of the material. The delay in the heat being transmitted through the material is termed *thermal lag* and is measured as the time difference between peak outside temperature and the peak temperature on the inside surface of an element. The ratio between the difference in the maximum and minimum temperatures on the inside to the difference on the outside is called the decrement factor.

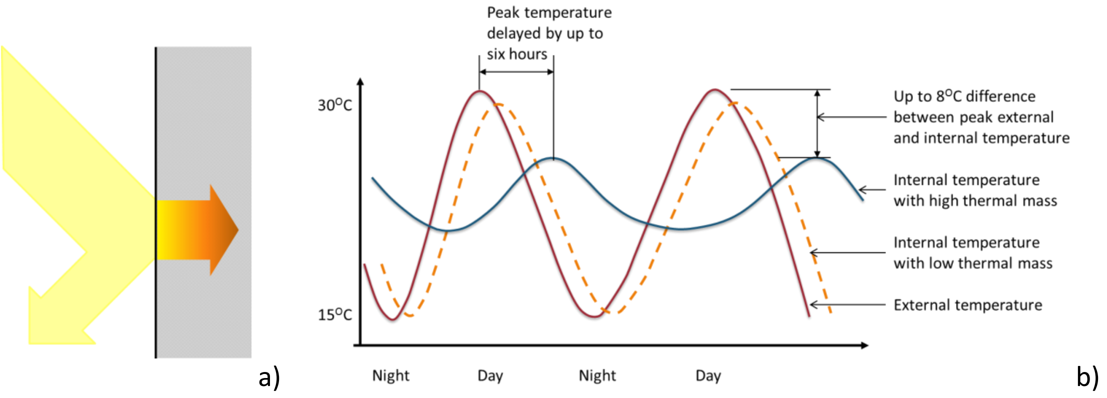


Figure 3-8 The effect of mass on thermal inertia

a) Shows solar radiation striking a surface of a dense wall and the majority of that heat conducted through the wall (after Goulding et al., 1992).

b) Shows an indicative graph of the time lag effect of thermal mass (after de Saulles, 2012).

The thermal inertia of a material is defined as the square root of the product of the thermal conductivity of the material and the volumetric heat capacity, where the latter is the product of density and specific heat capacity. The density at any point of a homogeneous object equals its total mass divided by its total volume. The specific heat capacity, often called specific heat, is the heat capacity per unit mass of a material, that is the heat required to raise the temperature of a unit mass by one degree Celsius.

Thermal capacity and inertia is an important feature of low energy buildings, elements with high values, such as concrete, can be used to store and release heat at later times. This storage potential can be employed in larger, internally loaded buildings, to store heat generated during the day with excess heat removed by ventilation overnight when the outside temperatures drop. Heat is gained by such buildings through solar gain and incidental gains from people and appliances such as computers and electric lighting. The use of night-time purging of heat by ventilation can reduce the requirement for energy intensive air-conditioning. The daily cycle of absorbing and releasing heat continues on a year-round basis and can also reduce the energy needed to keep a heavyweight building warm during the heating season. In addition to this daily cycle, thermal mass is also known to respond to effects over longer time periods. For more information on thermal mass see the Concrete Centre website[14]. Elements with lower values of thermal capacity and inertia, such as lightweight insulation typically used in timber frame buildings, will have a quick response time and may be useful for buildings with intermittent heating requirements.

Latent heat

Latent heat is the heat released or absorbed by a substance during a change of state, this can be important where the evaporation of water from a surface reduces the temperature of that surface and thus it can assist in cooling a building.

Ventilation to achieve good indoor air quality

Ventilation, needed to achieve good indoor air quality and provide any necessary cooling, is typically measured in air changes per hour, this is the number of times all of the air in a space is completely exchanged with fresh air in an hour. In cold conditions ventilation to provide these air changes can place an additional load on the heating system dependent upon the temperature difference between inside and outside. In effect energy is required to raise the cold fresh incoming air to room temperature; whilst the warm stale air that leaves the space removes an equivalent amount of energy. With low energy buildings, such as those satisfying the Passivhaus standards, air changes are often much lower and mechanical extraction with heat recovery systems employed to counteract this heating load.

In warm, and particularly in humid conditions, to improve occupant comfort, ventilation may be encouraged beyond the recommendations to maintain good air quality. This can be achieved by either mechanical and natural means or a combination of both. Natural

---

[14] http://www.concretecentre.com/technical_information/performance_and_benefits/thermal_mass.aspx

ventilation is dependent upon the position and state of openings, the building geometry and wind speed and direction.

Infiltration is unplanned ventilation through the fabric, via leakage through porous materials and building fabric junctions such as doors, windows and roof eaves. Normally a notional figure is applied to this, but with high performance buildings it can become a very significant factor.

Heat gains

Incidental heat gains are those due to occupants and equipment and vary significantly according to the use of the building and the levels of occupation. With high performance buildings the number of people and their associated activities such as cooking and using appliances can have a significant effect, often giving rise to the need for cooling. The result of any simulation is dependent upon quantifying these parameters. Often this data is given to simulation software as schedules of occupancy and is of necessity a best guess as to how the building will be used. User aspects are considered to be often under-appreciated in simulations (Hensen & Lamberts, 2011).

Solar energy can be a significant factor in determining comfortable conditions. It needs to be considered in the context of heating a building in cold climates and being excluded in warmer conditions and sometimes a combination of both. Calculation of radiation heat transfer between the sun and building surfaces involves the following (Spitler, 2011):

- Absorptance, the ratio of radiation absorbed to the radiation incident on the surface.
- Emittance, the ratio of radiation emitted by a surface to that emitted by an ideal ‘black’ body at the same temperature.
- Reflectance, the ratio of radiation reflected to the radiation incident on the surface.
- Transmittance, the ratio of radiation transmitted by a translucent surface to the radiation incident on the surface.

In terms of building materials, the degree of opacity is important. A totally opaque element, as illustrated in Figure 3-8 a), can be used to absorb solar energy during the day and radiate it at night. The colour of the surface material influences the solar collection with a dark surface being more absorbent than a lighter surface.

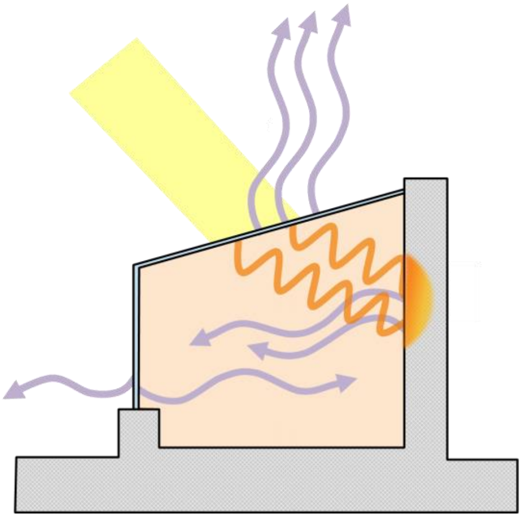


Figure 3-9 A glazed building subject to incident solar radiation

The section through a small building shows solar energy incident on a translucent surface. Part of this energy is stored by the rear wall and re-radiated out as long wave radiation (after Goulding et al., 1992).

A translucent element such as glass in a window responds to solar energy in three ways: part will be reflected; part absorbed and the remainder directly transmitted. The directly transmitted radiation will strike an internal surface and some of the radiation will be absorbed by the fabric as illustrated in Figure 3-9. The absorbed energy will heat the fabric, some will be stored and re-radiated as long wave radiation. As glass is a poor transmitter of long wave radiation (compared with short wave radiation) this energy will be trapped in the space resulting in a rise in temperature. In low energy buildings this effect can be used to heat the interior of a building, however care must be taken not to overheat the space. Control devices such as overhangs and shading devices can be employed to restrict solar gain when the sun is high in the sky, but allow penetration in the winter as illustrated in Figure 3-10.

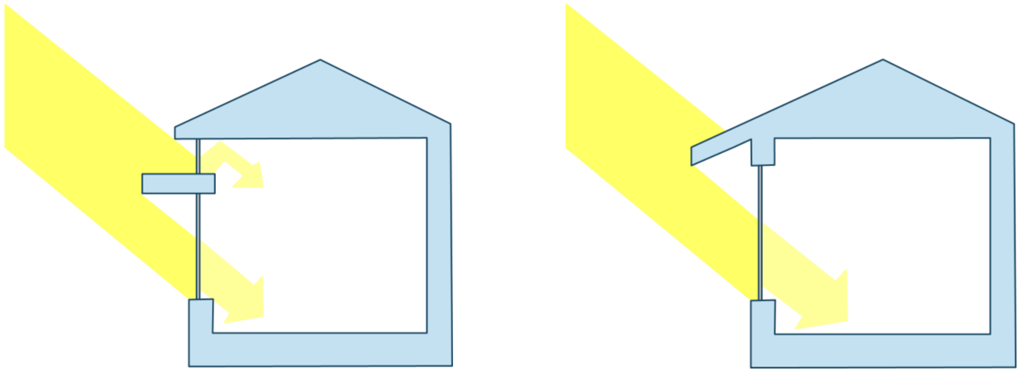


Figure 3-10 Solar shading devices

A diagrammatic section through a building showing the effect of wall thickness and shading devices on both daylighting and solar gain. In the summer the sun will be higher in the sky and more solar energy is excluded. In the winter when the sun is lower in the sky more energy is admitted into the building (after Goulding et al., 1992).

The provision of windows is as much an art as a science. They can be employed for aesthetic reasons such as framing a view but they are also have important thermal properties; they offer relatively low insulation and can be a significant source of heat loss but can also act as energy sources as discussed above. They also provide lighting for tasks and thus reduce the necessity for electric lighting. There is no commonly acknowledged method of how to assess the performance and quality of a daylighting system in terms of energy savings, glare prevention, daylight, and the view to the outside (Galasiu & Reinhart, 2008). There has been a movement in modern buildings towards smaller windows to save energy and thus remove some of the enjoyment of the space (Dyckhoff, 2011). Simulation has an important part to play in modelling to maximise on the benefits of daylighting, solar energy and shading devices.

3.4 Approaches to the design of a low energy building

The professional architectural design stages outlined in the previous chapter were sequential *waterfall methods* and partially mask the iterative holistic nature of design. Whilst the design process must be sequential for both professional (fee billing) and practical reasons (getting the project built), it is also known to be an iterative process, where a number of concepts are developed concurrently. Figure 3-11 illustrates the four concepts that an architect would deal with concurrently:

- Aesthetics: how the building looks
- The brief: the client's list of requirements, the detail can vary significantly, from a short description of what is wanted to a detailed schedule of both accommodation and standards, for instance a modern hospital
- Buildability: how the building will stand up and be built
- Environment: how the building mitigates external and internal effects to make the occupants reasonably comfortable.

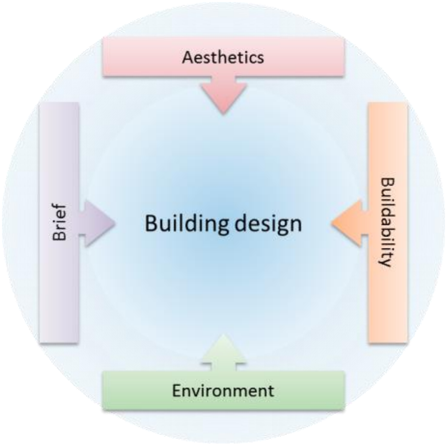


Figure 3-11 Holistic building design

The architect considers the brief (the client's requirements), the buildability (the structure and construction), the aesthetics (how it looks) and the environment (the comfort of the user) concurrently.

Architects have always considered the first three from the inception of a project. However, as discussed earlier, environmental concerns have often been considered after the design has been finalised. There are exceptions, for instance the design of an auditorium where the acoustic considerations can be a major form generator.

The optimisation of a building to use as little energy as possible could also be considered in a similar, holistic manner. Figure 3-12, illustrates the concept, at the centre is the building and the occupant, the aim is to make the users as comfortable as reasonably possible.

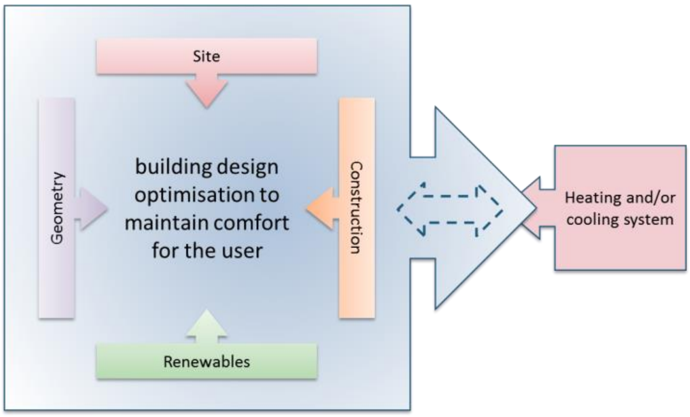


Figure 3-12 The optimization of a building design to maintain comfort conditions

Optimization of the building design should occur iteratively between: the response to the site, the proposed geometry, the building construction and renewable systems. Once the building is fully optimized, by consideration of the four parameters, then the requirement for a heating or cooling system can be assessed. If an HVAC system is required, that may then affect the geometry and construction options which will need to be re-visited.

As discussed earlier, the climate, dictated by the site location, can affect the response of the building form, especially for smaller, domestic scale projects that are envelope or skin loaded. Rules of thumb as to how the building will respond are often adequate in the early stages of design, with simple tools employed later in the detailed design stage. However, when the building is larger internal loads become very significant. With more complex building forms and varying occupancy the thermal response is less predictable and dynamic simulation is required. That is simulation that takes into account change over time (at relatively small time intervals, typically 15 minutes) and the thermal response of the building fabric (typically over weeks if there is a significant amount of thermal mass incorporated in the building). Larger buildings will typically be composed of many spaces, all of which require consideration to determine the thermal interactions between them. For example as well as heat exchange between an internal space and the exterior there will be transfer between spaces affected by the thermal properties of separating walls. Heat transfer mechanisms of conduction, convection and radiation will all be involved. Thermal capacity will also be important and hence the need for dynamic simulation. In addition energy can be transferred between spaces by ventilation.

Small buildings, especially if they are complex in form can also have multiple interactions, requiring modelling and simulation of a number of spaces. An example would be a courtyard plan, or building with a light well/atrium. The internal, semi-enclosed, space would require simulation to investigate interactions between the various parts of the building.

The building usage can affect the building form or geometry. For instance H plans are often employed for office buildings to maximise on natural daylight and natural ventilation. However the use of natural daylight becomes increasingly less effective once the building is taller than four or five stories for spaces on the internal faces close to ground level. Also the site may not permit an H form and/or there may be obstructions such as trees or buildings to affect the daylight. In hot and humid climates the use of natural ventilation (often mechanically assisted) is important and is again affected by the built form. In these instances both visualisation in 3D and simulation will aid the design decision making process.

The decision to incorporate thermal mass as part of the construction will be affected by usage, geometry and climate. It is a typical response to hot, dry climates to store heat during the day for release during the night. However, in cooler climates it may not be appropriate for buildings with intermittent usage, when a lighter construction could be considered as it can be quicker to reach acceptable temperatures after starting up a heating system. In larger buildings, that are load-dominated, thermal mass can be employed to even out diurnal temperature variations when combined with night-time cooling. However, this method requires the building form to incorporate effective natural and/or mechanical ventilation, the design of which again requires modelling in 3D and simulation.

Renewable energy, from sources such as solar radiation, wind, air-source and ground-source heat pumps can make a contribution to the energy balance in a building. However, the feasibility of employing these will be largely affected by the site location, site area and building form. Wind turbines require an area where wind can flow unimpeded, with the power generated in proportion to the area swept by the blades, which means large blades are required to generate significant power. In addition to passive heating strategies, solar energy can usefully be employed to heat water (solar thermal collectors) and generate electricity (photovoltaic panels). The positions of these devices can have a significant impact on the construction of the building and the aesthetics. For instance roof systems can be specified that are completely assembled as an integrated energy roof comprising photovoltaic panels, solar hot water and rooflights, an example is HiminZED[15]**.** Again the ability to visualise in three dimensions and simulate the output of these types of system would be valuable.

Design optimisation involves carrying out 'what if' explorations of the interdependencies as discussed above in an iterative manner. This involves manipulating the building geometry and the construction to achieve the best use of climatic conditions to achieve the optimum performance. Normally only after the building form and envelop have been optimised should the heating/cooling system be considered. Whilst passive strategies are to be encouraged, often the climate can be too extreme to be handled by such methods and some form of mechanical solution will be required. Once this has been determined there will be a requirement to re-consider the built form in the context of the mechanical solution.

Whilst the site (location) is usually fixed and leads to the determination of the current weather conditions, with the threat of climate change and the need to adopt adaptation strategies, the weather can also be thought of as a variable. This may require comparative studies on how the building design would respond to different weather scenarios.

3.4.1 Knowledge required for the design of low energy buildings

As discussed in the previous chapter, some architects may struggle with the knowledge required for the design of low energy buildings. For instance, once the location of the building project is established the architect requires knowledge such as:

- What is the typical climate for that area?
- What is the traditional building form for that type of region?
- What are the traditional building materials for that region?
- What is the potential for renewable energy?

---

[15] http://www.himinzed.com/index.html

Once the building occupancy has been set the architect would need to know:

- What are the comfort conditions/standards (thermal, ventilation and lighting) required for that building type?
- How might the occupancy vary over time?
- What regulations affect that building type (this is also affected by location)?

The above knowledge will enable the architect to make strategies decisions regarding the form, orientation and construction of the proposed building. The resulting building design will then require analysis with energy simulation software and the architect will require support regarding simulation results. Information that is needed includes:

- What are the energy standards relevant to the building type and location?
- What are appropriate energy goals for the project and parts of the project?
- How does the design performance compare with those goals?

Ultimately the building design should provide a comfortable environment. Typical advice might be:

- The need for a heating requirement.
- The need for a cooling requirement.
- Strategies to minimise or deal with those requirements.
- Strategies which could be used to maximise daylighting and minimize glare.

The above illustrates the variety and range of the type of knowledge required. They demonstrate the iterative nature of optimisation of the building for energy used/generated and the posing of ‘what if’ questions.

3.5 Discussion

The previous chapter outlined the influences affecting any proposal for new software tools and identified a number of strands. This chapter has provided more detail on the technical aspects of the problem domain; the design of low energy buildings. The concepts surrounding the proposed ‘zero carbon’ UK legislation were outlined from which the need for buildings with very low energy demands has been identified as paramount.

An overview of the physical parameters involved in relation to energy consumption in buildings has been provided and approaches to the design of low energy buildings discussed, from which three themes can be identified, these are the need for:

- Dynamic energy simulation to predict internal comfort conditions, integrated into the design process, to support the design of buildings with very low energy consumption. This has been argued in the context that the energy consumption of future buildings must considerably lower than general current practice.
- Information support to aid decision making. This has been discussed with examples of the type of knowledge required for design decisions given.
- Iterative design practices and optimisation of the building design for energy usage. This was discussed in the context of “holistic iterative design”. As stated by Gething, design attitudes need to change to achieve low energy, sustainable buildings (2012, p.17).

These three themes are employed as a basis to establish early software requirements for integrated design and simulation tools in the next two chapters. The next chapter reports on empirical work that establishes the limitations of typical software in current use. The first study was used to identify the problems associated with using a BIM and BES tool to design low energy buildings. The second study involved a group of architectural students using BES software to model and simulate the energy performance of a low energy building. It confirms many of the problems highlighted in this and the previous chapter.

Chapter 4

Empirical Studies into Software to Design Low Energy Buildings

This chapter reports empirical work employed to frame and define the research question for this thesis. The aim was to explore and describe the limitations associated with typical, current software to support iterative design processes for the reduction of building energy usage. The motivations for this study were twofold: first to gain experience in using BIM and BES software, secondly to gain in-depth understanding of the process and problems involved in carrying out thermal modelling and energy analysis and in particular devising strategies for improved energy performance. This study has been a crucial step in forming the research question for this thesis. Objectives for the chapter were:

1. Identify and analyse problems with typical, current BIM and BES software in the modelling of a low energy building.
2. Record user requirements for improved software.

Empirical work, in the form of two case studies, is reported in this chapter. The case studies were employed to gain an understanding of how technology "functions or does not function in contemporary settings" (Perry *et al.*, 2006, p.1046). This is a further exploration and focusing of the problem domain as part of discover and define phase of the Research Through Design approach of this thesis (Zimmerman & Forlizzi, 2008).

An initial explorative case study, carried out in 2010, was employed to gain insights into the process of modelling of a low energy building with BIM and BES. Understanding the context of use can provide software designers with 'novel and deep design possibilities' (Anderson, 1994, p.30). This first case study was exploratory in nature, employed to gain an understanding of the problem with "rich, qualitative data", from which tentative theories can be built (Easterbrook *et al.*, 2008, p.288). The study was instrumental in forming the research question for this thesis. Initially the study was instigated to gain an understanding of the knowledge demands for the modelling of low energy buildings. However, significant shortcomings with the software were identified. Such unexpected discoveries can be the motivation and trigger for invention (Suwa *et al.*, 2000). A similar, though more detailed, study employing the same software was subsequently reported by Somboonwit (2011) where the building form and orientation was modified to reduce the energy demands of the building. Both the work reported here, and the study by Somboonwit, included energy analysis in the conceptual stage of the building design. At this stage parameters such as orientation, building form and external materials can be manipulated or changed, in response to simulations run to estimate the energy-saving potential of these modifications, before the design becomes fixed.

A second case study involving a group of architectural students set a task to model a low energy building with BES software, again in the early conceptual design stage, is outlined. This larger study had a number of purposes; firstly, to confirm some of the findings of the first study, to begin to build a coherent picture of the problem domain (Easterbrook *et al.*, 2008) and to elicit early user requirements for the design for new software (Sommerville & Sawyer, 1997). A survey was employed to gather qualitative and quantitative data from the students. This data was used to elicit requirements as to how software might be better designed to enable the holistic design of low energy buildings. These user requirements have been employed as a means to define, focus and synthesize responses into themes that are developed later in the thesis.

4.1 Case study 1– Modelling a small building using BIM and BES software

Some of the problems associated with the use of BIM and BES software can be illustrated through their application to the design of a small building. This explorative case study, carried out in the first six months of the thesis, was employed to gain insights into modelling software and the challenges faced by architects in the design of low energy buildings. The data collected was qualitative.

The steps taken in the study were:

1. A building model was created in BIM software, consisting of a number of rooms of varying size and function. Although the model was simple there was enough complexity to create a number of thermal zones, volumes of thermally

consistent air, as shown in Figure 4-1. The form was also sufficiently complex to explore the effect of varying volumes, cross sections, roof forms and window positions. This ‘purposive’ example was used as a typical, relevant case (Easterbrook *et al.*, 2008, p.296).

2. The building model was then exported in the form of a gbXML file and imported into BES software.

3. The energy required to run the building was then obtained from simulations in BES software, building parameters such as the proportion of fenestration, building fabric (materials) and ventilation rates were then modified to attempt to reduce the predicted energy needs. The building model, modified as a result of this optimization, was then exported from the BES software as gbXML, however it was not possible to import this model into the BIM software.

4. Qualitative data relating to the experience of using the two types of software was then collected and analysed.

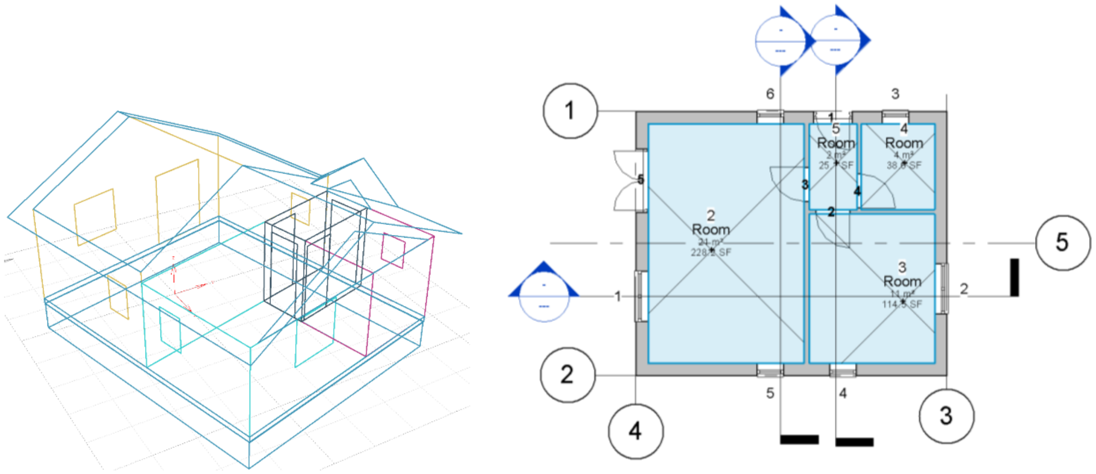


Figure 4-1 A model and plan of a small building employed in the first case study

The building model was created in BIM software and consisted of a number of rooms of varying size and function.

The software used for this example was:

- Autodesk Revit Architecture 2011, Building Information Modelling software.
- Autodesk Ecotect Analysis 2011, Building Energy Simulation software.

Software from one company, AutoDesk was used, because:

- Autodesk is the market leader for AEC software (Revelation Research LLP, 2009).
- Ecotect is reported to be user-friendly to architects and provides a reasonable level of analysis (Attia *et al.*, 2009; Thoo, 2008; Crawley *et al.*, 2008).

The alternative combination of Graphisoft's ArchiCAD and EcoDesigner were considered, however, EcoDesigner does not provide as wide a range of functions as Ecotect. The case study also had to be scoped – learning BIM and energy analysis software is non-trivial and time-consuming and so it was restricted to one BIM and BES package.

4.1.1 Problems associated with the design of a small low energy building

The following sections describe the key findings from this study.

Issues associated with interoperability of data inhibited the use of iterative building design processes

Figure 4-2 shows the process of data transfer from the BIM software to the energy analysis software. Different methods of modelling are required in the different types of software; BIM assembles 'objects' whereas energy analysis software requires the building to be modelled as 3D 'zones'. These can be extracted from the BIM in the gbXML format by a semi-automatic process with the zones derived from enclosing building objects. This can result in the efficient exchange of geometric data being problematic. In this example this was shown by the inconsistent geometry transferred between the software packages; for example a roof space, which is a significant thermal zone, was not transferred from the BIM to the energy analysis software which affected the thermal analysis. In addition, data relating to materials were lost or over-written on transferring the model between the software and had to be re-entered manually. The need for manual repair of geometries and to re-enter data can potentially lead to discrepancies and resulting errors.

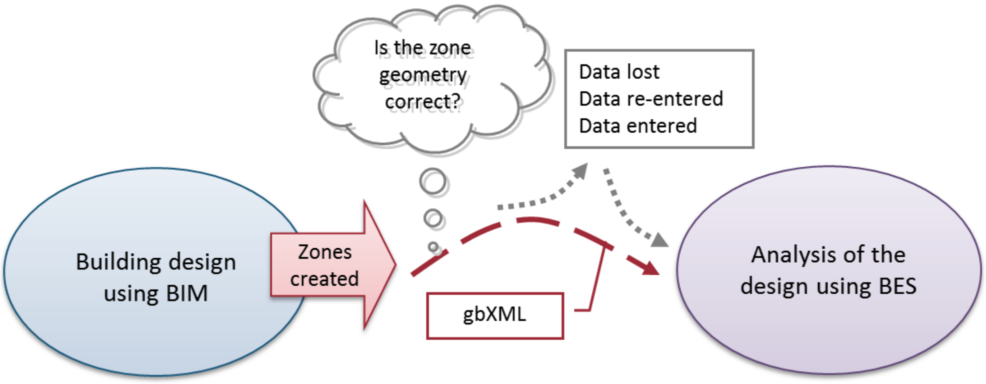


Figure 4-2 Transfer of data from BIM software to BES software

The diagram shows a gbXML file of a building design exported from BIM software and imported into BES software. The model geometry was found to be inaccurate and data relating to material properties was lost or over-written.

The issues of poor interoperability of data inhibited the use of an iterative building design process, as illustrated in Figure 4-3. Some data could be moved from the BIM to the energy analysis software in the form of the gbXML mesh. However, if the building is then modified in the thermal analysis software in order to improve energy performance, for instance by altering the size and position of windows, these changes could not be transferred back to the BIM environment. Any changes had to be entered manually, again giving rise to the possibility of errors. Also, because the process is time-consuming, it hinders the iterative approach necessary for the design of inovative low carbon buildings.

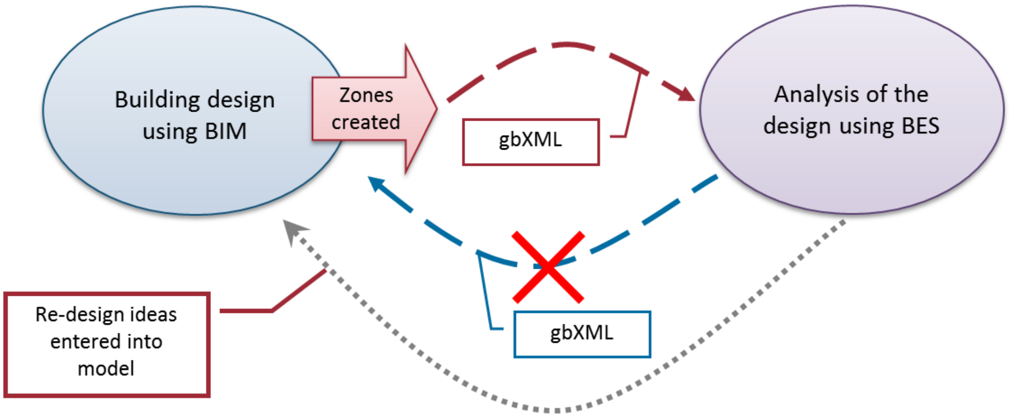


Figure 4-3 The current process of energy analysis – an obstacle to iterative design

The was no method to import a gbXML file back to the BIM software. Any changes to the design in the BES software had to be entered manually, giving rise to potential errors.

Difficulties encountered in modifying the building design to achieve low energy targets

Specific difficulties encountered in modifying the building design were associated with building materials: the standard material libraries, (containing wall, roof, floor construction details) in both design and analysis software were dated in term of levels of insulation. High levels of insulation can be crucial to low energy design. The lack of standard high performance materials in the libraries makes designing low cenergy buildings more difficult. Although it is possible to create new components, this takes time and experience. It was also difficult to make global changes by selecting groups of building elements. Geometry was difficult to manipulate in the BES software, compared with the BIM environment. In particular, selection of nodes and edges to enlarge components such as windows was tricky.

Understanding and confidence in the energy data produced was limited. The data produced by the energy analysis software were very detailed, consisting of a large number of graphs and tables of data. It was difficult to interpret this numerical data and relate the information to the building design expressed as a 3D model. There was no guidance to inform decisions regarding appropriate design modifications and optimisation.

Visualisation of zone meshes and data is very important

Visualisation is crucial, for instance, to confirm 'is the mesh extracted from the BIM model correct?' Also seeing clusters of information is also important to enable holistic design. For example: graphically seeing where significant heat loss occurs, ventilation rates and daylight factors, alongside the 3D model. Only one set of data could be viewed at a time, for instance, monthly heating loads.

The effect of inconsistent interfaces on software learning time

Inconsistent interfaces between the BIM and BES packages lead to a reduction in the predictability of key aspects of modelling and hence resulted in it taking a longer time to learn how to use the software.

4.1.2 Summary

This study suggests that in order to design buildings to very low energy standards architects need better tools than exist currently. A number of issues were identified; however the major problem is with the differing methods of modelling. BIM has been developed around the concept of structured data, where building elements are 'intelligent objects'. This method of modelling is primarily about objects such as walls, windows, roofs, floors that form an enclosed space. If a door is added to a building model, data is then contained within the model describing the door: material, size, manufacturer, etc. Thermal modelling, however, requires the building to be divided into 'zones' which describe environmentally consistent volumes. BIM 3D meshes tend to be complex, recording items like door handles with detailed geometry, whereas zone meshes need to be simple. These different methods of modelling the building design result in poor interoperability and thus inhibit iterative design

The next case study involving a group of students was employed to confirm some of the findings of the first study and elicit user software requirements. It was not possible to completely replicate all of the stages in the first study as will be discussed in the next section.

4.2 Case study 2 – Student experience with modelling a building using BES software

This second, larger, case study involved a group of 55 architectural students. The study was conducted with students in their final undergraduate year and on a taught MA programme at the School of Architecture at the University of Liverpool. The students were taking an elective module, *Modelling the Environmental Performance of Buildings*. The undergraduate students were due to qualify as practicing architects when the proposed policies on zero carbon domestic buildings become a legal requirement. As design students all participants should be able to apply design principles when providing opinions on how the software might be better designed.

The students were asked to investigate the performance of a building more complex than that used in the initial study. This provided a deeper understanding of issues involved in using such software, such as the presence of circulation spaces, multiple stories and to provide opportunities for more varied construction types. The building study consisted of a two storey accommodation block (motel) with a pitched roof, as shown in Figure 4-4. The accommodation consisted of 20 double rooms with en suite bathrooms on each floor; 10 rooms each side of a central corridor, plus some ancillary service spaces. Strategies for achieving optimum performance were to be investigated at two climatically diverse locations, Munich and Sydney, where different problems might be expected, for instance overcooling in Munich and overheating in Sydney. The objectives of the project were:

1. To achieve satisfactory thermal comfort in Winter and Summer whilst minimising the consumption of energy and emission of carbon dioxide.
2. To ensure the provision of an adequate supply of domestic hot water heated by solar energy.
3. To ensure the provision of adequate electrical energy generated by solar radiation.

The project brief can be found in Appendix 2.

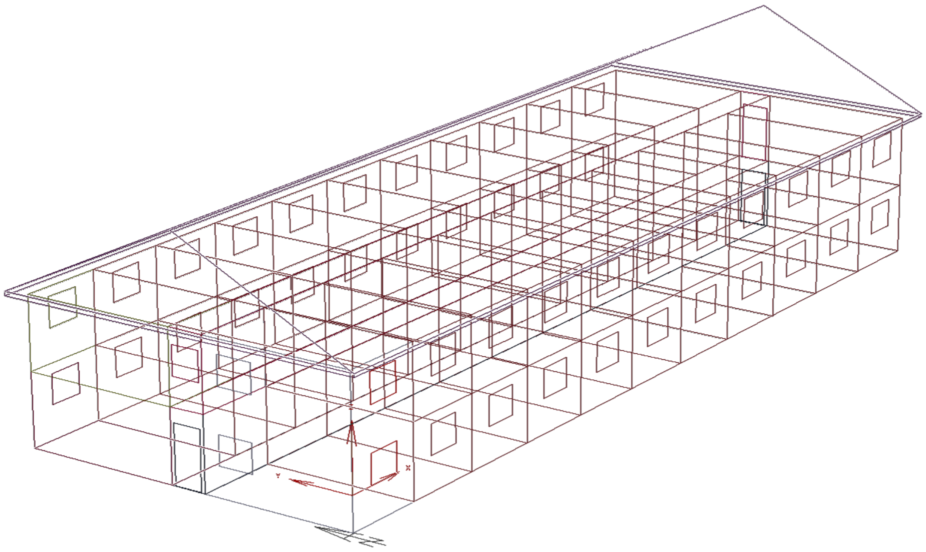


Figure 4-4 A thermal zone model of the building used in the second case study

The model of a motel is comprised of thermal zones, employed in a student study concerned with design strategies for a low energy building.

4.2.1 Survey of students experiences and opinions

Following the modelling exercise, a survey was employed to gather qualitative and quantitative data from the students. The aim of the survey was firstly, to confirm the findings from the earlier case study, and in addition to elicit suggestions as to how software might be better designed to enable the holistic design of low energy buildings. This section describes the methodology for the survey. It outlines the aims, the rationale for the sample, the design of the questions, discusses the results of the survey and finally conclusions are drawn.

Aim

The aim was stated to the students at the beginning of the survey as recommended by Oppenheim (1992).

The survey is to support a research project into the design of improved thermal modelling software. The aim is to establish the deficiencies of current software, test attitudes to *possible alternative approaches to improving software and to solicit any additional suggestions from you.*

This aim was broken down into a number of variables to be tested based on the findings of the earlier case study, plus the requirements of the student project brief. The survey, provided in Appendix 3 was structured with questions grouped in sections as follows:

1. **Previous computer experience** - to establish the student's level of experience in using computers. This is important as background information; it was expected to establish that these students are competent computer users with experience in 3D modelling and so able to provide informed opinions.

2. **Creation of the thermal zone model** – to establish how easy it was for the student to create a zone model and how the process might be improved.

3. **Establishing performance criteria** – to measure how well the software assisted in the definition of performance criteria and to seek suggestions as to how it might be improved.

4. **Interpretation and implementation of energy analysis data** - to establish how useful the energy analysis data provided by the thermal simulation software was found to be, how easy it was to use this information as part of the process to reduce the predicted energy demand of a design and to seek suggestions as to how data visualisation might be improved to assist holistic decision making.

5. **Modifying the construction** – to measure how easy it was to apply an iterative design procedure, to reduce energy demand by making systematic modifications to the constructional details.

6. **The appearance of the building** – to seek opinions on how the software might be improved to facilitate design decisions to be made by balancing both the energy and aesthetic aspects.

7. **Using the software** - to establish how the student learnt the software and found information relating to the project. Additionally questions were used to establish views by the students as to how the low energy design process might be improved

with the use of computerised support systems, such as expert and decision support systems.

8. **Personal information** - this was used to differentiate between two groups of students taking the module. Although it was a third year elective, it was also taken by MA students, who were in the main from overseas. There was concern about differing levels of technical knowledge, cultural and language issues influencing their responses. It was also used to ask for volunteers to take part in a focus group or possible future surveys.

This survey was intended to confirm the findings from the earlier case study and elicit early software requirements. Figure 4-5 illustrates how the question sections above map with the requirements and the findings from the earlier case study. Sections 2-5 related to the experiences of the students from completing their assignment. Sections 1- 7 were all used to establish the requirements and gathered opinions that extended beyond the specifics of the project. Sections 2-7 mapped onto the first case study as follows:

- Altering the building design to achieve low carbon was not easy; this is covered in sections 2-5.
- Understanding and feeling confident about the energy data produced was difficult; this is covered in section 4.
- Visualisation of meshes and data is very important to enable the efficient application of the information; this is covered in sections 2 and 4.
- Inconsistent interfaces increase the required software learning time; this is covered in section 7.

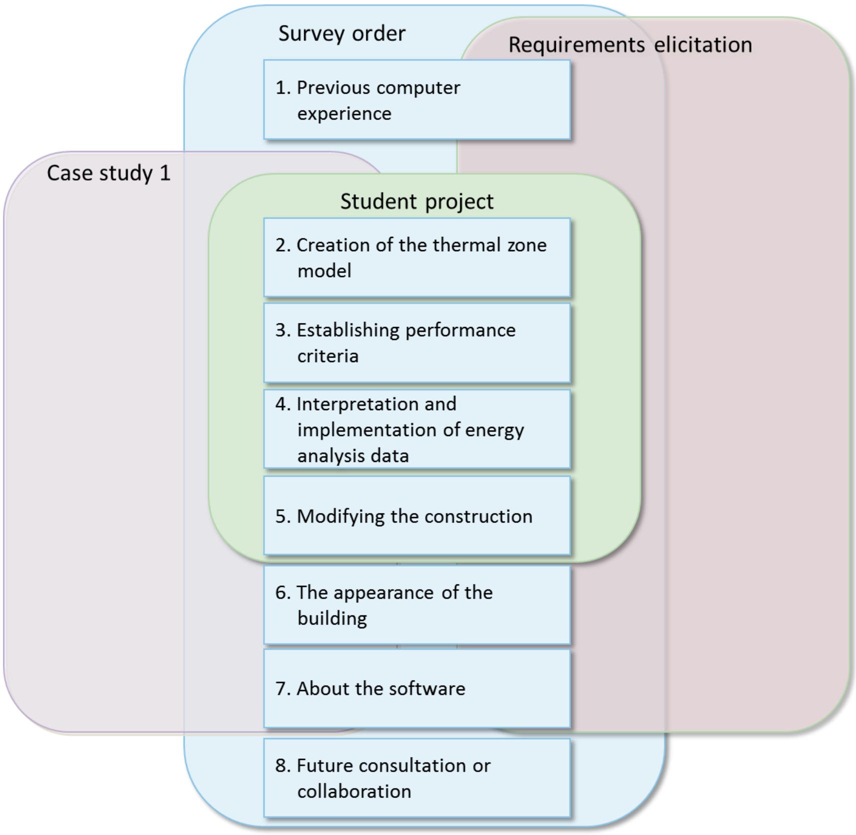


Figure 4-5 Mapping of the student survey with the earlier case study

Sections 2-5 related to the students experiences of the students from completing their assignment. Sections 1- 7 were employed to establish the requirements. Sections 2-7 mapped onto the first case study.

Issues of interoperability of data transfer between BIM and BES software packages, inhibiting an iterative building design process, was not investigated for two reasons. Firstly, it would have added another layer of complexity to the project, as it would require the students to learn a complex BIM system which would have required more time than was allowed for this module. Secondly the limited interoperability is already recognised (Hitchcock & Wong, 2011; Jardim-Goncalves & Grilo, 2010; Steel *et al.*, 2010; Eastman *et al.*, 2010; Ferrari *et al.*, 2010) and was not considered to need further corroboration[16].

Initially it was intended to ask the students to evaluate a number of thermal simulation packages. However, following an evaluation of alternative software packages, it was concluded that these alternatives could not be learned easily or quickly by non-experts. This meant that the students would require a higher level of support than could reasonably be provided within the scope of the module and the allocation of more time than was allowed for the practical element of the module. Ecotect, used in the first case study, was selected as the majority of students had some experience of this software in earlier years of the course. It is generally considered as easier for designers learn and use than most alternatives (Attia *et al.*, 2009; Schlueter & Thesseling, 2009; Crawley *et al.*, 2008).

The survey sample

A judgement was made that students would be a rich source of opinions. Many will become practicing architects when the proposed zero carbon policies on domestic buildings become a legal requirement. As a group they have all been taught some of the principles of low carbon building design and have some hands-on experience of environmental modelling software. *Judgment sampling* is a common non-probability method, based on the opinion of an expert (StatPac Inc, 2010). It can also be used in the initial stages of requirements elicitation (Rogers *et al.*, 2011). As design students they should be able to apply design principles when providing opinions on how the software might be better designed.

Professor Oldham of the University of Liverpool offered to collaborate with this research. The elective module, “Modelling the Environmental Performance of Buildings”, was taken by 55 third year architectural and MA students. The module covers the acoustic, thermal, ventialtion and lighting modelling of buildings, the knowledge and experience gained by the students in this module means that they could supply highly relevant, informed, opinions and suggestions as to possible improvements in the software. A high level of response was expected as taking part in the survey formed a small element of the formal assessment of the module.

---

[16] The first case study was carried out in the early part of 2010, before these publications appeared.

This is a non-probability sample, rather than a tool for population measurement. The results were examined for internally consistent relationships of opinions of software requirements. It was not meant to be a representative sample (Oppenheim, 1992) of practicing architects and would not be used to draw conclusions for the architectural profession. Surveys that involve a non-probability sample are not considered externally valid and there is no way of measuring their bias or sampling error (StatPac Inc, 2010).

Consent is a necessity for any research dealing with human subjects. The survey sample are students at the University of Liverpool so consent was dealt with by the Ethics committee of that institution.

Survey design and question types

The survey was designed to be delivered online using the University of Liverpool's course management tool, Blackboard. Using this online tool has a number of advantages:

- Easy to administrate, track respondents, fast to deliver and low cost.
- Data collection and analysis is computerised.
- Less evaluation anxiety, the students can complete at their leisure and in comfortable surroundings.
- A standard design can be used which means that the layout is clear and presentation consistent.

The main disadvantage is that no interviewer is present to clarify questions or issues (Survey Monkey, 2010).

The question sequence started with more general questions relating to the experience of the students. The middle section contained questions specific to the use of the software arranged in the same order that the students would have encountered its functions whilst completing the project. Finally, the survey concluded with more personal questions, in particular the willingness of students to take part in further research and provision of contact details.

The clarity of questions was considered important and every effort was made to avoid ambiguity. The survey was discussed at length with Professor Oldham with subsequent re-fining and re-wording of questions. The survey was initially piloted with 5 students with the following adjustments made in response to their experience and the running of the survey system:

- A simple, but potentially, useful question was suggested and added - 'Rank in order of difficulty the tasks you found hardest in this project'.
- Copying and pasting from Word applications gave rise to stylesheet mark-up appearing in the spreadsheet results making them difficult to analyse. Consequently, the survey form was rebuilt and the students asked not to copy and paste from other applications.
- The decision to leave many of the questions as 5-point rating scales (see discussion later) was vindicated, one student suggested an even longer scale, but this was discounted on the grounds of being time-consuming to analyse and unlikely to add any significant information.

To provide interest the survey contained a mix of open and closed questions. The majority were closed, with selection from a list of prescribed choices. This enabled quick response and ease of quantification (Oppenheim, 1992). The closed questions with multiple option responses were used to gather attitudes and opinions. Initially the majority of the questions in the questionnaire were designed with bipolar five-point rating scale, used to allow discrimination by the respondents, composed of an equal number of positive and negative labels, with a middle neutral area (Frary, 1996) as illustrated in Figure 4-6. However, following discussions with Professor Paul Garthewaite, from the Mathematics and Statistics Department of the Open University, this was revised. Unlike Likert scales, which are used to measure attitude in populations (Oppenheim, 1992), the responses were not going to be rated or aggregated into a score. Instead, it was planned to handle and report each variable separately. Professor Garthewaite advised simplifying the survey by moving some questions towards a binary response of 'Yes' or 'No', to enable quicker analysis and to reduce selection fatigue and acquiescence bias by students. This question type was used for background information, for instance the number of students who felt confident in using computers. However, binary or dichotomous responses were not considered adequate for all questions. Trichotomous choices were used to give students a slightly wider choice from 'Yes', 'No' or

‘Not sure’, for instance, to express an opinion on confidence in the results of the thermal simulation. Trichotomous choices were also used to test opinions on features of the software, for instance on the use of Passive Gains breakdown analysis a choice of ‘Not used’, ‘Useful’ and ‘Very useful’ was provided.

However, five point questions were used where it was considered important to measure more accurately opinions and allow respondents to express their feelings more fully (Preston & Colman, 2000). This was considered important when measuring attitudes as part of requirements elicitation, for instance, on the possible development of thermal analysis software integrated with conventional 3D modelling software. The five point categories were listed from the lower level to the higher in a left-to-right order. A bipolar five-point rating scale was used to allow sufficient discrimination, composed of an equal number of positive and negative labels, with a middle neutral area (Frary, 1996). This use of a balanced keying (an equal number of positive and negative statements) was used to obviate the problem of acquiescence bias reported with the use of rating scales (Survey Monkey, 2010).

How important do you think the availability of thermal analysis software integrated with conventional 3D modelling software might be for enabling the design of aesthetically pleasing low energy building?				
Not important	Little importance	Neutral opinion	Important	Very important

Figure 4-6 An example of a five-point scales employed in the survey

Open questions were used less frequently as they can take longer to analyse. However, they can also be a rich source of qualitative data. They were located at the end of sections to enable the respondent to elaborate on concepts raised by the preceding questions (Oppenheim, 1992). These were all marked as optional as it can be difficult for respondents to find something else to say and they would take time to fill (Survey Monkey, 2010).

4.2.2 Results from the student survey

As discussed earlier this survey was designed to fulfil two purposes, confirmation of some of the findings from the earlier preliminary case study and also to elicit requirements for the design of new software. Requirements were employed as a means to synthesize the qualitative data collected from the users (students) of the software. The requirements section covers a wider range of questions than the confirmation of the case study. As discussed earlier, the majority of the questions are closed (multiple selection) with possible requirements suggested to the students as to how new software might be designed. This list of requirements were drawn up as a result of the experience of using software in the initial case study. The open questions were provided to allow free or unrestrained responses.

The results were analysed on responses from 52 students. Of the 55 students registered for the module, 2 had ‘dropped out’; 53 responses were submitted, one respondent left all of the questions un-answered. The majority of the students [92%] spent over 20 minutes on the survey, with the average time spent being 41 minutes. In addition, there were positive, and at time lengthy, responses to the optional open questions, as discussed later. This suggests that the students took time to consider and answer the questions thoughtfully and the results could be considered to have a high level of validity.

This section is arranged in the order of the groups of questions the survey; the results are given and discussed both in terms of confirmation of the first case study and elicitation of requirements for each group of questions.

Software requirements have been arrived at by two methods. Firstly they were suggested to the students through the use of closed questions. These questions were arrived at from experience of using the software in the first case study and in consultation with Professor Oldham. An example is *would you like to be able to create and then export the model from conventional building modelling software*? Where questions of this type have been used to confirm requirements, the result is labelled *(RN-c)* where *R* stands for Requirement, *N* is the number and *c* stands for confirmed.

Requirements have also been deduced from responses to the open questions. Representative statements made by the students are reproduced to support the discussion, the complete set of responses are given in Appendix 3. The statements are labelled *(RN-d)*, the *d* relates requirements that have been deduced. The requirements are compiled into a list at the end of each section labelled *RN* and are then organised into themes at the end of the chapter.

Previous computer experience

As a cohort, the students considered themselves to be confident in using computers [96%] and with modelling in three dimensions [87%]. All of the students reported using at least one type of building design modelling software [100%] with many being able to use two or more [63%] and some with three or more [29%]. The most popular software was Sketchup [92%], with AutoCAD being the next most popular. BIM, such as Revit [15%] and Bentley Microstation [6%], were less popular. The use of software to carry out thermal analysis before taking this module was limited [31%]. The expertise reported validated the opinion that the students would be an authoritative group from which to elicit opinions on requirements and software design, rather than practicing architects whose skills in using, and hence understanding, many of the principles in modelling software would be less uniform or guaranteed. In addition, the majority [81%] considered themselves to have average or above knowledge of low energy design before taking the module.

Creation of the thermal zone model

Few of students found the creation of the zone model difficult [12%] and the majority ranked it the least difficult task in the project [69%]. This correlates with their good modelling skills. However, just over half [52%] found zone modelling more difficult than using other 3D modelling or CAD software. The majority of the students [77%] would like to be able to create and then export the model from conventional building modelling software. (*R1-c*)

There was a good response [63%] to the optional, open, question asking for suggestions on ways that the zone modelling could be improved. In general they voiced frustration in the lack of sophistication in the modelling tools provided by the software, as evident from statements[17] such as:

---

[17] The responses from students are given as entered and not corrected.

> *Dimensioning of zone boundaries was quite difficult…..*(*R2-d*)
>
> *Zone modelling could be improved to be more dynamic…..*(*R2-d*)
>
> *Making it more explorable in terms of being able to grab zones, windows and objects and move them with a snap tool helping you position them to other nodes.* (*R2-d*)
>
> *Change parameters by right clicking* (*R2-d*)
>
> *I think a view-history box, like the one you see on adobe photoshop, would be very useful. Allowing you to revert easily to a previous design* (*R2-d*)
>
> *Hot keys?* (*R2-d*)
>
> *Ecotect basic layout could be set out to be more user friendly* (*R2-d*)

A particular area of concern was the creation of adjacent zones and materials, with the students suggesting:

> *Software could become more intelligent on how it handles adjoining zones. e.g. Floor and ceiling becoming one element* (*R2-d*)
>
> *There were issues regarding surfaces between zones where differing materials conflicted eg. a plaster suspended ceiling ground floor clashed with concrete slab construction* (*R3-d*)
>
> *Accurate modelling, ie realistic thickness of wall and floor slab and ceiling* (*R3-d*)

There was also concern regarding how the software dealt with zone heights, as illustrated by:

> *Be able to put all three X,Y and Z dimensions rather than just drawing X and Y dimensions and then changing Z after to change the height* (*R2-d*)
>
> *When drawing the zones out, the default extrusion or z value seemed to always be 2400mm. I think it would make things easier if the zone was drew like a flat plane similar to sketchup then an extrusion can be done by selecting the surface, rather than currently trying to select the floor and change the z value* (*R2-d*)

A number of the students re-iterated the desire to import models, with the following being typical:

> *Allow importing of models from programs such as sketchup and autocad architecture* (*R1-d*)

These results confirm that the software, although considered to be one of the most 'architect friendly' tools (Attia *et al.*, 2009; Crawley *et al.*, 2008), does not have the sophistication of other building design software, with the geometry difficult to manipulate. However, the students found designing using the concept of zones reasonably straightforward.

Requirements confirmed by the closed questions and deduced from the open questions relating to creation of the thermal zone model discussed the need for:

R1. The ability to move models between design and analysis software (confirmed and deduced)

R2. More intuitive modelling techniques as found in design software (deduced)

R3. More complex 'realistic' modelling techniques in simulation software (deduced)

Establishing performance criteria

The students had been asked, as part of their project, to establish performance requirements for their design. This involved setting comfort standards such as acceptable room temperatures and ventilation rates; and estimating the volume and setting temperature levels of domestic hot water and electrical power loads. It can be seen from Figure 4-7 that this involved consulting a variety of sources, in addition to the software, with the most frequently used being the Internet [67%] and fellow students being the next most frequent. The majority of the students [58%] stated that they used the software defaults (*R4-d*).

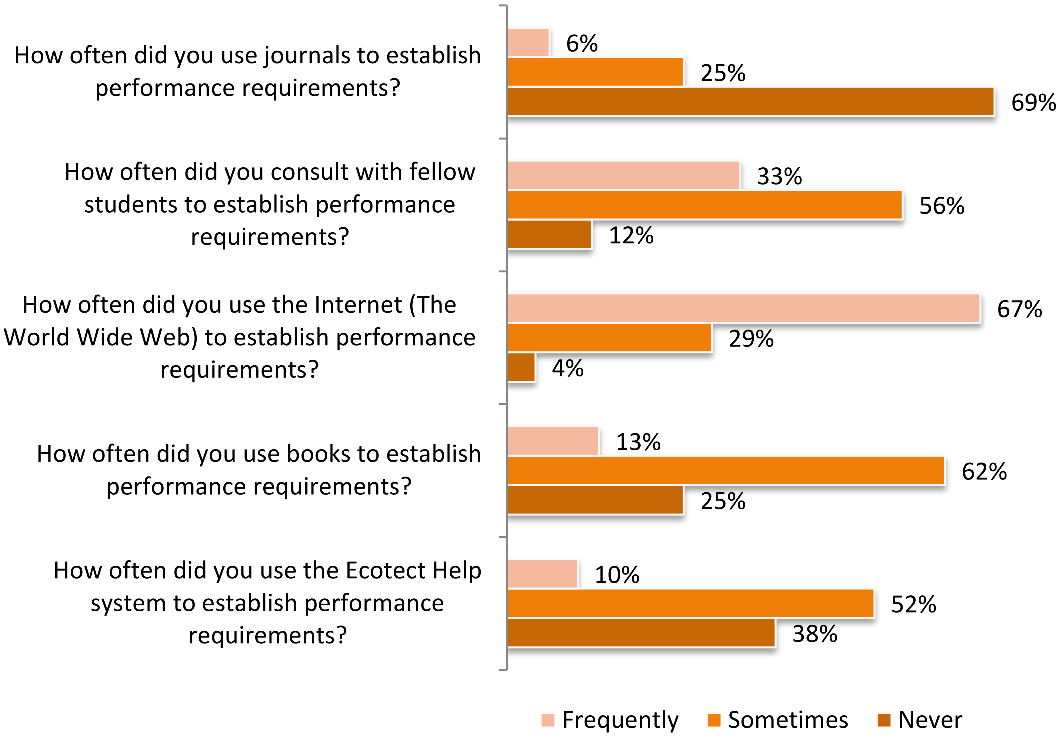


Figure 4-7 Survey results: information sources

The graph illustrates the information sources employed by the students to set performance criteria.

A range of lowest bedroom temperatures for comfort were reported from 16°C to 23 °C with 18 °C being the most frequently used [63%]. A wider range of highest bedroom temperatures for comfort were reported from 21°C to a rather high 32 °C with 26 °C being the most frequently used [42%]. The total energy requirement to heat the domestic hot water and the total electrical energy required for the year, estimated and reported by the students, resulted in a wide, and inconsistent, range of values.

There was a low response [21%] to the open question on how software might be improved to assist in establishing performance criteria. The responses were, however, illustrative of the difficulties the students experienced with both numerical calculations and finding information.

> *Coming from not a particularly physics or mathematical background I found myself slightly confused with some of the calculations I did for myself. I got confused with*

> *units. If you were able to type in the numbers, ecotect explained how to generate the numbers and then did the calculation for you, it might perhaps be easier.* (*R5-d*) (*R6-d*)
>
> *Could list potential appliances and give some basic information such as wattage/ temperature/ litres of water used, making it quicker to do personal calculations.* (*R5-d*) (*R6-d*)

These results illustrate the difficulties the students experienced in setting performance standards for low energy buildings; in general they were choosing temperature in a mid range, 18 to 26 °C. In the future, with energy usage being restrained, it may be necessary to compromise on previous standards such as ideal higher and lower indoor comfort temperatures (Lane, 2011). The reliance by the students on software defaults is an area of concern, as values used as defaults can often be set by programmers, rather than users. The value used as the default can often be arbitrary, for instance, the lowest/highest value or those used on out-dated standards. A requirement can therefore be deduced: the values of default settings such as temperatures, ventilation rates, need to be made apparent explicitly. (*R4-d*)

The problems experienced by the students in setting energy requirements, as evidenced by wildly differing numbers, and reinforced by replies from the open question given above was also of concern. Architectural students are often perceived to have difficulties with handling numeric data. A study of architectural education in 2002 found that this is a common trait with architectural students (in the UK at least). In the survey of architectural educators it was reported that they believe there exists a "*students' predisposition against numerical knowledge and calculation*" (Estrada, 2002, p.231). It is not necessarily appropriate to criticise students for a lack of understanding, but rather to accept that that architects handle data in a different way from technologists or engineers (Attia *et al.*, 2009). Further requirements can be deduced from this data: the need for a knowledge (*R5-d*) and calculation (*R6-d*) support system with a strong emphasis on visual display methods (*R7-d*).

Requirements confirmed by the closed questions and deduced from the open questions relating to establishing performance criteria, with the need for:

R4. Values used in simulations to be made explicit (deduced)

R5. The provision of a knowledge support system (deduced)

R6. The facility for calculation support (deduced)

R7. The display of data in an manner appropriate for a designer (deduced)

Interpretation and implementation of energy analysis data

This set of questions sought to establish how useful the energy analysis data provided by the thermal simulation software was found to be and how easy it was to use this information as part of the process to reduce the predicted energy demand of a design. It also asked for suggestions as to how data visualisation might be improved to assist holistic decision making.

There are various standards which set targets for the energy consumption of buildings. For example, the Passivhaus standard requires that the total energy demand for space heating and cooling is less than 15 kWh/m^2 per year (Nicholls, 2008). This value corresponds to a very energy efficient building and could be used to help to assess the relative performance of a design. The majority of the students [90%] said that they would find it useful to have an energy target, displayed by the software alongside the results, to act as a target for the building thermal design (*R8-c*).

The solar exposure calculation feature provided by the software was rated as at least adequate by most of the students [90%], many [87%] would like it enhanced by the ability to 'place' and visualise solar collectors for hot water and photo voltaic panels for electricity generation on their model together with the option to display their output (*R9-c*). There was an open question on how the software could have assisted more in determining potential for renewable energy provision. There was a consensus regarding renewable energy equipment, illustrated by comments such as:

> *Maybe a walk-though guide to applying renewable energy equipment*. (*R9-d*)

> *Maybe if it has physical solar collectors and wind turbines maybe even as far as ground source heat pump systems, so you could determine which one to use for a particular climate.* (*R9-d*)

> *Have renewable energy systems available to edit like materials.* (*R9-d*)

Ecotect offers the option of examining a large number of parameters obtained from energy simulations in the form of graphs or tables. The responses from the students confirmed that some are significantly more useful than others. It can be seen from Figure 4-8 that the students relied primarily on three types of analysis, *Monthly loads/discomfort* [98%], *Passive gains breakdown* [79%] and the *Hourly temperature profile* [69%] to support decision making in their project.

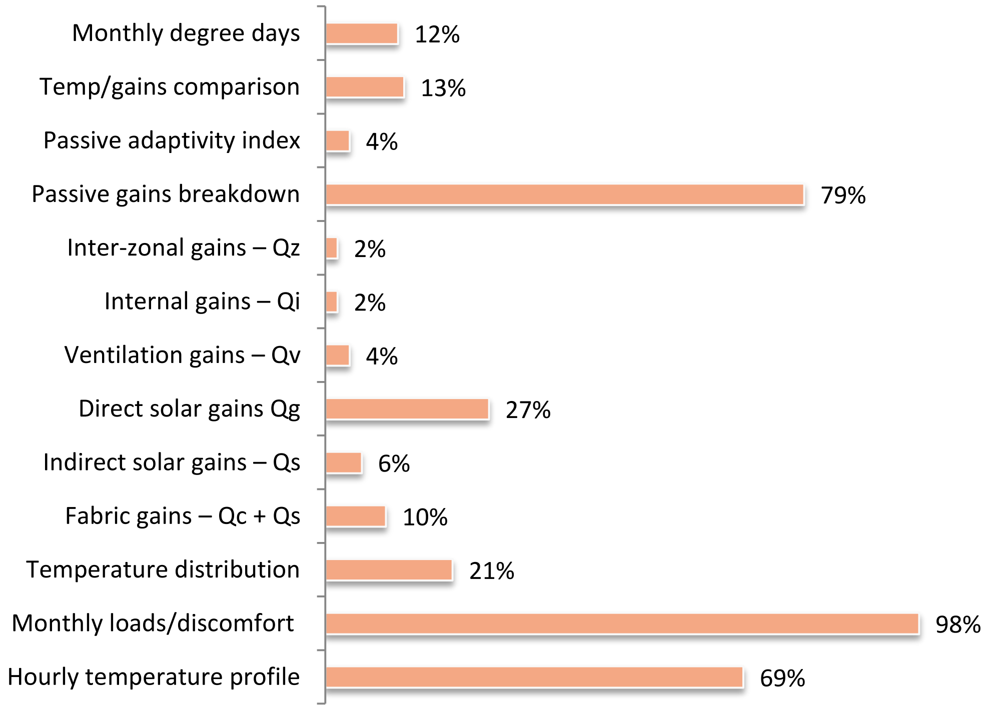


Figure 4-8 Survey results: the usefulness of graphs in decision making

The next set of questions related to software requirements. Many of the students [71%] would have liked to be able to see multiple graphs next to the 3D model to enable the direct comparison of results (*R10-c*). With the majority [92%] agreeing it would be useful to be able to see a summary of the currently set input parameters, such as ventilation rates, heating systems, occupancy, etc., displayed alongside the analysis (*R11-c*). A dashboard display, resembling an automobile's dashboard, was suggested to the students. The dashboard would be employed to display current input parameters and analysis results, was also considered would be a useful feature [67%] (*R11-c*). When asked to rank in order of preference those items that they would be useful to see in the dashboard, as can be seen from Figure 4-9, an overall energy target [51% for first and 17% for second] and details of energy usage [34% for first and 40% for second] were preferred by the majority of the students.

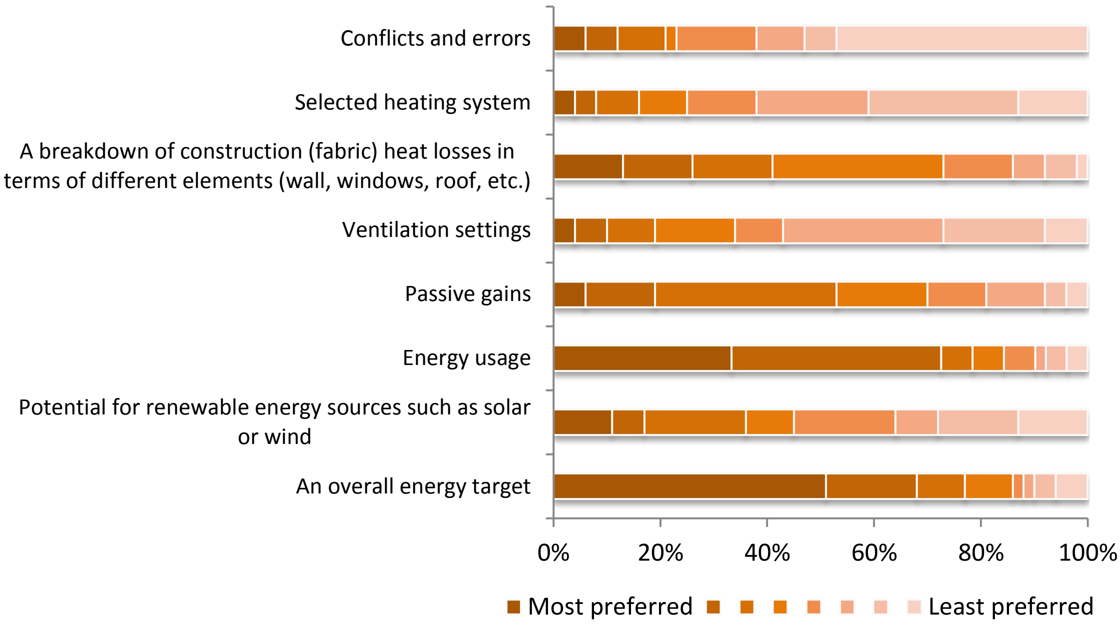


Figure 4-9 Survey results: items for inclusion in a dashboard

The graph show the relative preference for items that the students thought would be useful in a dashboard

When asked 'did you have confidence in the results of the thermal simulation' less than half [37%] selected 'yes'. The optional question on how the visualisation of data might be improved to assist your design process was answered by over a third of the students [37%]. One issue commented on by a number of students was the way the graphs changed vertical scales (auto-ranged) depending upon the maximum value, a typical comment was:

> *The changing of scale of the graphs make them useless in terms of direct visual comparison.* (*R12-d*)

Students also would like to see historical tracking of data, as evidenced by the following responses:

> *It may be useful to display a previous test's results next to the current ones, and also display the difference in these values in terms of + and -.* (*R13-d*)

> *Some sort of logging system where the date is recorded and out put as a separate file, I found I was using screen capture and manually writing down stuff that was already on the screen.* (*R13-d*)

> *It would be useful to flick between current and past graphs to directly see their change.* (*R13-d*)

Comments on the concept of the dashboard were mixed with most in favour, but not all, as illustrated by:

> *The dashboard is a very good idea, which would show you parameters so you can be sure that it is a fair experiment by keeping these values constant.* (*R11-d*)

> *Create screen where everything is on the same page rather than flicking between editor and analysis pages.* (*R11-d*)

> *…. If it were to be updated in real time.*

> *I think it would be useful to be able to pick and choose multiple graphs to view at once, but not just from the building as it stands in that current time, the feature to record changes and view data in a 'before and after' type way would be very useful for direct comparison. I think that the ability to view multiple graphs on the hourly temperature profile would also be useful eg. The ability to simultaneously view the hottest and coldest days………, I have used so called 'dashboard' interfaces before and think they are either too simple, with too few features, or too confusing with too many features, or graphics that distract from the actual purpose of the program. Simple menus and toolbars are much better.*

These results confirm the case study findings that understanding and feeling confident about the energy data was difficult. In particular, the lack of confidence in the results of the thermal simulation by the students was pertinent.

Requirements confirmed by the closed questions and deduced from the open questions relating to interpretation and implementation of energy analysis data, with the need for:

R8. Methods to set and display an energy target (confirmed)

R9. Methods to calculate and display renewable energy options and potential (confirmed and deduced)

R10. The display of multiple sets of data to enable comparison of alternatives (confirmed)

R11. The display of input and output together, possibly through the use of a dashboard display (confirmed and deduced)

R12. The improved display of data, in particular, graphs (deduced)

R13. The facility to both record and then re call historical data (deduced)

Modifying the construction

In the project the students were expected to reduce energy demand by making systematic modifications to the constructional details. There are various strategies that they could have explored, including improving insulation, use of thermal mass, control of the ventilation of occupied zones, ventilation of the roof space and utilisation of direct solar gain. The aim of this section is to determine how easy they found it to use the software for this iterative process.

Only just over a third of the respondents [38%] found the level of support that the software provided to enable the formulation of a strategy for energy reduction as ‘Good’ with none finding it ‘Excellent’. When asked for suggestions as to how the software could give more support to enable the formulation of a strategy for energy reduction, certain themes were re-iterated, such as how useful a dashboard display would be and a history or tracking feature. Other interesting suggestions were:

> *The passive gain is very useful feature and extension to this could be to show on your model where the gains and loss are….Identifying specific key elements to change which will reduce energy levels.* (*R14-d*)
>
> *Software gives no support- no indication of how using thermal mass, high density materials, low u-value materials etc would help to reduce loads. It is all relying on own knowledge. Some help would be useful, giving suggestions for strategies according to climate selection.* (*R15-d*)
>
> *The option to create a checklist feature. The user could create their own or the software formulate a quick step way of reducing the energy of the building.* (*R15-d*)
>
> *Perhaps a walkthrough guide again, maybe explaining the theory behind any modifications to be made.* (*R15-d*)

A minority of the students [17%] found making changes to the construction details difficult or very difficult. The assistance given by the software in making decisions about modifying construction details in order to improve the energy performance received a mid range response, with just over a third [37%] saying it was ‘Poor’, just under a third saying it was ‘Good’ and a quarter being undecided. However, there was a clear favourable response, ‘Somewhat’ and ‘Very’ useful [75%], to the suggestion regarding the availability in the software of a database of high performance standard construction details for making decisions (*R16-c*). There was a similar answer [81%] to the question ‘In the 3D model, how useful would it have been to select and visualise all elements with the same construction, for instance, use different colours for each construction type’ (*R17-c*).

The students are in broad agreement regarding the need for more support in the software to make modifications to the materials and construction details in the model to reduce the energy demand of their design.

Requirements confirmed by the closed questions and deduced from the open questions relating to modifying the construction with the need to:

R14. Identify areas of energy gains and losses using surfaces on the 3D model (deduced)

R15. Provide greater support in decision making with use of tools such as checklists, walkthrough guides and expert knowledge systems (deduced)

R16. Provide a database of high performance materials (confirmed)

R17. Improve visualisation of materials in the 3D model (confirmed).

The appearance of the building

All of the available marks for this assignment were given for the energy study and none were allocated for building aesthetics; a very simple building type was employed as a vehicle for the project to ensure that most of the limited time available was used to gain an understanding of energy simulation. However, one of the objectives of improved software would be to enable buildings to be designed holistically so that they are both energy efficient and aesthetically pleasing. This section aimed to establish opinions from the students as to how the software might be improved to facilitate design decisions to be made balancing both energy and aesthetic aspects.

The students generally found it difficult to achieve a low energy building, with almost half [44%] finding it 'Difficult' or 'Very difficult' and many [40%] 'Undecided'. Few of the students [17%] rated the appearance of their proposed building 'Acceptable' and none 'Excellent'. Only a small proportion [20%] thought there would be no increase in energy usage if they tried to make the building more aesthetically pleasing, with over a quarter [27%] predicting a considerable increase. Window areas are an important feature that affects the quality of light and enjoyment of buildings. The students gave a mixed response as to how well the software assisted making decisions about windows.

There was consensus [83%] that the availability of thermal analysis software integrated with conventional 3D modelling software to enable the design of aesthetically pleasing low energy building was 'Important' or 'Very important' (*R18-c*). There was a similar, very positive, response to the suggestion that it would improve the overall design process to have energy simulation functions integrated into standard design software (CAD or BIM) [92%], with only a few [8%] saying it would make 'No improvement' (*R18-c*).

A theme on render and display of the model emerged from the optional question on how energy simulation software could be improved to enable design decisions to be made in which aesthetics could be considered, typified by:

> *Better visual 3D modelling* (*R20-d*)

> *The better the physical form of a building can be expressed the better the thermal analysis of it will be.* (*R20-d*)

There were opposing opinions about combining design and analysis software. One student discussing enthusiastically how good it would be if the functions could be combined within one piece of design software:

> *I think a programme with all the design features of CAD and the energy simulation of Ecotect would be a huge leap in terms of low energy design, the separation of these two pieces of software may represent typical attitudes towards low energy and design as two separate fields, ideally they should be one and the same and a piece of software that could bridge that gap would be very useful in designing aesthetically pleasing and low energy buildings, without one factor becoming an afterthought.* (*R18-d*)

However another student would prefer the two functions to be kept as separate software tools with good compatibility (interoperability?).

> *If we are talking ecotect as an example its 'visualise' part is horrible, mainly it wasn't designed with aesthetics in mind so the building is very difficult to edit. When compared with traditional 3d modelling software it doesn't provide the opportunities or user interface which allows people to easily edit the design. In my mind design software and environment software are separate so is it necessary for on program to do both? What is important is making different modelling software compatible with environmental software so that design can be tested but built in programs that are very good at what they do and every one knows how to use.* (*R19-c*)

The responses from the students confirm the findings of the Case Study, that it is not easy to achieve a low energy building design. The students also confirmed that they believed that there would need to be a compromise between aesthetics and thermal performance. That is they understood that a better-looking building might have an associated energy penalty. Better support of the design process through integration, through either combination of the two types of software or improved interoperability, was a theme of the requirements aspect of this part of the survey. There was also an emphasis on better visualisation of the building design.

Requirements confirmed by the closed questions and deduced from the open questions relating to the appearance of the building, with the need to:

R18. Provide integration of thermal simulation with design software (confirmed and deduced)

R19. Improve interoperability (confirmed)

R20. Improve visualisation of the building model (deduced)

Using the software

This section aims to establish how the students learnt to use Ecotect and located information relating to their project. The aim of the questions was to establish their views as to how the low energy design process might be improved with the use of computerised knowledge and decision support systems.

Most of the students found the software relatively easy to learn [Difficult 17%, Okay 58%, Easy 17%]. As can be seen from Figure 4-10 they used a variety of methods to find information and solve problems. Fellow students [61%] was the most preferred with the *Internet* as the next popular [53%]. Books were *Rarely* or *Never* used by the majority of the students [69%] with the software *Help* system and the next method hardly used [59%].

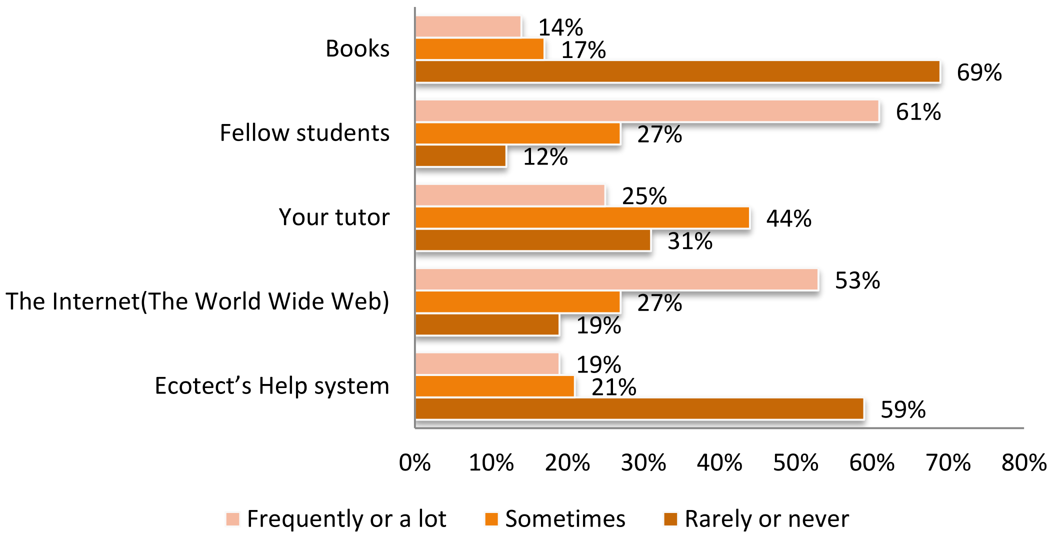


Figure 4-10 Survey results: the methods employed to solve problems

Almost half the students [46%] had problems that they did not solve. The optional question was to the nature of these problems, the replies were varied with no theme emerging, other than general struggling to understand both how to input data into the software and understand the output as typified by:

> *Does this graph look correct or not?* (*R21-d*)
>
> *Why is it that if you change one little aspect of the building the whole analysis changes to something that doesn't make sense!*
>
> *When certain error messages appeared within the analysis the option to isolate the problem still did not give any clarity on what was wrong with the model* (*R22-d*)
>
> *When I was making a new material for the wall, I was not quite sure which attribute would affect the U-Value of wall. It will be much better if it is showed in the software as a help.* (*R23-d*)
>
> *What determines degree hours and environmental temperatures?* (*R23-d*)

As part of the requirements elicitation the students were asked for their opinion of computerised systems, such as 'Expert Systems' and 'Decision Support Systems'. It was explained in the survey that such systems can provide expert knowledge and aid decision making in specialised professional fields, such as architectural design. The difference from a traditional Help system being that in that, in addition to containing a knowledge base, it aims to apply rules to interpret information relating to the design and to provide recommendations to aid decision making. Ideally it is similar to having an expert permanently on hand to answer questions. Such systems are frequently stand alone programmes, but it is envisaged that it could be integrated within a software package that provided combined 3D building modelling and thermal simulation functionality.

Four slightly different questions were asked in the survey relating to the integration of 'Expert Systems' and 'Decision Support Systems' into design software. It can be seen that in Figure 4-11 that they were broadly in favour on all four questions [71-73%] (*R24-c*).

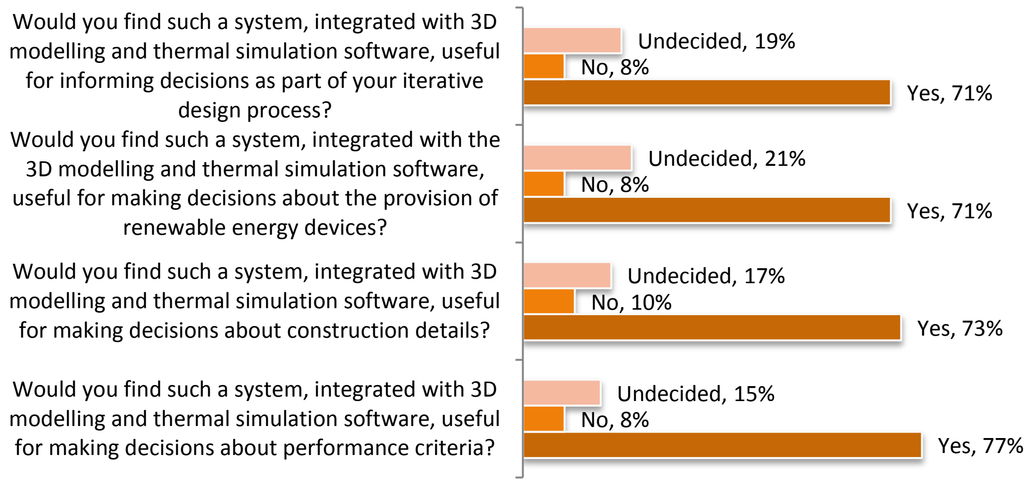


Figure 4-11 Survey results: Expert and Decision Support systems

Graph showing the responses to questions on the opinions as the usefulness of integrating 'Expert Systems' and 'Decision Support Systems' into design software.

In the open question the students were asked to comment on any other aspects relating to how an Expert or Design Support System could assist their design process? A selection of the responses are given below:

> *Having never heard of an Expert or Systems Design Software I am not sure what they are.*

I only answered no because personally I have never used any programs 'help' or 'support system' they are not where I naturally defer to if I have a problem. I much more likely to look it up online or ask someone I know

If a certain location was specified in the model, maybe the option to view local materials, or the embodied energy of certain materials reaching the site. (*R25-d*)

A graph showing your progress from your initial building performances to the latest- this would help you understand what aspects have improved the building the most. (*R26-d*)

Explaining what the graphs for thermal analysis do (*R21-d*)

What if it could integrate air flow, form, ventilation and solar gain all in one model. I feel more visual aspects using the actual model would be far more help than a graph (*R27-d*).

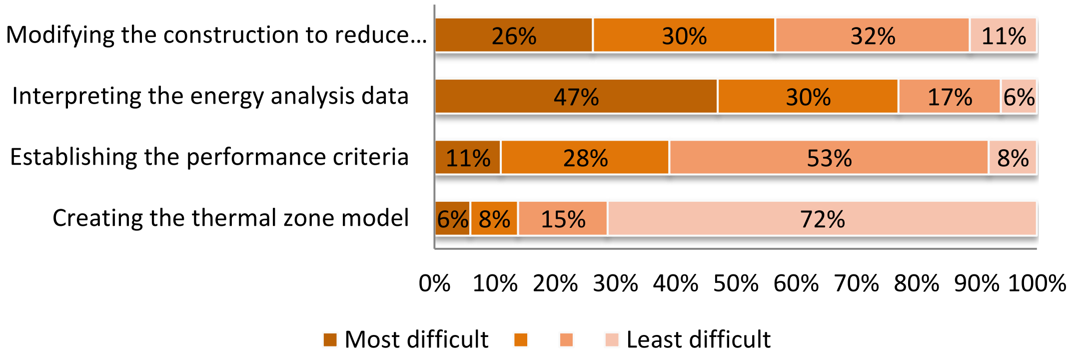


Figure 4-12 Survey result: percentage of students finding tasks difficult

The final question in this section was suggested by a student in the pilot survey (the students who completed the pilot answered this question by email). The question asked which of the tasks the students found most difficult. As can be seen in the graph in Figure 4-12 the students found *Interpreting the data* most difficult [77% for both first and second place] with *Modifying the construction to reduce energy demand* and the second most difficult [56% for both first and second]. They found *Creating the thermal zone* the least difficult, which is not surprising as they were all experienced 3D modellers.

This section confirmed that with the software, whilst the basic modelling was relatively straightforward, finding out how to perform particular actions was difficult for many of the students. Whilst the return in favour of a *Design Decision Support* system was good [>70%], there would also appear to be a lack of understanding how it would work and the role it is intended to fill, as expressed in the first two responses to the open question above.

Requirements confirmed by the closed questions and deduced from the open questions relating to using the software, with the need to:

R21. Provide help with explaining graphs (deduced)

R22. Provide help with error messages (deduced)

R23. Provide help with explaining attributes or parameters (deduced)

R24. Provide an ‘Expert System’ or ‘Decision Support System’ (confirmed)

R25. Provide local details; availability of materials and transport of materials to site (deduced)

R26. Provide tracking of results as the design evolves (deduced)

R27. Provide alternative visualisations to graphs (deduced)

And finally

The final section asked if any of the students would like to take part in a focus group to discuss the form of future software. The response to this optional question was encouraging, with 13 [25%] of the students indicating a willingness to support the project further.

4.2.3 Software requirements

The early requirements elicited in this case study fall into two categories. Firstly there are the suggested requirements that formed the basis of closed questions. The second set of requirements were deduced from responses to the open questions. These are listed below as they arose in the sections of the survey.

Requirements confirmed by the closed questions and deduced from the open questions relating to creation of the thermal zone model:

R1. The ability to move models between design and analysis software (confirmed and deduced)

R2. More intuitive modelling techniques as found in design software (deduced)

R3. More complex ‘realistic’ modelling techniques in simulation software (deduced)

Requirements confirmed by the closed questions and deduced from the open questions relating to establishing performance criteria:

R4. Values used in simulations to be made explicit (deduced)

R5. The provision of a knowledge support system (deduced))

R6. The facility for calculation support (deduced)

R7. The display of data in an manner appropriate for a designer (deduced)

Requirements confirmed by the closed questions and deduced from the open questions relating to interpretation and implementation of energy analysis data:

R8. Methods to set and display an energy target (confirmed)

R9. Methods to calculate and display renewable energy options and potential (confirmed and deduced)

R10. The display of multiple sets of data to enable comparison of alternatives (confirmed)

R11. The display of input and output together, possibly through the use of a dashboard display (confirmed and deduced)

R12. The improved display of data, in particular, graphs (deduced)s

R13. The facility to both record and then re call historical data (deduced)

Requirements confirmed by the closed questions and deduced from the open questions relating to modifying the construction:

R14. Identify areas of energy gains and losses using surfaces on the 3D model (deduced)

R15. Provide greater support in decision making with use of tools such as checklists, walkthrough guides and expert knowledge systems (deduced)

R16. Provide a database of high performance materials (confirmed)

R17. Improve visualisation of materials in the 3D model (confirmed).

Requirements confirmed by the closed questions and deduced from the open questions relating to the appearance of the building:

R18. Provide integration of thermal simulation with design software (confirmed and deduced)

R19. Improve interoperability (confirmed)

R20. Improve visualisation of the building model (deduced)

Requirements confirmed by the closed questions and deduced from the open questions relating to using the software:

R21. Provide help with explaining graphs (deduced)

R22. Provide help with error messages (deduced)

R23. Provide help with explaining attributes or parameters (deduced)

R24. Provide an ‘Expert System’ or ‘Decision Support System’ (confirmed)

R25. Provide local details; availability of materials and transport of materials to site (deduced)

R26. Provide tracking of results as the design evolves (deduced)

R27. Provide alternative visualisations to graphs (deduced)

4.2.4 Requirements themes

Analysis of the requirements listed above to find similarities or patterns lead to a reduction from the original eight survey questions to three themes. The three themes are: *improved modelling processes*, *visualisation of data* and the *provision of a design decision support and knowledge system,* as shown in Table 4-1.

Theme	**Requirements**	
Improved modelling processes	R1	The ability to move models between design and analysis software (confirmed and deduced)
	R1	More intuitive modelling techniques as found in design software (deduced)
	R3	More complex 'realistic' modelling techniques in simulation software (deduced)
	R14	Identify areas of energy gains and losses using surfaces on the 3D model (deduced)
	R17	Improve visualisation of materials in the 3D model (confirmed)..
	R18	Provide integration of thermal simulation with design software (confirmed and deduced)
	R19	Improve interoperability (confirmed)
	R20	Improve visualisation of the building model (deduced)
Visualisation of data	R4	Values used in simulations to be made explicit (deduced)
	R7	The display of data in an manner appropriate for a designer (deduced)
	R8	Methods to set and display an energy target (confirmed)
	R9	Methods to calculate and display renewable energy options and potential (confirmed and deduced)
	R10	The display of multiple sets of data to enable comparison of alternatives (confirmed)
	R12	The improved display of data, in particular, graphs (deduced)
	R13	The facility to both record and then re call historical data (deduced)
	R21	Provide help with explaining graphs (deduced)
	R26	Provide tracking of results as the design evolves (deduced)
	R27	Provide alternative visualisations to graphs (deduced)
Design decision support and knowledge systems	R5	The provision of a knowledge support system (deduced)
	R6	The facility for calculation support (deduced)
	R15	Provide greater support in decision making with use of tools such as checklists, walkthrough guides and expert knowledge systems (deduced)
	R16	Provide a database of high performance materials (confirmed)
	R22	Provide help with error messages (deduced)
	R23	Provide help with explaining attributes or parameters (deduced)
	R24	Provide an 'Expert System' or 'Decision Support System' (confirmed)
	R25	Provide local details; availability of materials and transport of materials to site (deduced)

Table 4-1 Three themes identified from the results in the student survey

Theme: Improved modelling processes

The results of both case studies support opinions that current software tools are difficult to integrate with the design process (Punjabi & Miranda, 2005) or there is poor support for the rapid evaluation of alternative designs (Augenbroe, 2002). The students expressed frustration in the modelling environment within the thermal simulation software at all levels from basic modelling, through to visualisation of the building, as can be seen by the requirements listed in Table 4-1. They were drawing from their experience of using building design software in responding to the questions on modelling functionality.

Theme: Visualisation of data

Inputting of data is tedious and requires extensive training (Attia *et al.*, 2009) and thermal simulation produces copious amounts of data (Prazeres & Clarke, 2005). This survey supports conclusions drawn in a comparison of tools by Attia et al. that architects want better graphical representations of simulation inputs and outputs. Both Attia et al. and Augenbroe (2002) call for comparative reports for multiple alternatives and 'memory' between repeated evaluations. The requirements listed in Table 4-1 illustrate how visualisation has a significant role to play in how building designers can assimilate and handle this data and gauge the impact of design decisions.

Theme: A design decision support and knowledge system

Design decision support and intelligent knowledge systems are seen to be an important aid for designers working in the field of energy simulation (Attia *et al.*, 2009; Hensen, 2004; Augenbroe, 2002). This has been confirmed, as can be seen in the requirements listed in Table 4-1 above, by the students undertaking this case study.

4.3 Conclusion

This chapter has reported on two case studies. The first study involved an initial exploration and definition of the limitations associated with existing software to support iterative design processes for the prediction of building energy usage. The second study was employed to confirm the findings of the first study and elicited early requirements for new software. The students who took part in the study were surveyed and the results analysed. Three themes were identified as important in the design of new software, the need for: improved modelling processes, better visualisation of data and the provision of a design decision support and knowledge system.

A limitation is that both studies involved only one piece of simulation software, Ecotect, however, as discussed earlier, it is considered to be the most 'architect-friendly' piece of software available. The disparity between design software and simulation tools can partly be explained by how the two types of software have evolved. There are 4 main BIM software products (Digital Building Lab, 2010). These have developed by well-resourced, large international companies, who invest significant resources into developing expensive, well-tested, reliable software. On the other hand thermal simulation software has, at present, a much smaller market (Papamichael & Pal, 2002) and although there are a large number of tools available (Crawley *et al.*, 2008), they have not had the same level of commercial investment and hence are not as mature as BIM products. Some of the tools have been developed by researchers and scientists whose aim has been to develop powerful and accurate tools to represent real-world complexity, rather than simple, intuitive tools (Punjabi & Miranda, 2005). The more commercial tools have been developed for code compliance checking and the sizing of HVAC systems and not to support iterative design practices.

At the time of writing, there is only one piece software fully linked with BIM software, EcoDesigner with ArchiCAD[18], which has relatively limited functionality. Project Vasari, under development by AutoDesk[19], provides early conceptual design and analysis for buildings and is linked to their Revit BIM software using their proprietary file type. The need for improved interoperability in the AEC industry has been discussed widely (Hitchcock & Wong, 2011; Grilo & Jardim-Goncalves, 2010; Ferrari *et al.*, 2010; Steel *et al.*, 2010) yet is still proving elusive. This will be discussed in more detail in Chapter 6. Integration of energy simulation processes with BIM software is seen as desirable but non-trivial (Technology Strategy Board, 2009; Augenbroe, 2002). This will be discussed, along with a proposed solution in Chapter 7.

---

[18] http://www.graphisoft.com/products/ecodesigner/

[19] http://labs.autodesk.com/utilities/vasari/

This chapter has investigated the problem domain from the perspective of the software user and established a set of early requirements. It can be concluded from these requirements that contemporary BES software could be significantly improved. The next chapter explores the problem space further with a further focusing and definition of the application domain. The differing, dichotomous views of the building models employed by BIM and BES processes will be more fully investigated. It will analyse the methods employed in BIM, BES and DAS approaches to compile a set of domain requirements relating to how the different types of software work.

Chapter 5

Domain Requirements for Software to Model and Simulate Low Energy Buildings

The previous chapter reported empirical work into the application of software in the design of low energy buildings and established early user requirements. These requirements indicated that closer integration of design and simulation functions by either better interoperability (discussed in the following chapter) or integrated within one application would enhance architectural design processes. This chapter analyses the problems and issues involved in this integration. The aim is to develop a rich picture and understanding of the application domain (Offen, 2002). The solution to the problem of providing a tool to support the design of good-looking low energy buildings requires the consideration of a number of complex interdependencies which will be described and analysed in this chapter. The aim is to examine how existing software systems model buildings and record associated information and to determine the obstacles to integrated software.

Objectives for this chapter are:

1. Describe and analyse the methods used by existing software tools.
2. Record and critically compare the salient geometric modelling, information and visualisation requirements for:
    - Building Information Modelling
    - Building Energy Simulation: thermal, daylighting and air movement
    - Design Advisory Systems.
3. Draw conclusions on the implications for new combined software.

This chapter is further focusing on and defining the problem, before embarking on the solution (Jackson, 2001). The methodology for this chapter involves the analysis of the various existing approaches to the creation of a virtual model of a building and associated information. Requirements are employed as a means to collect data and identify the factors in the problem, part of the synthesize phase of the Research Through Design approach employed in this thesis (Zimmerman & Forlizzi, 2008). As discussed earlier, no software exists currently to support both the design and detailed energy simulation and analysis of buildings. A new approach to software is proposed in this thesis rather than a brownfield development of existing software.

Chapter 3 introduced the concepts and legislation pertaining to low energy buildings. The previous chapter established a list of user, or stakeholder, requirements. The requirements compiled in this chapter describe another set of user requirements, the fundamentals of the application domain. This chapter is concerned with a description of the problem domain to model buildings along with their predicted energy consumption through the examination of existing software types and compilation of a list of the requirements. This is similar to architectural practice of researching, making visits and analysing comparable buildings prior to the commencement of the design of a new one. Domain analysis is seen as a method to extract unarticulated knowledge to gain a better understanding about systems, data and functionality. The requirements identified in this chapter are intended ‘high-level’ or ‘business’ requirements, employed to gain a better understanding of how existing software types operate (Robertson & Robertson, 2006). The requirements are employed to explore and identify reasons for the poor integration discussed in Chapters 2 and 4, rather than the development of a full working system.

The eventual development of the product would necessitate a substantially more detailed, and considerably longer, list of software requirements from which the system could be built. Ross & Schoman describe ‘good’ software requirements as complete, consistent, testable, traceable, feasible, and flexible (1977, p.7). Davis *et al* (1993) expand this list to: correct, internally consistent, externally consistent, achievable, design-independent, organized, traced, traceable, all annotations electronically stored and cross-referenced.

Multiple viewpoints of the domain are employed in this chapter to gain better coverage of the requirements and identify conflicts and inconsistencies (Sommerville & Sawyer, 1997). Ross & Schoman argue that successful requirements definition is achieved by examination of the problem from different viewpoints. The differing approaches employed in contemporary software to the modelling of buildings are analysed from the three perspectives of Building Information Modelling, Building Energy Simulation and Design Advisory Systems, in the context of:

- modelling methods,
- information,
- visualisation.

These viewpoints reflect the themes established in the previous chapter: improved modelling processes, visualisation of data and a design decision support and knowledge system. Conflicting requirements and interfaces between the domains are identified in summary tables and conclusions drawn for the solution, integrated software.

The requirements are arrived at by a number of different methods: from the literature, analysis of existing software descriptions or processes and the author’s tacit knowledge. The majority of this chapter is discursive, drawing upon my own knowledge of architecture and computerised building modelling. The employment of such a ‘voice’ is seen by Cohn et al as a valuable process in design methods (2010, p.54). Where drawn from the literature a reference is employed, otherwise the requirements are derived from direct knowledge in the subject gained from using building design and simulation software.

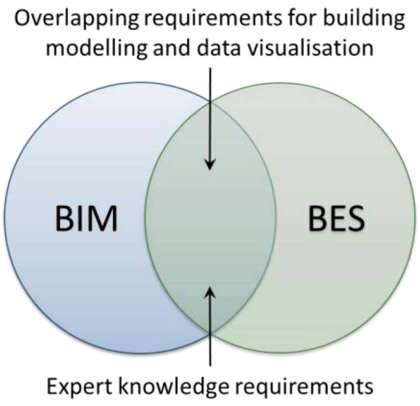


Figure 5-1 Venn diagram of BIM and BES processes

BIM and BES are separate processes with many software requirements. The key to integration involves the analysis of the overlapping requirement and possible resolution of conflicting requirements. Expert knowledge could help building designers cope with the additional cognitive demands of integrating BES into design processes.

BIM, compared to BES software, has reached a high level of sophistication with many functions expected in commercial software. The majority of BIM functions would not be affected by the integration of energy simulation and analysis processes, as illustrated by the Venn diagram in Figure 5-1. This chapter concentrates on the common software requirements between BIM and BES.

Each requirement is given a unique identifier, DR, which stands for Domain Requirement and a description. The requirement is given first and the rationale, if deemed necessary, in italics afterwards. These requirements are then organised into themes and critically compared by use of three matrices at the end of the chapter. Every effort has been made to make the requirements technologically neutral (Robertson & Robertson, 2006) however, as this chapter is in the main an examination of existing approaches, this is not always possible. Also, as discussed by Nuseibeh (2001), a strict separation between requirements and the solution can be difficult and often a better understanding of the problem can be achieved through consideration of the software architectures.

5.1 Existing software tools

Current design and simulation software tools have been developed in different ways from diverse roots and are used in very dissimilar ways. However, there is a need for closer integration of the tools if BIM is to evolve to support a “single project model” as outlined in the BIM Overlay to the RIBA Outline Plan of Work (Sinclair, 2012, p.6).

Cognisant of the growing importance of energy prediction as part of the building design process, large CAD and BIM software companies have recently acquired a number of third-party software companies. Autodesk have bought Green Building Studio[20], a web based *Software as a Service,* and Ecotect[21], a stand-alone package. Bentley Systems have acquired Hevacomp[22] and entered into discussions regarding the distribution of EDSL's Tas[23].

---

[20] http://usa.autodesk.com/green-building-studio/

[21] http://www.autodesk.co.uk/ecotect-analysis

[22] http://www.bentley.com/en-US/Products/Building+Analysis+and+Design/Hevacomp.htm

[23] Environmental Design Solutions Limited (EDSL) http://www.edsl.net/main/

Graphisoft have developed EcoDesigner[24], which uses the same simulation kernel as the VIP Energy[25] product. IES remains an independent analysis software provider with IES VE-Ware[26] a free analysis module compatible with Sketchup[27] and AutoDesk's Revit[28] and IES VE-Pro[29] a more complete analysis tool (Wong, 2010). DesignBuilder[30] also remains independent; it has a 3D interface to the EnergyPlus[31] dynamic thermal simulation engine. OpenStudio[32], a plugin for Sketchup, is an open source project, still in development, created by the National Renewable Energy Laboratory for the U.S. Department of Energy that also uses EnergyPlus (U.S. Department of Energy, 2010).

Figure 5-2 shows the relationships between the major players at the time of writing. The solid red line indicates good interoperability. The dotted red line indicates limited interoperability between the software packages. However, at the present, no software supports fully integrated BIM and dynamic energy simulation. The processes remain dichotomous with poor interoperability.

---

[24] http://www.graphisoft.com/products/ecodesigner/

[25] http://www.strusoft.com/index.php/en/products/vip-energy

[26] http://www.iesve.com/software/ve-ware

[27] http://www.sketchup.com/

[28] http://usa.autodesk.com/revit/

[29] http://www.iesve.com/software/ve-pro

[30] http://www.designbuilder.co.uk/

[31] http://apps1.eere.energy.gov/buildings/energyplus/

[32] http://openstudio.nrel.gov/

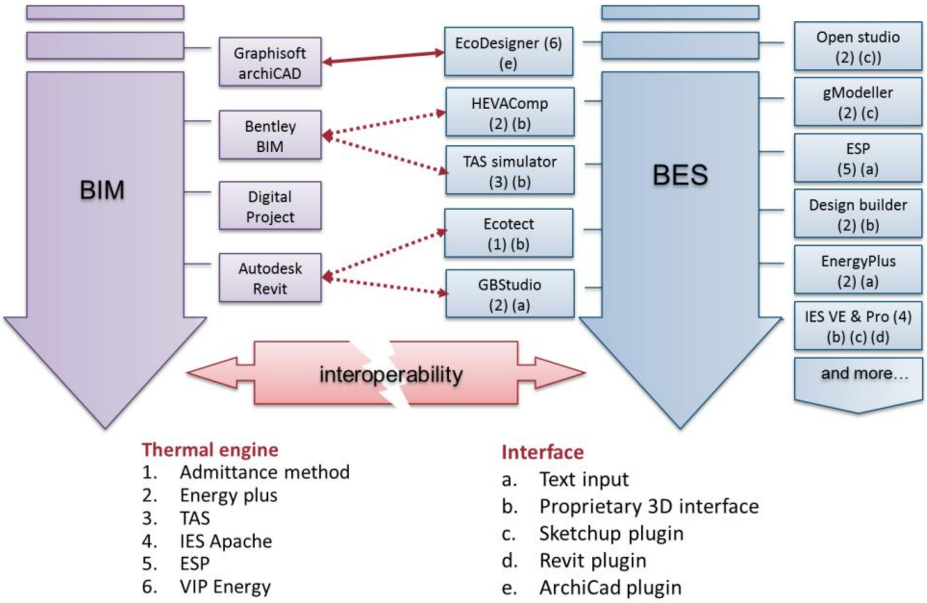


Figure 5-2 Relationship between BIM software and BES software

The solid red line indicates good interoperability between BIM and thermal analysis packages. The dotted red line indicates limited interoperability between the software packages.

5.2 Building design software

The field of AEC software is subject to rapid changes and undergoing constant revisions. In general the major software vendors issue yearly updates with the addition of new features. The generic types of design software used by architects are briefly introduced in this section. BIM is then discussed in greater detail.

The capabilities of CAD software can vary from *2D vector-based drafting*, intended to replace pen and paper, *3D solid modellers* that support the virtual sculpting of buildings and *surface modellers* that can be used to create photo-realistic rendering of scenes with lighting and materials. There is also significant overlap of features, with some software supporting many of these modelling approaches and providing a range of visual outputs. The outputs can range from 2D plans, to photorealistic rendering to animated flythroughs.

In the UK the NBS [National Building Specification] have recently produced a National BIM Report based on an online survey completed by 1000 respondents (National Building Specification, 2012). Although aimed at recording the opinions and usage of BIM it also covers CAD. Interestingly some 35% of respondents did not use any form of CAD or BIM and 30% worked solely in 2D CAD. Autodesk's AutoCAD was the most widely used software, and Revit the most widely used BIM package. Sketchup[33], although not developed as a CAD tool, is also used as an early massing/conceptual tool.

CAD software, whilst still used extensively in the AEC industries will probably be superseded by BIM in the near future (due to government pressure for adoption). Also dynamic building performance simulation for low energy design requires the type of data recorded in a BIM model; a 3D geometric model plus components and materials properties (Jankovic, 2012).

A review of design software can be found on the AECbytes website[34], or *BIM in Small-Scale Sustainable Design* (Lévy, 2012).

5.3 Building Information Modelling

Although object-based parametric modelling has existed since the 1980s, BIM software has evolved rapidly in the last few years (Eastman *et al.*, 2011). BIM software contains not only the building geometry and spatial relationships of building elements in 3D, it can also hold geographic information and quantities and properties of building components. Each component is an 'intelligent object' recorded in a backend database. The software can be used to facilitate team working with consultants and manage building data during its life cycle. Succar (2009) describes BIM as a catalyst for change, predicted to reduce fragmentation in the AEC industry and improve efficiency/effectiveness. Eastman et al. describe BIM as 'vast', predicted to result in a dramatic change in AEC processes through new approaches to design, analysis, construction and facilities management.

---

[33] Google sold Sketchup to Trimble in June 2012, see http://www.trimble.com/3d/

[34] http://www.aecbytes.com/reviews.html

5.3.1 Building modelling methods

Much of the focus on research into BIM has been focused on making the technology work, Holzer, describes it as "Technocentricity – focus on software instead of design culture" (2011, p.466). He argues that this focus has led to difficulties in understanding BIM as a method for conceiving buildings with the criticism of BIM lying with the perception that it is a documentation tool rather than a design environment. This situation is in many ways compounded by the legislation in the UK making the application of BIM compulsory for public projects. The motivation is to save money (Cabinet Office, 2011), not to raise design standards. The statistics above, from the NBS, suggest that building design software in general is not widely employed by the architectural profession. The focus of this thesis is on the functional integration of BES and DAS with building design software, however, any new integrated software needs to be at least as user-friendly as existing BIM software.

DR1. The software shall provide a user-friendly building design environment

This requirement could be considered as a project goal, the highest level of requirement (Robertson & Robertson, 2006). Whilst it lies beyond the scope of this thesis it is important that it is recorded and not forgotten. Whilst existing BIM software has reached a high level of sophistication the user-friendly aspects of the software could still be improved as evidenced by the limited adoption by the architectural profession.

Existing BIM software employ *parametric building objects*; the objects are defined geometrically and have associated data and rules. Parametric[35] building objects maintain

---

[35] A parametric model is defined by rules and constraints, which define aspects of the building and their relationships to each other. Changing a rule or constraint, or modifying a part of the model itself, almost always has implications on the entire model. Parametric tools allow relationships among components in the model to be defined, and parameters that control aspects of the building to be defined and changed—from physical characteristics to environmental parameters, and even aspects such as projected occupancy. For example, a building can be described as an extruded rectangular form with a pitched roof. As the dimensions or shape of the rectangle or the height of the extrusion is changed, the roof will automatically be modified in order to still fit. For more information see http://www.aecbytes.com/viewpoint/2007/issue_32.html

relations to other objects, if an object changes, then all related objects will also change. Parametric objects re-build themselves automatically according to associated rules. The rules may be simple, requiring a door to be wholly within a wall, or complex defining size ranges, and detailing, such as the physical connection between the door and the wall. Objects can be generic or product-specific and can be a solid shape or void-space oriented. For instance a wall will have properties regarding the material from which it is made and rules concerning how it can be joined to other objects such as other walls or floors. The geometry is intended to be non-redundant with no inconsistencies permitted; this means that a plan and elevation of an object should be consistent. Rules for objects mean that associated objects and their geometries will be automatically modified. An example is when a window or door is added to a wall. Objects can be defined at different levels of aggregations or hierarchies. If a wall is constructed of a number of layers and one layer is altered then the remaining layers in the wall are adjusted accordingly. Should a change cause a violation of a rule, for instance resulting in an inappropriate size, the conflict can be identified by the software. Parametric building element classes can have over 100 low-level rules for definitions and properties.

A distinction can be drawn between those elements that make up the building shell and hence interact with other elements and those that do not vary with their context. For instance if a wall is extended, other elements joined to it may be affected. However, fittings such as those for a bathroom or kitchen, often contained in external libraries, will not interact with other objects.

Most software contains a library of pre-designed, customizable objects. For example, a door may be the name of a *Family* (a term used by AutoDesk with Revit). It may have *Types* describing different sizes, and the actual building model will have *Instances* of those types placed in walls.

DR2. The software shall provide a method of modelling a building with objects that represent real world entities such as doors, walls and windows with rules as to how they relate and connect to each other

---

The virtual building model would be assembled as a collection of objects. Rules would be required to state how they can be assembled together to form the building model.

In addition to interoperability between software tools there is a need for support for multidisciplinary collaboration. According to Harty and Laing (2011a) a BIM model can be employed to provide three purposes: the clients financial model, the design model and the building facility model. The BIM environment has the potential to support a high level of complexity in the design model through the facilitation of: performance analysis, project delivery methods and information coordination of a building project. Within the design model a there will be a number of consultants adding to or working on a building project that may include: architects, structural engineers, MEP [Mechanical, Electrical and Plumbing] consultants, landscape architects, highways and civil engineers, interior designers, contractors, etc. The degree of collaboration that a BIM approach can support brings numerous challenges to existing working practices, relationships and interdependences. These range right through from inception to the delivery and running of a project. The challenges include the legal aspects of procurement and delivery by project members, supply chain procedures and importantly for this thesis, software and the method of storing, sharing data and simultaneous working practices.

Data relating to building objects then needs to be stored, with BIM software this is generally achieved using a backend database. Existing software houses support sharing of data from the database by different methods, examples of implementations are:

- Autodesk, with their BIM software Revit, employs a project database stored on a file server on either a LAN [Local Area Network] or VPN [Virtual Private Network]. Each user works on a copy of the central file (known as the local file), stored on the user's workstation. Users then save to the central file to update it with their changes and to receive changes from other users. The central file checks to see if another user is editing an object before it can be altered. This procedure prevents two users from making a change simultaneously and avoids conflicts.

- Graphisoft have developed a BIM Server concept for ArchiCAD. Only the changes and differences are sent to the central storage allowing remote access to the same project over the internet.

DR3. The software shall provide a method to record and share information about the building model

---

The objects that make up a building model, along with associated information, need to be stored in a persistent manner to enable recall and development of the virtual building model. A central repository for the model would enable teams of consultants to work on one project simultaneously.

BIM works with data-enhanced parametric objects that can be inserted into the virtual building model using point-defined, line-defined, or path-defined positioning.

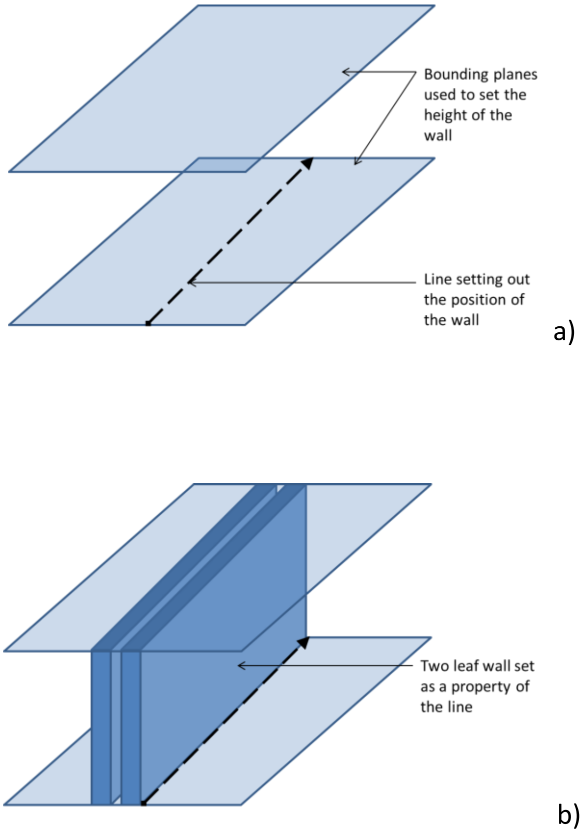


Figure 5-3 The creation of a wall in BIM

a) showing planes used to bound an element such as a wall, if the position of the planes is altered the wall will be resized accordingly b) the wall has been positioned using a line and given properties such as thickness, number of leaves.

Defining the position of objects employed by BIM has similarities to the vector graphics often found in 'paint-type' software. An example is the creation of a cavity wall in a model along a line. Planes will usually have been created at the beginning of the modelling process to represent the position of horizontal elements such as floors or ceilings as shown in Figure 5-3 a). A line is then 'drawn' on one plane and properties chosen for the wall such as cavity, solid, timber frame, etc. These properties establish how the wall is constituted and the overall thickness. Options can be set to position the wall along the line, for instance on the centre line or internal/external face. The wall is then extruded up to another plane as shown in Figure 5-3 b).

DR4. The software shall provide a method to enable building objects to be positioned in 3D

Building objects, such as walls, windows, doors, floors that comprise the building need to be positioned in 3D by means of a Cartesian coordinate system.

However, recently other methods of modelling buildings, in addition to building object modelling, have been added to software such as Revit. These methods are intended to be employed as conceptual design tools with both surface and solid modelling available to support volumetric or massing design of building forms (Autodesk, 2011). These volumetric or massing models are often employed in early design stages to enable the building designer to rapidly produce simple 3D models of the proposal and explore alternative solutions. Free-form tools are now provided to model curves easily by employing NURBS[36] (Autodesk, 2012). Once the building mass has been created the surface is converted into a wall panel system.

---

[36] NURBS [Non-Uniform Rational Basis Spline] provide a mathematically precise representation of complex curved surfaces like those used for aerospace surfaces, ship hulls and car bodies. NURBS surfaces are functions of two parameters mapping to a surface in three-dimensional space. The shape of the surface is determined by control points.

DR5. The software shall provide methods to generate 3D models of building volumes: extruded 2D shapes and 3D primitives, combined with surface modelling with NURBS

Building volumes, either as external massing models or internal spaces, need to be modelled in 3D. This can be achieved by combining initial volume generation through extruded 2D shapes, involving giving a 2D shape height or 3D primitives such as cuboids, spheres, cylinders, cones etc. These volumes can then be manipulated employing polygonal mesh manipulation or NURBS modelling is employed to create curved surfaces through parameters mapped to a surface in three-dimensional space.

5.3.2 Information associated with building models

Existing building models hold significant amounts of information in addition to the building geometry and spatial relationships of building elements. This information can be about the building objects themselves, such as product type or material properties. It can also be about the building, such as geographical information and management of equipment.

DR6. The software shall provide schedules of building objects, materials, geographical information and equipment

Quantities and properties of materials can be extracted easily from the building model.

There are significant differences as to how parametric modelling is implemented by software companies. Each provide different families of objects and their associated rules which results in dissimilar design behaviours. Pre-defined objects also, by their nature, cannot include every possible element in a building and hence may limit design, no matter how complex the software application. The behaviours of objects, implemented by different software companies, makes interoperability of these objects difficult if not impossible (Eastman *et al.*, 2011). Although there are difficulties with recording objects, behaviours and rules, as discussed earlier, interoperability is important, with considerable industry effort applied to IFC.

DR7. The software shall provide the facility to export the building model in a standard format

There will be a need to export the building model data in a standard format for either back-up reasons or to work with in other design software. The current standard is IFC.

BIM can be used to record the entire building life cycle. Lifecycle assessment can be employed in design stages to analyse, evaluate and compare alternatives for the life of a building. An examples is where typical construction methods can be compared with high performance methods to estimate the energy savings over the lifetime of the building. For instance, the embodied energy of a heat retaining material, such as concrete, can be compared with the total energy savings predicted by employing this approach over the lifetime of the building. During construction the building model can be used to record changes made as the scheme is built and then be employed over the lifespan of the building to facilitate management of the operation through monitoring of resource use such as energy and water consumption. Dynamic information from the building, such as sensor measurements and control signals from the building systems, can be incorporated within the building model to support analysis of building operation and maintenance. At present a variety of software tools are required to carry out this type of analysis (Eastman *et al.*, 2011).

DR8. The software shall facilitate lifecycle data documentation

The building model can be used to record the entire building life cycle, including the processes of construction and *facility operation. Once built, the building model can be employed to support running and analysis of the building operation and maintenance.*

This section aimed to cover the aspects of BIM relevant to energy analysis, as discussed earlier, it is not a comprehensive list of software requirements, for more detail on BIM see *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractor* (Eastman *et al.*, 2011) or *Handbook of Research on Building*

Information Modeling and Construction Informatics: Concepts and Technologies (Underwood & Isikdag, 2009)

5.3.3 Visualisation of building models

Building information modelling covers geometry, spatial relationships, geographic information and quantities and properties of building components. BIM software provides visual depictions of the building as plans, sections and elevations, along with textual information such as legends and schedules. Plans, elevations, and sections are generated from the three dimensional virtual building model and are constantly updated if the user 'rebuilds' the view. Detail drawings are based on enlarged portions of the model, with 2D detail added as required. Systems, assemblies and sequences can be shown in a relative scale within the context of the entire building or project.

DR9. The software shall provide 2D and 3D visualisation, rendering and printing imaging

The software should facilitate the building designer to work with either a 2D or 3D representation on the screen. Two-dimensional drawings should be imaged in order for them to be exported or printed. A rendering engine to make a realistic image or video of the proposed building should also be provided.

BIM software can perform collision (or clash or interference) checking, which detects if different components of the building are occupying the same physical space. An example would be a waste pipe passing through a structural element. Whilst not directly related to energy usage, it can dramatically reduce wastage on site, previously estimated to be up to 10% of the building cost (Gallaher & Chapman, 2004).

DR10. The software shall provide collision detection

The software should detect if more than one building element is occupying the same physical space to prevent collisions and possible re-routing during construction.

Software such as Autodesk's Project Vasari provides the ability to import a Google street map or satellite view, based on the site location, onto which the building project can be 'placed'[37].

DR11. The software shall provide the facility to set the location and use a satellite map to position the proposed building

The location is important for design visualisation to establish adjacent features such as buildings, trees and roads. By employing a satellite map, such as that that can be obtained from Google maps, a 3D massing model of the surrounding environment can be created quickly. Also, as will be discussed later, the location is important for energy analysis.

5.4 Building performance simulation

Carrying out a simulation should enable comparisons of design alternatives to be made (Augenbroe, 2011). The complete building design is modelled mathematically, taking all the various sub-systems into account, and subjecting the hypothetical structure to a dynamic response to internal and external inputs as discussed in chapter 3.

There will be uncertainties in any simulation results which will be dependent upon both the quality of the inputs and the simulation algorithm (Augenbroe, 2011). The choice of the correct algorithm and complexity of input data is an important decision relating to the stage in the design process. Hensen & Lamberts (2011) state that increasing the resolution (complexity) of the modelling can increase the potential error in the results and that there is an optimum level of complexity that can be employed in a design beyond which the uncertainty grows An additional problem with running dynamic simulation software is the use of default values. According to Jankovic (2012), simulation engines can contain generic building model data. As values are entered this generic data will be altered, but many values may remain unchanged, potentially leading to significant errors/variations in the analysis.

---

[37] See http://wikihelp.autodesk.com/Vasari/enu/B1/Help/0032-Start_a_32/0037-Using_In37/0056-Importin56

However, if the values are left blank the algorithm will crash. The types of algorithms used are discussed in the following section.

5.5 Building energy simulation

BPS covers the wide range of subjects relating to how a building performs environmentally; BES is a subset that includes those that relate specifically to the energy consumption of a building, these are:

- The thermal load (heating and cooling).
- Daylight performance, this affects the requirement for supplementary electrical lighting.
- Ventilation performance.

The simulation process involves the following three stages that are all discussed in more detail in the next sections:

- Simulation engines employed to predict the performance of the building.
- Model creation where the building is represented by a simplified virtual model, the type of representation is dependent on the type of simulation to be run.
- Presentation of results of the output of the simulation software that describe the predicted energy performances.

Thermal simulation

Over the past 50 years numerous building energy programs have been developed, many as a result of research programs that have since disappeared. The tools that are in use today are difficult to categorise, many using different methods to simulate heat transfer.

The thermal load of a building is the energy required to heat or cool the building to achieve human comfort. It is possible to estimate how comfortable a building is likely to be by considering the total energy inputs, external solar loads, outside air temperatures, wind velocities, etc. There are numerous tools that can be employed to carry out this type of calculation ranging from relatively simple to more complex. Most of the thermal simulation tools consist of an 'engine', which contains mathematical and/or thermodynamic algorithms, and a graphical user interface. According to Maile et al. (2007) there are two types currently in use; *design* tools employed to size HVAC equipment (note this is not the design of buildings, but of equipment to achieve thermal comfort) and *simulation* tools to predict the annual energy performance of the building. The tools and methods discussed below are a small subset of those available; a full list is available from the Building Energy Software Tools Directory at the US Department of Energy website[38].

Simple design tools base their calculations on the worst case scenarios, such as the summer or winter extremes, to provide an estimation of the required HVAC equipment capabilities. They are usually based on static calculations, known as *steady state* models with the assumption that both indoor and outdoor conditions are non-changing. Steady-state methods estimate the total heat losses/gains through the use of building fabric U-values and monthly or annual degree-day figures. These methods are being replaced by dynamic simulation tools that factor in the effects of thermal mass. This is important in climates with a high diurnal temperature range and internally loaded buildings, whereby the energy produced by internal activities during the day can be soaked up by the fabric and purged during the cooler night. These dynamic simulation tools provide the basis for the requirements listed in this section.

There are a number of approaches in the development of dynamic simulation tools. In a comparison of the capabilities of the twenty major building energy simulation programs, it was noted that there is no common language to describe the methods used by the tools (Crawley *et al.*, 2008). The situation is further complicated by the relationship between research generated by academia, publically funded institutions and the private sector. Examples of this are the DOE2 simulation engine where a number of private software vendors have developed graphical user interfaces for use with the software which they can then market. A number of private software companies have also developed their own thermal engines.

---

[38] http://apps1.eere.energy.gov/buildings/tools_directory/

The comparison of tools by Crawley et al. categorised the methods employed by the tools into the following groupings (2008):

- Frequency domain,
- Time response,
- Finite difference / volume.

Marsh (2006b), developer of the Ecotect software package, gives the following categorisation with explanation, which has overlapping features with the above list.

The dynamic *response factor* of a building is modelled through incrementally modelling the changing condition of surfaces within building space boundaries. Partial differential equations are employed to define the response of each surface to changes in temperature and thus model the flow of energy within the building fabric

The *frequency-domain* response factor models the cyclical response of the building. A variant of this is the CIBSE *Admittance Method*. It uses a characteristic, known as the admittance of a material surface, along with thermal lag and decrement factors, to define the dynamic response. The admittance method is a simplified method developed to estimate maximum temperatures in buildings, in particular that due to solar gain through glazing. It assumes a sinusoidal pattern of variation of the outside conditions and calculates the instantaneous variation of internal conditions about their mean. This method is used by Autodesk’s Ecotect and can be useful for the comparison of alternatives in early design, as it is quick to run, rather than for the detailed prediction of energy usage. More sophisticated dynamic simulations take into the effect the storage effect of thermal mass over long periods of time to more realistically model real world environmental conditions.

The *time-domain* response factor employs hourly weather data as an input to calculate hourly internal conditions. It is employed by DOE2 and EnergyPlus, both developed by the US Department of Energy, discussed later.

Finite difference methods are *numerical* methods that utilises powerful computing systems to calculate the heat flows between each layer of each material within the building fabric in relatively small time increments. An example of this method is ESP-r developed by the Energy Systems Research Unit (ESRU), based within the Department of Mechanical

Engineering at the University of Strathclyde. The code for ESP-r is available freely and is employed mostly for research purposes. It is useful for modelling the performance of novel (or new) building fabric systems but requires the user to have considerable expert knowledge. For more information see *Energy Simulation in Building Design* (Clarke, 2001).

Analogies between heat flow phenomena and electrical flow have led to the development of the *Electrical Analogue* method. A mathematical description of an electrical system can be employed to model a thermal system due to analogies in behaviour. Similar behaviours can be found in electrical and building materials such as resistance, conductance and capacitance (Davies, 2004). This technique is predominantly employed as a research tool.

The range and capabilities of BES software, both commercial and academic, are described in *Contrasting the capabilities of building energy performance simulation programs* (Crawley *et al.*, 2008) and *Building simulation: an overview of developments and information sources* (Hong *et al.*, 2000).

The software developed by, or supported by, the U.S. Department of Energy for thermal modelling of buildings is worth further description in the context of this thesis. This includes DOE-2 and BLAST, which although both over 30 years old are still in current use, and the more recently developed EnergyPlus. All three programs are in the public domain and can be used by third party developers with extensive online support[39].

DOE-2, developed by the Lawrence Berkley Laboratory, is still used as the thermal simulation engine by a number of private software companies who provide a GUI [Graphical User Interface] to aid the user. Blast (Building Loads Analysis and System Thermodynamics) was developed to estimate peak load and annual energy performance (Crawley *et al.*, 2008).

---

[39] http://www.doe2.com/ and

http://apps1.eere.energy.gov/buildings/energyplus/energyplus_documentation.cfm

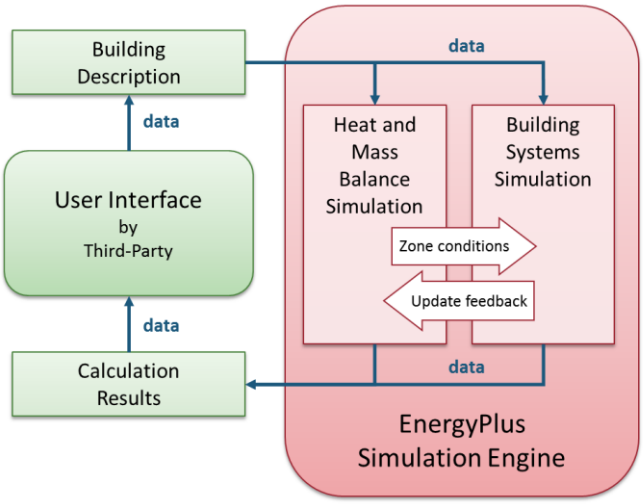


Figure 5-4 The EnergyPlus simulation engine

EnergyPlus has a basic, non-graphical user interface, created with the intention that an interface can be developed by third-parties (after Crawley et al., 2001).

EnergyPlus was developed to combine the best features of DOE-2 and BLAST with new, modular, structured code. A comparison between DOE-2, BLAST and EnergyPlus is given by Crawley et al, significant improvements in EnergyPlus are the integrated, simultaneous simulation of the building with the HVAC equipment and the ability to define the time set interval. EnergyPlus reads input and writes output as simple ASCII text files. It has a basic, non-graphical user interface, created with the intention that an interface could be developed by third-party as illustrated in Figure 5-4 (Crawley *et al.*, 2001). Market leading software such as DesignBuilder and Bentley (AECOsim and Hevacomp) use it as the analysis engine, for more information see *EnergyPlus Graphical User Interfaces* [40].

DR12. The software shall provide an interface to multiple thermal simulation engines, both inbuilt within the software and as standalone software

There are a range of thermal algorithms and simulation engines, many freely available, that should be either fully integrated into software or maintained as standalone software linked to new software. Given the level of development, support and the extensive documentation supplied with EnergyPlus at the present time, it would be prudent that new software should be capable of employing it as a thermal engine.

---

[40] http://apps1.eere.energy.gov/buildings/energyplus/ep_interfaces.cfm

Key to this thesis is the fact that, although there are many methods and software to simulate thermal performance, all use the concept of the 'thermal zone' to describe the geometry of the building. This will be discussed in detail later in this chapter.

Daylighting simulation

Daylight refers to the level of diffuse natural light coming from the surrounding sky dome or reflected off adjacent surfaces. In comparison with the complex interactions of thermal simulation, daylight level predictions rely on basic geometry and are based on average 'ambient sky conditions'. There are three common methods to model daylight in buildings; the *split flux*, *radiosity* and *raytracing*.

A number of simulation programs now support multiple daylighting simulation engines (Reinhart, 2011). The factors employed in any simulation include the building and surrounding features and the condition of the sky, as illustrated in Figure 5-5, and are the same for all methods.

The BRE [Building Research Establishment] *Split flux* method estimates natural light arriving at a point inside a building in three ways. The Sky component is light direct from the sky, through an opening such as a window. The externally reflected component is light reflected off the ground, trees or other buildings. The reflected component is the inter-reflection of light from other surfaces within the room.

The *Radiosity* method treats each surface in the space as a perfectly diffuse reflector. Radiation exchange between two surfaces can be described by a single number that depends upon the scene geometry and the reflective properties of the surfaces.

The r*ay tracing* (backward) method simulates individual light rays in space "backwards" from the point of measurement to a light source to calculate the luminance of that given viewpoint.

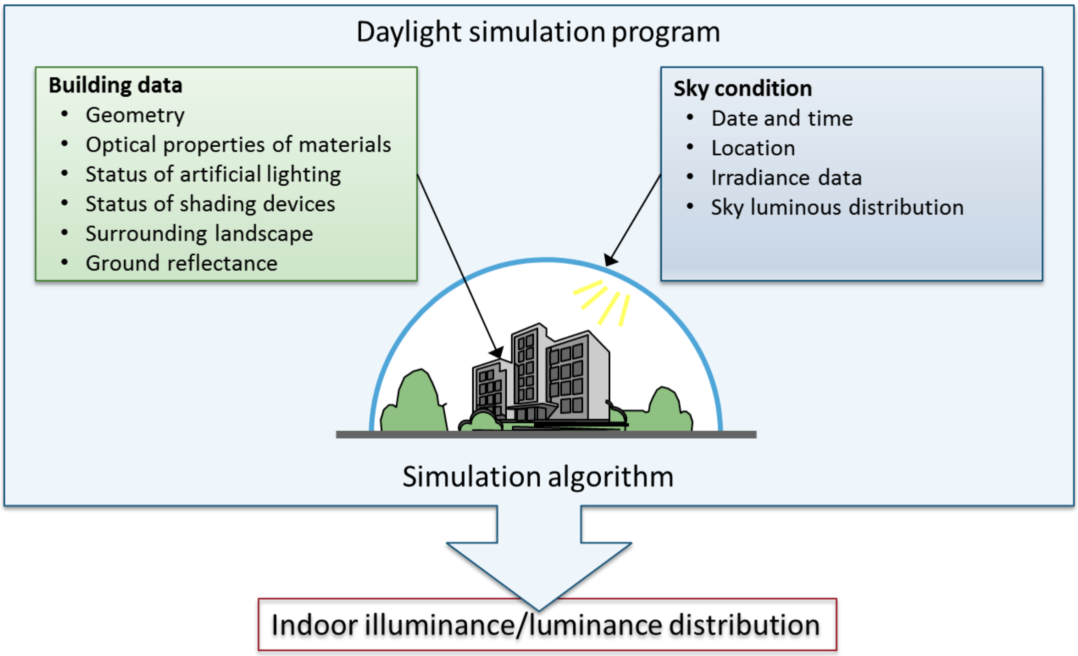


Figure 5-5 The factors that affect internal illuminance distribution

The building factors that affect the level of light on an internal surface include the geometry of the building, the optical properties of the materials, internal lighting, shading devices, surrounding landscape and the ground reflectance. The sky condition factors are determined by the date and time, the location, irradiance and the luminous distribution (after Reinhart, 2011).

A detailed description and comparison of the methods for daylighting simulation is given in *Building Performance Simulation for Design and Operation* (Reinhart, 2011). The split flux method has largely been superseded by the other two methods, due to inaccuracies in the results. Radiosity is less computationally demanding than ray tracing and hence quicker. Ray tracing can give better results with complex building forms. The Lawrence Berkeley Laboratory has developed Radiance, a freely available suite of tools that employ ray tracing algorithms that could be included in any proposed software.

DR13. The software shall provide an interface to daylight simulation engines, both inbuilt within the software and as standalone software

There are a range of daylight algorithms and simulation engines, many freely available, that could be either fully integrated into software or maintained as standalone software linked to new software.

Irrespective of the method used for daylight simulation, the requirement for the geometrical model of the building used in the calculation remains the same, as will be discussed later in this chapter.

Ventilation simulation

Most BPS has, until recently, been used for the design of HVAC systems to provide either heating or cooling to a space, in addition to providing fresh air. However, with the need to both reduce energy and provide better indoor air quality, there has been a move towards both natural and mechanically assisted ventilation where design parameters include the layout and size of windows and floor planning.

Srebric gives three methods of modelling airflow; *semi-empirical equations*, *multi-zone airflow networks* and *CFD* [Computational Fluid Dynamics]. However, there is at present, no standard design procedure for natural ventilation (2011).

Semi-empirical equations were developed and calibrated with empirical coefficients to predict airflow rates through building enclosures.

Multi-zone airflow networks rely on the subdivision of a building into a number of zones (or volumes). Algorithms are employed to estimate airflow both within a space and between zones through openings such as doors, windows and structural leakages. Problems with this method, in relation to large openings, have led to the *hybridization of multi-zone airflow networks*. These methods employ simulations of boundary conditions to model non-uniform conditions within the zone and hence improve the simulation.

CFD is employed to provide detailed predictions of air velocities, temperatures and contaminant concentrations. CFD uses numerical methods and algorithms to solve and analyse air flows in a building. It works by subdividing an interior volume into a number of cells that with air flow between neighbouring cells satisfying the laws of conservation of mass, energy and momentum.

A detailed description and comparison of the methods for ventilation performance prediction is given in *Building Performance Simulation for Design and Operation* (Srebric, 2011). Semi-empirical equations have mainly been superseded by the other two methods. Multi-zone airflow network models are considered to be adequate for buildings that are expected to have relatively uniform indoor parameters. CFD is recommended for more complex building types, such as theatres, with spaces containing large volumes of air. CFD, however, is computationally demanding and requires expert knowledge for its application.

DR14. The software shall provide an interface to ventilation simulation engines, both inbuilt within the software and as standalone software

There are a range of ventilation algorithms and simulation engines, many freely available, that could be either fully integrated into software or maintained as standalone software linked to new software.

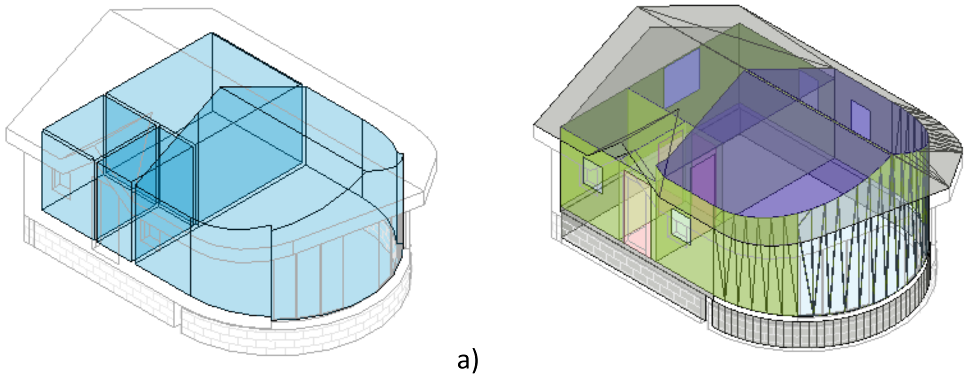
Multi-zone airflow network models and CFD models require different building geometries as will be discussed in the next section. EnergyPlus supports multi-zone airflows.

5.5.1 Methods for modelling a building for simulation

Modelling for simulation requires a degree of abstraction. Unlike an architectural model it is not a detailed representation of the geometry and objects that make up a building, but only those aspects that are important for the analysis in hand. Unnecessary detail will slow an already computationally demanding process. As discussed above, thermal, daylight and ventilation simulation each require different modelling methods which results in the need for specific requirements for the building model geometries.

The thermal zone is a concept employed for calculating heating and cooling loads in buildings. For calculation purposes and in particular computer modelling, zone boundaries are mathematical artefacts separating regions of the building with different internal conditions. They are usually actual physical objects such as walls and floors, but their constructional details such as thickness and composition are not used directly in calculations. These details are however, used to calculate parameters employed in mathematical models. Thus in preparing a 3D model for use in thermal simulation engines, the interfaces between the zones and the exterior and neighbouring zones must have zero thickness. In a temperate region the internal air temperature of a zone is determined by the energy inputs such as thermal gain from people, equipment, solar radiation entering through windows and heating systems and the energy losses via the fabric and ventilation. In hot regions, the external temperature may be higher than the desired internal temperature and internal heat gain may be via conduction through the fabric. In both cases thermal storage effects will be important when considering heat flow through the fabric. In addition heat transfer through the fabric involves not only transfer through the exterior to the interior but also transfer between neighbouring zones.

Each zone should represent an enclosed volume of relatively thermally homogeneous air, normally a single room. However, for a very large space, with windows on all sides, it may be appropriate to sub-divide it into multiple zones to allow for differences between the north, south, east and west sides. Equally, two or more small inter-connecting rooms may be grouped into a single zone, as they are subject to the same thermal effects and can be considered to act as a single air volume. Each thermal zone requires a complete envelope of enclosing surfaces to enable the calculation of inter-zonal heat flow paths and incident radiation. The enclosing surfaces are planes of zero thickness with co-planar interfaces between neighbouring zones, i.e. the thickness of the real construction is not shown. Almost all thermal analysis algorithms calculate a single temperature for each zone which is assumed to be the average over the whole space. In practice the definition of the 'thermal view' of the building can be arbitrary as it involves the subdivision of the overall mass into a number of smaller volumes. Increased subdivisions may significantly slow any computation.



a) b)

Figure 5-6 Showing a model of a small building with a curved wall.

The curved wall is converted into a series of Cartesian points to enable use by thermal simulation software

EnergyPlus, uses zones defined by either rectangular shapes or sets of Cartesian coordinate points in its calculations (EnergyPlus Development Team, 2010). Cartesian points are coordinates that define a polygon in three-dimensions to position the element in space. Curved walls as shown in Figure 5-6 a) have to be converted into a series of planes as shown in b).

Thermal zone models need to be simple as any thermal modelling involving a number of zones is computationally demanding. Model details, such as skirtings and door knobs, add considerably to the computational load without significantly adding to the quality of the simulation. Walls, floors, roofs and internal partitions, sometimes described as "air walls", are deemed to be of zero thickness.

DR15. The software shall facilitate thermal modelling by supporting zone geometries that enclose volumes of thermally consistent air with zero thickness enclosing surfaces

The thermal zone is a subdivision of the total building volume for which internal temperatures and heat loads are calculated. Each thermal zone requires a complete envelope of enclosing surfaces to enable the calculation of inter-zonal heat flow paths and incident radiation.

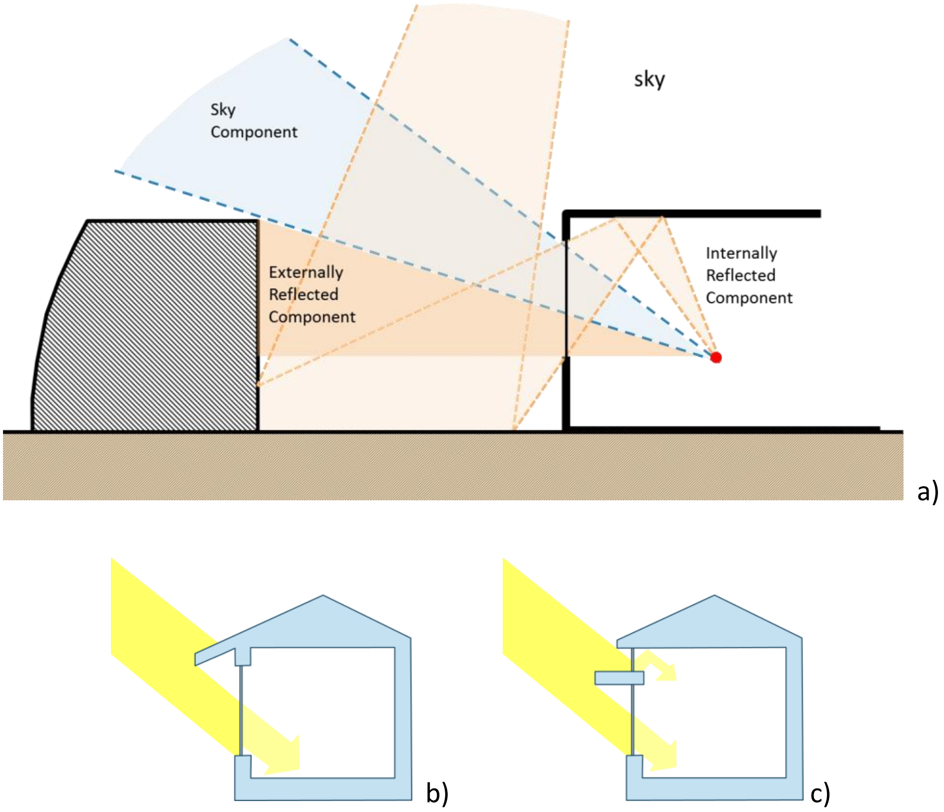


Figure 5-7 Daylight simulation in a building

A notional section through a building showing a) the available sky, an adjacent building causing an obstruction and the total light falling on a table top (after Reinhart, 2011), b) an overhang and c) a light shelf reducing direct sunlight into the building (after Goulding et al., 1992).

In contrast to thermal simulation, daylight level prediction may benefit from more a more detailed building model. The simulation method is simpler, in that it relates to the variation of sky luminance with the position of the sun in the sky relative to the building, but the building model geometry required is slightly more complex. Figure 5-7 illustrates some of the concepts involved. Adjacent objects such as buildings or trees need to be modelled in a block form as they will obstruct part of the available sky. Details of the building will also affect the daylight on the point of measurement, these include: the thickness of a wall, the size and position of openings, any overhang of a roof, shading devices and light shelves, as can be seen from Figure 5-7. In addition the optical properties, such as colour and reflectance, of external and internal materials need to be considered (Reinhart, 2011).

DR16. The software shall facilitate daylight simulation by supporting the provision of building element outlines complete with openings (wall, floor, roof, shading, plus windows and doors) and adjacent obstructions

Details of the building that will affect the calculated daylight at the point of measurement need to be modelled. This will include elements such as the thickness of a wall, the size and position of openings, any overhang of a roof and any shading devices/light shelves. Adjacent obstructions such as buildings or trees need to be modelled as they will obstruct part of the available sky. The modelling technique needs to be in the form of a simple outline of the elements.

As discussed in the previous section, there are two methods employed to simulate air flow in buildings, *multi-zone airflow networks* and CFD. Each method to predict ventilation patterns requires a different modelling technique.

As with thermal simulation methods, *Multi-zone airflow networks* requires simple zone models with zero thick enclosing surfaces (Srebric, 2011). However, as it is calculating airflow paths, each separate space requires an individual zone. In thermal models rooms with similar thermal properties, such as a row of offices, are often grouped together. Openings in the enclosures need to be modelled in order for the flow paths into and out of the building and between neighbouring zones to be calculated.

DR17. The software shall facilitate multi-zone airflow networks methods by supporting zonal geometries for each individual space with zero thick enclosing surfaces and openings such as doors and windows

Each separate space, totally enclosed by walls, floors and ceiling/roof requires an individual zone with zero thick enclosing surfaces. Openings in the enclosures need to be modelled in order for the flow paths into and out of the building and between neighbouring zones to be calculated.

CFD requires a different type of model to the zonal type described above, however, it is still a more simplified version than the detailed model that an architect would produce. CFD models are computationally demanding; a balance needs to be achieved between including elements that will obstruct airflow and over complicating the model.

DR18. The software shall facilitate CFD modelling by supporting the provision of a simplified outline of the building including internal partitions and furniture and occupants

The important elements are boundary conditions and may include internal partitions and furniture, such as tables and computers, in addition to enclosing elements such as walls, ceilings, and openings, all of which need to be modelled (Srebric 2011). Items such as computers or people are modelled as simple blocks, without any detail, to reduce the computational load

5.5.2 Information associated with simulation

This section is concerned with the range and type of data employed in BES calculations.

DR19. The software shall record the building type

The building type, or usage, needs to be recorded as it will affect occupant comfort standards such as temperature, ventilation and lighting levels. In addition equipment within the building needs to be taken into account as it will give rise to incidental heat gains.

DR20. The software shall record the location of the building site

The building location determines the weather and solar data employed in building performance calculations and the regulations relating to simulation methods.

DR21. The software shall facilitate the input of historical and predicted weather data

Although the building location would normally determine the current weather data to be employed in simulation, the need to consider future weather scenarios as a result of climate change should be facilitated.

DR22. The software shall facilitate the input and modification of dimensions, type, thermal and optical properties of materials surfaces.

The input and modification of building material properties are required as part of the iterative process of simulation and analysis of the performance of the building proposal. Whilst the dimension and type of a material would be contained within a building model, the density and specific heat capacity is currently not a standard property in BIM software but will affect thermal calculations[41]*. Other material properties are absorptance, emittance, reflectance and transmittance that are all employed in solar gain calculations. Optical properties, such as the reflection coefficient, will affect lighting calculations.*

DR23. The software shall provide the facility to export data in the gbXML format

There may be a need to run simulation and analysis in other types or performance prediction software. The standard interoperable format is gbXML.

5.5.3 Visualisation of energy simulation

The visualisation of data, both entered and as a result of energy simulation, is crucial to the understanding of the implications of building design decisions. This was one of the themes identified in the case study reported in Chapter 4.

---

[41] These values are to be included in the forthcoming version, 2013 of AutoDesk's Revit, see http://usa.autodesk.com/revit/architectural-design-software/#whats_new

DR24. The software shall display/confirm default values used in calculations

Simulation engines may employ default values for generic building models. If these values are incorrect for the simulation in hand and remain unchanged there is potential for significant errors/variations in the analysis (Jankovic, 2012). These values need to be made explicit.

The results of BES are numerical. With software such as Ecotect, they are typically displayed as both tables of numbers and graphs.

DR25. The software shall provide multiple methods to display results from BES

The integration of BIM and BES presents opportunities to display results in a variety of methods in addition to tabular and graphical, with incorporation within the 3D display.

As discussed in Chapter 3, the optimisation of a building design requires iterative explorations of the effect of modifying many parameters.

DR26. The software shall provide methods to record and display results from previous building designs/simulations

The comparison of results from previous design alternatives is an important feature for optimization of the building form to balance predicted energy performance with aesthetics.

5.6 Design Advisory Systems

A decision support system should assist the designer rather than replace the designer. The designer should make all decisions associated with conceptualisation, intuition and creativity. A computer can be employed to support the designer by providing speed of calculation, accuracy and the persistent storage and sorting of vast amounts of data (Pohl *et al.*, 2000).

Chapter 2 outlined previous work in the area of DASs. Three relevant systems were identified:

- The ICADS [Intelligent Computer-Aided Design System] (Pohl *et al.*, 1992) developed in the 1980's by the CAD research unit at California Polytechnic State University.
- The Building Design Advisor (Papamichael, 1997) developed in the 1990's at the Lawrence Berkeley National Laboratory.
- The MIT Design Advisor (Urban & Glicksman, 2006) developed in the 2000's.

The ICADS system was intended to support design decisions based on the comparison of alternative courses of action by taking into account a variety of performance considerations. These agents communicated via a centralised data handling system, called a *data-blackboard* that routed messages to the seven advisory components and handled conflict resolution. Any conflicts between two components, such as solar gain problems arising from increased window area for better daylighting could be flagged up. It employed CLIPS, a rule based expert system shell written in C (Pohl *et al.*, 1992). However, development of the ICADS system stopped around the beginning of the 1990s.

The other two systems, the Building Design Advisor and the MIT Design Advisor, although termed design advisors, only provide energy analysis functions which can be employed to compare design alternatives to support informed decisions. They both employ relatively simple BPS engines, with building geometry limited to rectangular forms, to give quick responses in the early stages of design. They support design decision making but do not offer guidance or support on either the input or output data. Nor do they afford the ability to compare a range of performative considerations. It could be argued that they offer no improvement over the use of standalone software such as Ecotect[42] or Project Vasari[43] used in conjunction with a spreadsheet to record the results of design iterations/alternatives. However, the Building Design Advisor was origionally intended to be more ambitious with,

---

[42] *http://*www.autodesk.co.uk/ecotect-analysis

[43] http://labs.autodesk.com/utilities/vasari

for instance, the use of links to web pages intended to provide users with examples of exemplar energy efficient buildings.

5.6.1 Modelling software and expert systems

A DAS is a type of expert system, which emulates the decision-making capabilities of a human expert and could be utilised as part of an advisory system. Expert systems are now employed in a number of fields such as agriculture, education, engineering, geology and medicine. They are a branch of Artificial Intelligence (Feigenbaum, 1982).

Expert systems work best in a narrow domain of reasonable complexity with well-defined boundaries (Feigenbaum, 1982). In addition, the implementation of an expert system can be lengthy and expensive with subsequent, additional high maintenance costs (Laudon & Laudon, 2012).

Typically there three components to an expert system: the *knowledge base,* the *inference engine and a user interface*. These will be discussed in the following sections and software requirements established.

DR27. The software shall provide a user interface to a Design Advisory System

The user interface enables the user to query the system and receive the results of those queries. A facility which explains how a result or solution was obtained should also be provided.

The geometry employed by the integrated CAD system was identified as a limitation of the ICADS system by (Pohl *et al.*, 1992). The ICADS system needed the building design to be represented as a high level of abstraction, that is as real world objects such as spaces, walls, openings etc. However, at that time, CAD systems represented buildings as a set of lines and points. Contemporary BIM systems now employ modelling with real world building objects which could overcome that drawback.

DR28. The software shall employ geometries that represent real world building spaces or objects

The use of zones, or spatial volumes, would enable a DAS system to provide targets and advice specific to a particular space or volume such as a building or a room or set of rooms in a building.

5.6.2 Information provided by the design advisory system

The ICADS system was ambitious being required to interpret and give advice on seven domains. The developers found it difficult to integrate the separate subject areas with sets of rules to give an adequate level of reasoning on the design (Pohl *et al.*, 2000). The system described here relates to the provision of advice rather than attempting to guide the design process.

In an expert system the *knowledge base* contains the knowledge provided by domain experts. It is a type of database designed for knowledge management. A knowledge base is a repository that enables information to be collected, organized, shared, searched and utilized. The *inference engine* manipulates the knowledge from the knowledge base to arrive at a result or solution. The inference engine employs logic to produce reasoning. Typically it uses rules in the form of IF… THEN….. Specific languages and tools have been developed for creating expert systems that require significant programming expertise. As a result 'shells' have been developed where the user supplies only the knowledge base. An example is CLIPS[44], a rule based expert system shell written in C, developed by the Software Technology Branch (STB) at the NASA/ Lyndon B. Johnson Space Center in the 1980s. Another example is Jess[45], developed for the Java platform by Ernest Friedman-Hill of Sandia National Labs.

The universal acceptance of Internet technologies such as the World Wide Web and Cloud computing, provide the means of both compiling and sharing the type of information discussed in this section.

---

[44] http://clipsrules.sourceforge.net/

[45] http://www.jessrules.com/

DR29. The software shall store building design information

In expert systems the knowledge base employs a database designed for knowledge management. A knowledge base is a repository that enables information to be collected, organized, shared, searched and utilized.

DR30. The software shall derive answers from information stored by the software and provided by users

In expert systems the inference engine manipulates the knowledge from the knowledge base to arrive at a result or solution.

DR31. The software shall provide advice on energy and targets

There are now emerging different approaches to measuring energy and setting targets, as discussed in Chapter 3. The software should provide advice on these varying methods.

DR32. The software shall provide details of exemplar projects and buildings

The new approaches to the design of high performance buildings and new methods of building construction arising from energy legislation can be shared by means of the DAS. New interactive methods of information presentation and interaction could be employed.

DR33. The software shall provide location advice

The building location can affect many decisions to be made by the building designer, from legal requirements, to building materials, to vernacular responses, to local climate.

DR34. The software shall provide advice on legal requirements

As discussed earlier in this thesis, legal requirements for buildings, particularly in the field of energy and carbon dioxide emissions, are currently undergoing rapid and radical change. The software could assist the building designer to assimilate and apply new legislative policies.

DR35. The software shall provide material, construction and product advice, including embodied energy and energy used for transport

In response to the changes in energy policies buildings are becoming more sophisticated and finely tuned. New materials and products are leading to changes in traditional building construction methods.

DR36. The software shall provide advice related to the design stage

Advice provided by the DAS would need to be related to the particular design stage. Stages could range from, inception, early design, detailed design through to construction and building management.

DR37. The software shall provide information regarding POE from other projects

DR38. The software shall record POE data

As discussed in Chapter 2, there is an acknowledged gap between predicted building performance, actual energy used and occupant comfort levels. AEC professions would benefit from access to data from POE from other, similar, projects and correspondingly should record data on completed projects to add to the pool of knowledge[46].

---

[46] See http://www.carbonbuzz.org/index.jsp

5.6.3 Visualisation of DAS information

DR39. The software shall support the comparison of energy performance prediction results with targets

Energy targets are key to the integration of BIM and BES software. The DAS component should be employed to monitor predicted energy performance against energy and comfort targets and display the results visually , perhaps integrated with the 3D building model within the building design environment.

5.7 Implications for new combined software

In this section the requirements for BIM, BES and DAS have been carried forward, organised into themes and complied into 3 tables which are further divided into subthemes, employed to structure the discussion in this section. The different approaches to the modelling of buildings between BIM and BES software are critically compared and the contribution the DAS could make to design decision making is discussed. Implications for future software development are drawn.

5.7.1 Building modelling and simulation

The theme of building modelling and simulation has been broken down into two subthemes: interface design and geometric modelling and requirements grouped accordingly in Table 5-1. Interface design is the first grouping, whilst it is not strictly building modelling, it is necessary to facilitate the process.

BIM	BES	DAS
Interface design		
DR1 The software shall provide a user-friendly building design environment	DR12 The software shall provide an interface to multiple thermal simulation engines, both inbuilt within the software and as standalone software DR13 The software shall provide an interface to daylight simulation engines, both inbuilt within the software and as standalone software DR14 The software shall provide an interface to ventilation simulation engines, both inbuilt within the software and as standalone software	DR27 The software shall provide a user interface to a Design Advisory System
Geometric modelling		
DR2 The software shall provide a method of modelling a building with objects that represent real world entities such as doors, walls and windows with rules as to how they relate and connect to each other DR3 The software shall provide a method to record and share information about the building model DR4 The software shall provide a method to enable building objects to be positioned in 3D DR5 The software shall provide methods to generate 3D models of building volumes: extruded 2D shapes and 3D primitives, combined with surface modelling with NURBS	DR15 The software shall facilitate thermal modelling by supporting zone geometries that enclose volumes of thermally consistent air with zero thickness enclosing surfaces DR16 The software shall facilitate daylight simulation by supporting the provision of building element outlines complete with openings (wall, floor, roof, shading, plus windows and doors) and adjacent obstructions DR17 The software shall facilitate multi-zone airflow networks methods by supporting zonal geometries for each individual space with zero thick enclosing surfaces and openings such as doors and windows DR18 The software shall facilitate CFD modelling by supporting the provision of a simplified outline of the building including internal partitions and furniture and occupants	DR28 The software shall employ geometries that represent real world building spaces or objects

Table 5-1 Requirements for BIM, BES and DAS collected into a building modelling and simulation theme

Interface design

The design of the interface will present challenges as the majority of the features listed in tables 5.1, 5.2 and 5.3 would need to be supported by the software. The requirements that relate specifically to an interface are: the building design component (DR1), the energy simulation components (thermal DR12, daylight DR13 and ventilation DR27) and the design advisory components (DR27). They are high-level goals that would require significant development into product specific technological requirements. As discussed earlier, the adoption of BIM by the architectural design profession and the use of BES is limited. Success for new software would rely on the development of an intuitive, user-friendly interface. Given the range and diverse mix of software functions listed in the requirements in this chapter this is a non-trivial task.

Geometric modelling

The modelling methods of BIM (building objects DR2 and positioning of those objects 0) and BES (zones for thermal simulation DR15, building outlines for daylight DR16, multi-zones for ventilation DR17 and building and obstacle outlines for CFD DR18) are very different. DAS requires building spaces and real world objects to link to the knowledge base (DR28). To encourage regular simulation, by either efficient interchange of data between the types of software (interoperability) or combined software, these different ways of providing geometric modelling must be reconciled. The solution to this conflict will be further explored in the following two chapters.

5.7.2 Information and design decision support

This theme has been employed to analyse all the data or information issues relating to the three components, BIM, BES and DAS of the proposed software. The theme has been divided into a number of areas: knowledge storage and retrieval, building type, location, building materials, interoperability and design stages. The requirements for BIM, BES and DAS are carried forward and organised into these subthemes in Table 5-2 and discussed in the following section.

BIM	BES	DAS
Knowledge storage and retrieval		
		DR29 The software shall store building design information DR30 The software shall derive answers from information stored by the software and provided by users
Building type		
	DR19 The software shall record the building type	DR31 The software shall provide advice on energy and targets DR32 The software shall provide details of exemplar projects and buildings
Location		
	DR20 The software shall record the location of the building site DR21 The software shall facilitate the input of historical and predicted weather data	DR33 The software shall provide location advice DR34 The software shall provide advice on legal requirements
Building materials		
DR6 The software shall provide schedules of building objects, materials, geographical information and equipment	DR22 The software shall facilitate the input and modification of dimensions, type, thermal and optical properties of materials surfaces.	DR35 The software shall provide material, construction and product advice, including embodied energy and energy used for transport
Interoperability		
DR7 The software shall provide the facility to export the building model in a standard format	DR23 The software shall provide the facility to export data in the gbXML format	
Design stages		
DR8 The software shall facilitate lifecycle data documentation		DR36 The software shall provide advice related to the design stage DR37 The software shall provide information regarding POE from other projects DR38 The software shall record POE data

Table 5-2 Requirements for BIM, BES and DAS collected into an information and design decision support theme

Knowledge storage and retrieval

The storage (DR29) and retrieval of design advice (DR30) are core features of an Expert System. Whilst this is a technical solution, it is included to gain an understanding of how existing systems work.

The contents of the knowledge base would include a mixture of rules of thumb (DR36), material, product and construction data (DR35), building exemplars (DR32), energy targets (DR31) and legislative requirements (DR34).

There would be interplay between many of the features listed in this section with the inference engine employed to supply relevant data. For example, given a location then the legal requirements for that area, the types of local building materials, the transport implications for materials, the typical building form, etc. could all be information required by the architect. For a given stage (DR36) in the building design, with a particular building type (DR19) and a particular location (DR33), the system would provide relevant advice. For instance in early building design stage (DR36) for an office (DR32 and DR37) located in the south of France (DR33) it might recommend an H plan form to facilitate natural ventilation and daylighting. It could also be employed to monitor the predicted building performance against energy targets (DR39, see table 3).

Building type

The building type (DR19) is recorded as a BES requirement; however, it is closely linked to the advice that could be provided by the DAS, such as exemplar buildings (DR32), legal requirements (DR34) and POE data (DR37).

Location

The location of the proposed building (DR20) affects weather data employed in BES. However, the location affects advice that the DAS could provide (DR33), for instance on exemplar buildings in the locality (DR32), relevant legal requirements for the area/country (DR34), typical vernacular approaches/materials employed in buildings (DR35), energy in transport associated with the both construction and use of the building, and POE data for similar building types in the locale (DR37).

Building materials

Building materials and product details are core to the setting the properties of building objects (DR2). Consistent and comprehensive recording of this data is important to: the provision of building schedules (DR6), interoperability of data (DR7 and DR23) the production and management of lifecycle documentation (DR8), visualisation and rendering of the building design (DR9) values employed in BES calculations (DR24) and construction and product advice (DR35).

Design stages

As discussed in Chapter 2 all buildings go through a number of stages from feasibility, early design, through detailed design to construction. A requirement of the DAS is to provide advice relative to the design stage (DR36). BIM is also being increasingly employed for lifecycle data (DR8) and POE for data to inform decisions during design (DR37) and after completion (DR38). Once a virtual model exists of the building design it can be employed to record changes to the building both as it is constructed and once it is in operation. Lifecycle data could include embodied energy and re-cycling potential (DR35) The inclusion of lifecycle data is not technically challenging but would involve significant changes in working practices and the software tools required. Whilst the main purpose of this thesis is concerned with the integration of BIM and BES software, employed primarily in the early and detailed design of buildings, to fully support energy modelling, future software will need to support all stages in the design process. As discussed in Chapter 2, and earlier in this chapter, predictive methods for energy consumption still require significant improvement to narrow the gap between predicted and actual usage. The improvement of the predictive methods relate directly to being able to record and extract POE data from building models (DR37 and DR38) to improve energy simulation.

The consideration of multiple design stages may influence the development of the design user interface (DR1).

5.7.3 Visualisation of the model and energy data

This theme has been employed to analyse the requirements relating visualisation of the model and associated data for the three components, BIM, BES and DAS of the proposed software. The theme has been divided into two separate areas, design visualisation and energy simulation. Requirements for BIM, BES and DAS are carried forward into Table 5-3 and discussed below.

BIM	BES	DAS
Design visualisation		
DR9 The software shall provide 2D and 3D visualisation, rendering and printing DR10 The software shall provide collision detection DR11 The software shall provide the facility to set the location and use a satellite map to position the proposed building		
Energy simulation visualisation		
	DR24 The software shall display/confirm default values used in calculations DR25 The software shall provide multiple methods to display results from BES DR26 The software shall provide methods to record and display results from previous building designs/simulations	DR39 The software shall support the comparison of energy performance prediction results with targets

Table 5-3 Requirements for BIM, BES and DAS collected into a visualisation theme

Design visualisation

The visualisation of the building model in a number of ways (DR9, DR10 and DR11) are standard features of existing BIM software and, although technically challenging, solutions to these problems already exist. However, along with the development of a suitable interface

(DR1) as discussed earlier, display of the building model in a user-friendly manner is a key goal for the acceptance of any new software by design professionals.

Energy simulation data visualisation

These requirements are where the opportunity for new approaches in the display of energy targets (DR31, table 2) and the input (DR24) and output (DR25) of data along with the 3D representation of the building model (DR9) exist. The display of different types of information would need to be incorporated including 3D models, these include textual information, numerical information and graphical information. The three components of the software could work together to aid the architect in gaining a better understanding of how energy is used in the building.

5.8 Conclusion

This chapter has described and analysed the methods used by existing software tools. High level domain requirements were established to describe how the proposed software should work. Domain analysis was employed to gain a better understanding about systems, data and functionality with this previously unarticulated knowledge (Robertson & Robertson, 2006). Multiple viewpoints of the domain, BIM, BES and DAS, were employed to gain better coverage of the requirements and identify interfaces, conflicts and inconsistencies (Sommerville & Sawyer, 1997). The salient geometric modelling, information and visualisation requirements for BIM, BES and DAS were recorded. These requirements were compared and conflicting approaches to the generation of the building model established. In particular the different ways of providing geometric modelling by BIM and BES was established. To encourage the regular use of simulation, by either efficient interchange of data between the types of software (interoperability) or combined software, this conflict must be reconciled and this will be further explored in the following two chapters.

Issues with the lack of or limited interoperability were highlighted in the literature in Chapter 2 and included in this chapter as requirements. The next chapter explores further the differing approaches to the recording of building geometry and building material properties by existing, industry standard interoperable languages. The IFC and gbXML standards are analysed in the following chapter to establish how geometry and building material properties are recorded and to explore if the conflicts identified could be resolved in order to better support iterative building design.

The analysis of domain requirements has resulted in implications for new integrated software being identified. This analysis will be employed in Chapter 7 to propose a new approach to building design software.

Chapter 6

The Building Model and Interoperability

The differing approaches of existing software for the design and energy simulation of buildings were analysed in the previous chapter. It was suggested that to achieve efficient interchange of information the conflicting methods of recording building models and in particular the geometries needs to be resolved. The aim of this section is to investigate how interoperable standards could be modified to better support automatic transfer of data both to and from BES and BIM. The following research questions are addressed:

1. What are the characteristics of current interoperable standards used in BIM and BES?
2. How is data relevant to thermal simulation handled by these different standards?
3. How could interoperability be improved to support reliable information interchange between BIM and BES and resolve the problems resulting from different geometrical approaches to creating building models in BIM and BES?

Effective interoperability is an important part of a vision for an integrated software toolset for a number of reasons. First, it enables ownership of all the building data with the client. Rather than ownership of a building model, constructed for a particular purpose, remaining with a consultant, using a particular brand of software, it should be capable of being moved to another software system. This means that the model can be used from the inception to beyond the completion of a project to enable life-cycle management of the building. Secondly, effective interoperability also enables transfer of models to and from different types of BES and BPS software. In particular, it would facilitate the transfer of data to thermal/energy engines not integrated into the proposed integrated software or other types of analysis software. Finally, it could form the basis for the data model for the proposed integrated software to enable real-time, iterative and on-going thermal analysis. According to Eastman et al. (2011) some BIM applications use IFC as their native data model.

This section of the thesis takes the form of a *speculative investigation*, with a potential practical application. Speculative theoretical investigation involves the development of concepts (Génova, 2010). The investigation is employed as part of the *generate* phase of the Research Through Design approach of this thesis (Zimmerman & Forlizzi, 2008). A critique of existing interoperable languages is undertaken with new framings investigated and new approaches to handling building data proposed. The aim is to produce knowledge and gain validation of the ideas through communication of the concepts developed to the community of researchers for review[47]. The practical application could influence the development of interoperable standards in the AEC industry.

The concept of interoperability is introduced and the application in the AEC industries is outlined. The interoperable languages relating to BIM and BES, IFC and gbXML are described and compared. Options for changes to the standard to resolve the differing approaches to geometrical representation of the building are presented and compared. Finally recommendations are proposed for changes to rules included in the IFC standard for model composition and the provision of building construction/material exemplars, relevant to the transfer of data for energy modelling,

6.1 Interoperability

There are many definitions of interoperability. The definition, given by the IEEE Glossary, is the most relevant to this context; it is "*the ability of two or more systems or components to exchange information and to use the information that has been exchanged*" (IEEE Computer Society, Standards Coordinating Committee, 1991)

---

[47] A paper entitled 'Integrated Building Design, Information and Simulation Modelling: The Need for a New Hierarchy' based on this work was accepted for Building Simulation 2011, following a double blind abstract review and a double blind review of the full paper. A travel grant of $1000 US was awarded by IBPSA to attend the conference. The award was based on the quality of the paper.

Interoperability and Open Standards [standards that are publically available and usually implemented on a 'Royalty-Free' basis] aim to provide efficient, effective exchange of information between computer systems. The mechanism for accomplishing that goal is achieved in different ways, however, Open Standards imply interoperability. Interoperability affects power relationships in the software industry. Software companies do not always support interoperable standards as their adoption can threaten the maintenance of dominant market positions. This has been demonstrated by the European Union versus Microsoft competition case (European Commission Legal Service, 2007). Microsoft was found to have deliberately restricted interoperability between Windows work group servers and non-Microsoft work group servers.

In the AEC industry there is concern that software companies are now developing suites of modelling and construction-related software with good data interchange within these suites of tools but not to applications produced by competitors (Jardim-Goncalves & Grilo, 2010; Hamza & Horne, 2007). An example of this is Revit Architecture ↔ Revit Structural ↔ Revit MEP all developed by Autodesk[48]. With this suite of software proprietary formats, RVT and RFA[49], are employed to exchange and coordinate data between building design consultants working with Revit products, rather than Open Standards that would allow the use of software from other companies. Although it is possible to export building data in the form of both IFC and gbXML, the case study reported in Chapter 4 highlighted that the data contained in these formats were limited with important information not always retained in both data files.

6.1.1 Standards in the AEC industries

Standards have an important role in the construction industry and the widespread growth of IT has resulted in the need for improvement and development of data transfer methods. Interoperability in the AEC field began with file-based exchange formats limited to geometry

---

[48] http://usa.autodesk.com/

[49] Revit *Projects* have a file extension *.rvt.* Revit *Families* have a file extension *.rfa*. Revit *Projects* contain the geometry and information relating to a building project. Revit *Families* are files external to the project that are either preloaded in *Project* templates or loaded as required into Revit *Projects* to represent building components such as doors, windows, furniture, casework, structural members, fixtures & equipment, etc.

such as DXF and DWG [DraWinG]. Geometry exchanges between CAD-type applications, using these well-established exchange formats, are fairly robust and reliable. However, the need to include semantic data, describing properties of parts of the building, has resulted in the development of new data models to support product and object model exchanges in the various sections of the AEC industry. A review of this development is given in *Product Modelling in the Building and Construction Industry: A History and Perspectives* (Dado *et al.*, 2009). BIM, developed in the last 10 years, carries significantly more information compared with CAD and so places more demands on interoperable languages. Poor interoperability, in addition to the more obvious penalties of time and error associated with the manual transcription of data, can also restrict business practices. Good interoperability has the potential to open up new possibilities through the use and speed of automation (Eastman *et al.*, 2011).

There are many distinct professionals involved in the construction industry with each using computer applications designed for their specific needs, with their own method of representation of a building. This results in many types of exchange formats used in AEC applications for data transfer. This ranges from COBie [Construction Operations Building Information Exchange], containing non-graphical information in a spread sheet format to IFC, intended to contain all of the different information regarding a building over time. The predominant standards in current use for data exchange between BIM and BES software are IFC and gbXML (Eastman *et al.*, 2011; Dong *et al.*, 2007). These standards will be dealt with in depth in the following sections.

The exploratory case study reported in Chapter 4 found that there are limitations associated with the export and import of data between BIM and thermal simulation software. The findings from the case study relate to two areas:

- The use of different methods of modelling in the different types of software, BIM assembles ‘building objects’ whereas energy analysis software requires ‘thermal zones’, defined by enclosing surfaces of zero thickness, thus making the exchange of geometric data problematic.

- Data relating to materials used for building elements were lost or over-written with default values during transfer between the software and had to be re-entered.

6.1.2 Interoperability and information exchange

This section provides a more in-depth review of the published work relating to interoperability than that presented in Chapter 2. The aim of Chapter 2 was to establish the need for improved software, of which interoperability is a part, but in order to make recommendations for change, a better understanding of the topic of interoperability in the AEC industry is necessary and thus a more detailed analysis is provided in this chapter.

Interoperability, enabling building professional software to exchange information, is seen as important by both industry (McGraw-Hill Construction, 2008; Khemlani, 2004), academia (Amor & Dimyadi, 2010; Eastman *et al.*, 2010; Howard & Bjork, 2008; Bazjanac, 2002) and government (Gallaher & Chapman, 2004). Interoperability is seen to be critical for the success of BIM with the lack of it adversely affecting business and management processes (Grilo & Jardim-Goncalves, 2010). In comparison with computing subjects such as Requirements Engineering, the published research into interoperable standards is relatively limited[50], especially given the commercial implications to the AEC industry (Howard & Bjork, 2008) and the cost of inadequate data transfer. In 2004 it was estimated the cost of inadequate interoperability in the U.S. capital facilities industry was $15.8 billion per year (Gallaher & Chapman, 2004). The development of interoperable standards has been led by the software industry, however, the depth of commitment of the software vendors has been questioned (Howard & Bjork, 2008; Grilo & Jardim-Goncalves, 2010). Eastman et al. (2011) discuss the implementation of technological interoperable frameworks by computer scientists through the development of languages such as EXPRESS (the basis for IFC) and XML. They argue that domain experts, such as architects, could be better at defining the content of information exchange – *"user-defined exchange standards seem an imperative"* (Eastman *et al.*, 2011, p.104). Hence the motivation for this chapter.

There has been a significant increase in published work relating to interoperability in AEC software in the last two years (as can be seen by the number of references in this thesis

---

[50] A search carried out on 24th January 2012 using Google Scholar on the term "requirements engineering" since 2009 returned 10,100 results, with the top return cited by 1625. A similar search on "industry foundation classes" returned 608, with the top return cited by 10. An alternative search tem of "building information modelling", thought to widen the search, returned only 610, with the top return cited by 43.

dated 2010 and 2011). The emerging themes regarding interoperable standards, such as IFC and gbXML, form the basis for the following section include:

- The need for tighter implementation of the standards.
- Questioning the form and content of the standards.
- Concern regarding the future development of the standards.

A ‘BIM Schema’ describes the structure and content of information about buildings used in project communication. A tighter implementation of BIM schemas is regarded as an imperative by many, with suggestions for improved documentation, testing and certification (Cerovsek, 2011). Eastman et al. (2010) blame incomplete and incompatible data exchange on the lack of specific task-orientated information. The breadth of the IFC schema means that errors can occur due to poor documentation relating to specific contents and level of detail of workflows. MVD [Model View Definitions] have been developed to establish a method of model exchange (BuildingSMART International Ltd, 2011b). MVD’s are described as subsets of the IFC Model Specification, created to enable data exchange between different types of software application (Hietanen, 2006). However, a more rigorous and formal manner in which to define MVD’s, with strict guidelines, is suggested to achieve a uniform mapping of building objects between BIM tools and IFCs (Venugopal *et al.*, 2010). MVD’s are discussed in more detail later in this chapter.

The nature of ad hoc testing of software and lack of rigour is an area of concern. Current IFC compliance of BIM tools involves the use of standardized test models only to inspect the visual output of the software. At present, there is no assessment of the handling of semantic data by the tool (Steel *et al.*, 2010). Lipman et al (2011) recommend improved conformance testing, comparable with that used in other engineering and industrial disciplines. Amor and Dimyadi (2010) have created an online repository for IFC data models to enable testing of software for interoperability. A standard set of IFC data files is planned that will represent the data requirements of particular processes in the AEC industry. However, they conclude that the repository is not yet sufficient to act as a suitable resource.

The form and content of BIM schemas have been questioned. Although, schemas such as IFC have been available for over a decade, a significant impact on the range of problems of AEC data interoperability has not been achieved (Eastman *et al.*, 2010; Pazlar & Turk, 2008). Cerovsek states that, although there have been drastic changes in collaborative processes and ICT in the AEC industry, the paradigms used in BIM have not changed in over 30 years. For instance, due to the ISO STEP [Standard for the Exchange of Product] legacy, discussed later, an IFC building model is a single file. He suggests that multiple schema could enable better traceability and eliminate data redundancy. Redundancy is a recurring subject in the literature. The IFC standard has been developed to enable translations from a number of commercial software vendors, each with their own internal data structures (Cerovsek, 2011; Khemlani, 2004). A consequence of this flexibility is redundancy. The IFC standard enables multiple ways in which to define objects, relations and attributes (Steel *et al.*, 2010; Venugopal *et al.*, 2010). This redundancy can potentially lead to inaccurate data exchanges.

Suggested future developments for BIM schemas include the integration of the diverse data models used in the various AEC sectors, for instance IFC and gbXML (Cerovsek, 2011). The necessity for rules and guidelines and general tightening of IFC is seen as important. The compulsory and consistent use of object identifiers, GUID [Globally Unique Identifier] or UUID [Universal Unique Identifier] by tools is discussed. Currently they are applied loosely (Steel *et al.*, 2010). This, however, is being addressed (but not yet implemented in software certification) through the current development of MVD (BuildingSMART International Ltd, 2011b). MVD's list the software implementation requirements for standard IFC based data exchange (See, 2011)[51].

The definition of modelling style guides by discipline-specific industry groups is identified by Steel et al in order to overcome problems with buildings modelled by different sectors (2010). An example is where an architect prepares a building model to appear or 'render' correctly, whereas an energy expert is concerned with the physical properties, as opposed to the visual properties of a material.

There is much less published work on gbXML or on how the standards are structured or work together. Dong et al. have created an extension to gbXML to provide an information infrastructure for a lighting simulation application. The work involved a limited comparison of IFC and gbXML. IFC is described as complex, using a 'top-down' approach in comparison

---

[51] The author's surname is See

with gbXML which uses a ‘bottom-up’ approach. The simplicity of gbXML was considered to be better for their project in the development of a lighting design support prototype as there was no need to understand all the elements in the larger IFC schema (2007).

Hamza and Horne (2007) have researched into interoperability with design software, such as CAD and BIM, and building performance tools. They have employed semi-structured interviews of AEC professionals to establish their opinions of BIM and BPM [Building Performance Modelling]. The improvement on previous methods in using gbXML to transfer the geometric detail from BIM to BPM was acknowledged, however, significant manual correction of the model was still required. In addition, the inability to transfer the data back to BIM was also noted. The loss of intelligence, or semantic data, embodied in the BIM in the transfer process was also reported. Although design iterations are discussed as occurring within the BPM environment, the implication is that it is seen as a one-off event after which the ‘final’ building model is recreated in the BIM environment. Ferrari et al. (2010) confirmed the complicated procedures to prepare models for analysis and the inability to move data from the simulation to the design environment after analysis.

A number of directions for research into IFC have been outlined by Eastman et al (2011) that are relevant to this work. They see interoperability, currently restricted to the 3D appearance and geometry (that is where building objects appear in the model relative to each other), expanding to include relationships between the building objects and the data required by different disciplines. They discuss the need for further research into the different model geometries needed for different types of analysis such as energy analysis and computational fluid dynamics.

The following sections discuss the two standards, IFC and gbXML, firstly in general and then in detail regarding how they deal with building enclosures/geometries and semantic information relating to building materials. Other factors, such as ventilation rates, schedules for heating and heating systems, although important, are more straightforward to deal with as they are discreet values.

6.1.3 Industry Foundation Classes

Development of the IFC schema started in 1997, intended as a product data model for the design and full lifecycle record of buildings. Although it has already endured a lengthy standardisation process it is still evolving (Cerovsek, 2011). The process has been led by industry-dominated buildingSmart (formerly the International Alliance for Interoperability). BuildingSmart has wide international and commercial support with over 450 corporate members from over 18 countries. Although it has notional support from the majority of software companies, the implementations can be inconsistent (Eastman *et al.*, 2011) and there exists a perceived “failure to deliver seamless interoperability” (Grilo & Jardim-Goncalves, 2010, p.526). However, expectations are arguably too high for such a complex process of recording every element and process in a building. Khemlani (2004) argues that in order to facilitate full interoperability between applications, the IFC schema would have to be a superset of all data models. This would be a practically impossible task given that there are (at the time of writing) 133 applications by 92 vendors implementing IFC’s (BuildingSMART International Alliance for Interoperability, 2011b). Hitchcock identifies the problem as it being difficult to develop IFC-compliant software prior to having a stable, robust IFC data model. However, it is difficult to define a stable, robust model, until there are software tools that can be used to test and improve the model (2003).

The IFC schema is complex, reflecting the semantic richness of buildings. Information models of buildings are “large, complex, and highly inter-dependent” (Steel *et al.*, 2010, p.100). They can include architectural components, engineering systems for structural, electrical, HVAC (heating, ventilation and air-conditioning), and mechanical services, along with project management, scheduling, and cost planning/estimation details. The current standard is IFC2x3, with the next version, IFC2x4, coming to the end of its development phase[52]. IFC2x4 should become the standard during 2013, it is also in the process of

---

[52] The majority of the work in this section was carried out during the summer of 2011, since then there have been two more versions, Release Candidate 3 in October 2011 and Release Candidate 4 in September 2012 , see http://www.buildingsmart-tech.org/

becoming the official International Standard ISO 16739. It is intended to last at least five years to provide developers and users a long-term stable platform (Liebich, 2010a).

The IFC standard defines three file formats; each format provides different encodings of the same underlying data:

- IFC data file using the STEP model data physical file structure according to the method outlined in ISO10303-21. This is the most widely used IFC format, with the advantage of compact size yet readable text.

- IFC data file using the XML document structure. It can be generated from an IFC data file using the conversion following ISO10303-28. This format is suitable for interoperability with XML tools and exchanging partial building models. Due to the large size of typical building models and the verbose nature of XML, this format is less common in practice.

- IFC data file using the PKzip 2.04g compression algorithm. These files are typically compress an *.ifc* file by 60-80% and an *.ifcXML* file by 90-95% (BuildingSMART International Alliance for Interoperability, 2011a).

The IFC model is both rich and highly redundant, offering different ways to define objects, relations and attributes (Venugopal *et al.*, 2010). It has been developed to be generic, to meet the requirements of many factions in the AEC industry such as architects, engineers, contractors, suppliers, fabricators and government officials. It provides for multiple types of geometry, properties and relationships. The IFC standard is written in the EXPRESS language and defines an entity-relationship model. EXPRESS is a standard data modelling language for product data and is formalized in the ISO [International Organization for Standardization] STEP [Standard for the Exchange of Product] model (ISO 10303). STEP is a standard for product databases, data exchange and concurrent engineering. EXPRESS is a data definition language that can be employed to declare a schema to represent a product model. It "resembles a conglomeration of different languages including ADA, C, C++ and SQL" (Goh *et al.*, 1996, p.306).

The IFC standard consists of over 800 entities structured into an object-based inheritance hierarchy. Examples of entities include building elements such as *IfcWall*, geometry such as I*fcExtrudedAreaSolid*, and basic constructs such as *IfcCartesianPoint*.

The following is a brief overview of the IFC architecture (IFC2x4 RC4)[53] with particular reference to elements of the standard that are relevant to thermal simulation: the physical elements of a building enclosure, such as walls and their associated materials.

Entities in the IFC data model are either rooted or non-rooted. Rooted entities derive from *IfcRoot*, each with a GUID [Globally Unique IDentifier], attributes for name, description, and revision control. *IfcRoot* is subdivided into three abstract concepts: object definitions, relationships, and property sets. A table giving more detail can be found in Appendix 4.

An *IfcObjectDefinition* is the generalization of any semantically treated thing or process and can be either an object occurrence or an object type. It can be used for defining groups, relationships and contexts of building objects. It is a supertype of *IfcContext*, *IfcObject* and *IfcTypeObject*. *IfcObject* is employed for building components as they occur with a physical placement. *IfcTypeObject* contains information such as a product type with a particular model number and/or a common shape. An *IfcObject* is a supertype of: *IfcActor*, *IfcControl*, *IfcGroup*, *IfcProduct, IfcProcess* and *IfcResource*. A table giving more detail can be found in Appendix 4.

IFC, written in EXPRESS, is an entity-relationship data definition language (Goh *et al.*, 1996). IFC entities have three different kinds of attributes:

- Direct attributes may be defined as scalar values or collections including Set (unordered, unique), List (ordered), or Array (ordered, sparse), similar to a "field" in more common programming languages.

- Inverse attributes name and constrain an explicit attribute from one entity to another, similar to a "navigation property" in entity-relational programming frameworks.

---

[53] For more information on the IFC standard see http://en.wikipedia.org/wiki/Industry_Foundation_Classes#IFC.2FifcXML_Specifications and http://buildingsmart-tech.org/ifc/IFC2x4/rc2/html/index.htm

> Derived attributes are computed in some way from other attributes (BuildingSMART International Alliance for Interoperability, 2012).

IfcRelationship captures relationships among objects: composition, assignment, connectivity, association, and definition. For instance *IfcRelConnects* indicates a relationship that connects objects, an example is a floor slab connected to a beam, further details of relationships can be found in Appendix 4.

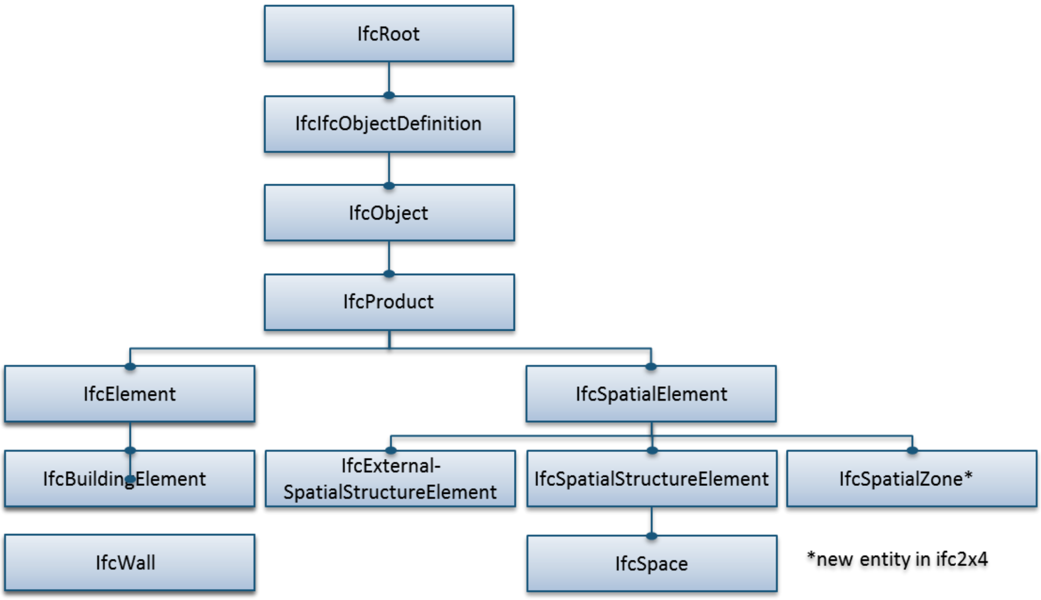


Figure 6-1 Part of the ifc2x4 hierarchy

This diagram includes the new entities for Spatial Elements and Spatial Zones[54]*. A wall appears as an entity IfcWall but inherits many attributes, such as IfcObjectPlacement that positions it in space, from IfcProduct. The left hand side of the diagram illustrates manufactured, supplied or created objects. The right hand side shows objects that are created indirectly by other entities, such as spaces that are defined by bounding elements.*

IfcProduct is the entity that handles any object that relates to a geometric or spatial context. In addition to manufactured, supplied or created objects it includes objects that are created indirectly by other products, such as spaces that are defined by bounding elements. Physical

---

[54] This diagram employs the conventions of EXPRESS-G, the standard graphical notation for the EXPRESS language

building elements include *IfcWall, IfcBeam, IfcDoor, IfcWindow* and *IfcStair*. Spatial elements include *IfcSite, IfcBuilding, IfcBuildingStorey, IfcSpac*e and *IfcSpatialElement*. Figure 6-1 shows the hierarchical relationship of a wall object. A wall appears as an entity *IfcWall* but inherits many attributes, such as *IfcObjectPlacement* that positions it in space, from *IfcProduct*.

IfcProduct has the following optional attributes: *IfcObjectPlacemen*t which is employed to position the object in space, *IfcRepresentation* is employed for multiple geometric representations of the object and *ReferencedBy* by which other subtypes of *IfcObject* can be related to the product. Various connectivity relationships are used for building elements such as walls having openings for doors or windows. The *IfcShapeRepresentation* provides the geometric representation of a product or a product component. A wide range of geometries are supported, ranging from points, curves, surface models, swept area solids, b-spline surface geometry, etc.

Non-physical elements such as building spaces, shown on the right hand side of Figure 6-1, are handled by the *IfcSpatialElement* entity, which has three attributes: *IfcExternalSpatialStructureElement*, *IfcSpatialStructureElement* and *IfcSpatialZone. S*patial concepts such as building stories and spaces have been included in the standard since IFC2 as subtypes of *IfcSpatialStructureElement: IfcSite*, *IfcBuilding*, *IfcBuildingStorey* and *IfcSpace*. Complex relationships between these instances of these building elements are handled by the use of *IfcRelAggregates* to describe a building project, as illustrated in Figure 6-2. The illustration shows a building project comprised of two buildings, each composed of a number of stories (floors). The IFC’s to represent such a project includes the site, buildings and building stories with *IfcRelAggregate* employed to describe the relationship between these elements.

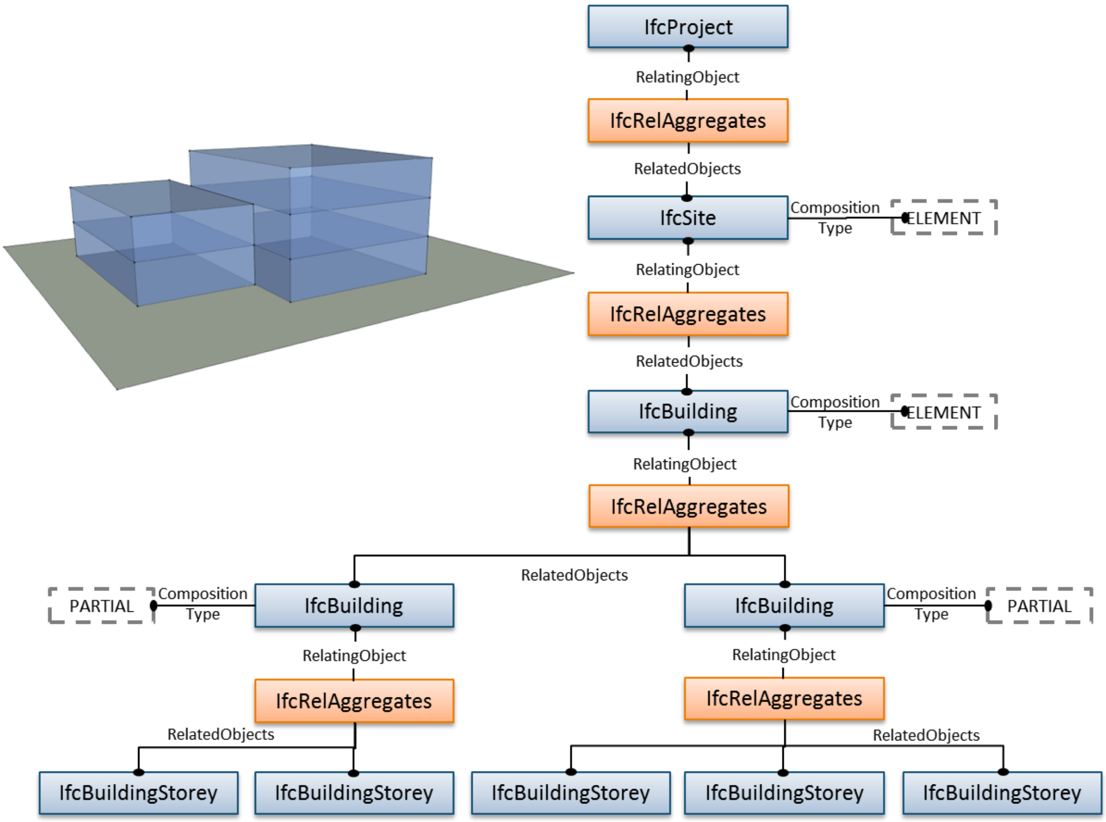


Figure 6-2 Composition of a building model in IFC

The diagram shows how a building project comprised of two of buildings, each composed of a number of stories (floors), recorded in IFC by means of the relationship IfcRelAggregates. As can be seen a building may have differing number of stories. This relationship is dealt with by the concept of Relating Object and Related Objects handled by the IfcRelAggregates (after BuildingSMART International Alliance for Interoperability, 2012).

IfcSpatialZone, included in the standard for the first time in IFC2x4, can be used to represent a thermal zone along with other types such as: a construction zone, a lighting zone, a usable area zone. It inherits its placement and geometry from *IfcProduct*. This entity has been included in the recent release to overcome issues with space boundaries (Liebich, 2010b). Figure 6-3 illustrates some of potential problems with space boundaries. Thermal transfer is normally calculated between co-planar surfaces, thus if the inside face of a wall is taken as the surface of a zone (as opposed to the centre line of the wall) it can leave small spaces between neighbouring zones that can be interpreted as 'small' additional zones as illustrated in Figure 6-3 a). Also the dividing wall may span multiple zones with different properties as shown in Figure 6-3 b). Finally a section of the wall surface might be ignored or related to a narrow long zone as shown in Figure 6-3 c). The inclusion of IfcSpatialZone in the standard means the thermal zone can have a volume other than that created by the enclosing physical object, usually the centre line of the wall.

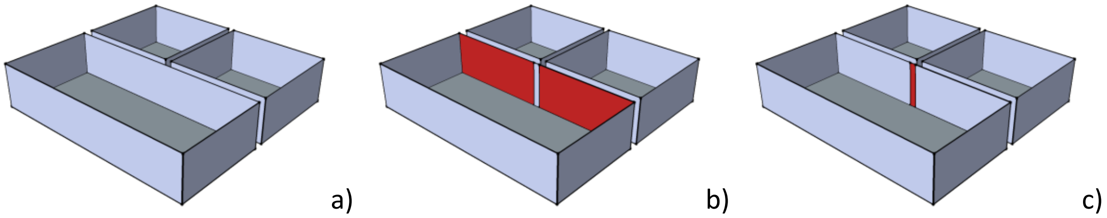


Figure 6-3 Issues with wall thicknesses and space boundaries for thermal calculations

Thermal calculations are normally calculated on co-planar surfaces, if this does not occur and inside faces are employed errors can occur, for instance a) the wall thickness can be taken as a zone, b) the dividing wall may span multiple zones and c) a section of the wall surface can be ignored (after Liebich, 2010b).

Shading devices, important for calculations in solar studies, both for lighting and thermal gains, are covered by the *IfcShadingDevice*. However, unlike the thermal zone, it is considered a building element. Other building elements such as protruding slabs or balconies can also act as shading devices. Those elements, as they have another primary purpose, are defined as *ifcSlab.*

Materials are defined as homogeneous or inhomogeneous substances that can be defined for products as a whole or as a composite (constituents, layers or profile). They are non-rooted and have a general supertype of *IfcMaterialDefinition*.

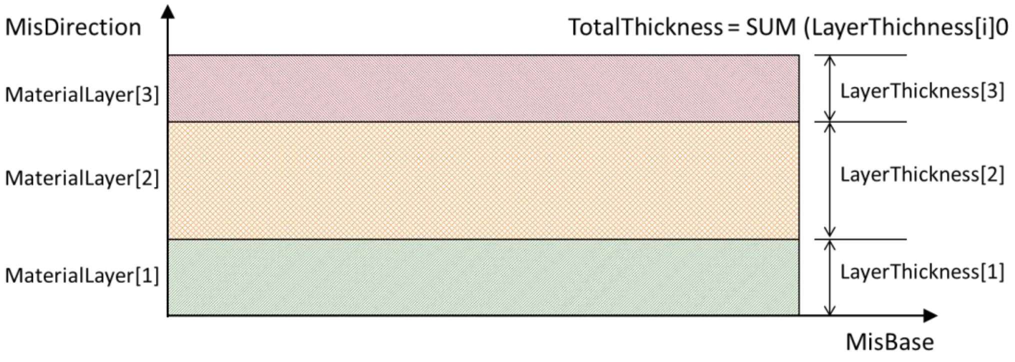


Figure 6-4 IFC building material layers

The diagram shows how layers combine into an IfcMaterialLayerSet (after BuildingSMART International Alliance for Interoperability, 2010).

There are four types of material: *IfcMaterial*, *IfcMaterialLayerSet*, *IfcMaterialProfileSet* and *IfcMaterialConstituentSet.* For more information on materials and their attributes see tables in Appendix 4. Building elements such as walls, floors and roofs, materials that combine a number of materials are recorded as a series of layers through the use of *IfcMaterialLayerSet*, as illustrated in Figure 6-4.

Additional properties, for instance thermal details, can be provided using *IfcExtendedMaterialProperties*. The range of properties relevant to thermal calculations is given in Appendix 4. It can be seen that there is a wide range of values provided in the standard.

A subtype instance of *IfcMaterialDefinition* can have either the material properties assigned, or use an external classification. The relationship *IfcRelAssociatesMaterial* can be employed to assign the material to either a subtype of *IfcElement*, or a subtype of *IfcElementType*.

IFC, BIM, IDM and MVD

BIM is intended to contain all information regarding a building over time. However, the method by which that information is communicated is equally important in order to maintain its quality. The IDM [Information Delivery Manual] was developed to specify the communication process covering the purpose, the interested parties and the information required for an exchange of data regarding a building model (BuildingSMART International Ltd, 2011b). The pertinent section to this study of the IDM vision is the MVD, developed to define the various model subsets of data that are relevant to data exchange between specific types of software. The intention is that software developers need only deal with the parts of the IFC Model Definition relevant to their purpose (IFC Solutions Factory, 2011).

A range of MVD's are listed on the IFC Solutions Factory website[55], covering information relevant to domains such as structural design, landscape design and energy and thermal simulation. The MVD for Architectural Design to Building Energy Analysis contains the following type of information:

- the space geometry and identifiers,
- space boundary geometry for walls, slabs, windows, doors, openings and also virtual space boundaries,
- construction types for walls and slabs,
- window and door types,
- the materials and material layers of the walls and slabs,
- building elements that will be used by middleware to generate second level space boundaries.

Snippets of this MVD for *Architectural Design to Building Energy Analysis* are shown in a table in Appendix 4. It is a list of information needed, whether it is 'required' or 'optional' along with the data type and the units used.

The IFC standard is large and has been many years in development. This section has outlined how IFC records building enclosures/geometries and semantic information relating to building materials. The next section outlines how gbXML deals with similar data.

---

[55] http://www.blis-project.org/IAI-MVD/

6.1.4 Green Building Extensible Markup Language

A company, Green Building Studio, initiated the development of the gbXML standard in 1999. The first version of the schema was published in 2000 with the current version, Version 5.10, released in January 2013[56]. The language was designed specifically for interchange of data between design modelling environments and energy analysis packages. It was not designed to provide a visual representation of a building (Marsh, 2006a). gbXML is written in XML [eXtensible Markup Language], a non-proprietary, persistent and verifiable file format for the storage and transmission of text and data both on and off the web (W3C, 2008). With the development of export and import capabilities in a number of CAD/BIM tools, gbXML has become an industry standard schema for building performance analysis (gbXML.org, 2010).

In comparison with the IFC schema, the gbXML schema is considerably simpler and easier to understand (Hamza & Horne, 2007). However, like IFC, the implementation of the schema varies significantly (Dong *et al.*, 2007). In this section, as in the previous section on IFC, the physical elements of a building, such as walls and their associated materials are considered[57].

There are some 288 elements (in the gbXML standard entities are called elements). All entities in the gbXML standard are rooted, with the entity gbXML at the top of the hierarchy as shown in Figure 6-5. There is no direct comparison the *IfcWall* entity, the closest item is an enumerated attribute of *Surface* either as an *InternalWall* or *ExternalWall*.

The node *Surface* has the following children: *Name, Description, FamilyName*[58]*, AdjacentSpaceId, RectangularGeometry, PlanarGeometry, Opening and CADObjectId*

The node *Surface* has an attribute, *surfaceType*, that can have the following values: *InteriorWall, ExteriorWall, Roof, InteriorFloor, Shade, UndergroundWall, UndergroundSlab,*

---

[56] This study was carried out in the autumn of 2011 when the current release was Version 0.37. There are no versions between 0.37 (December 2008) and 5.00 (January 2012), see http://www.gbxml.org/currentschema.php

[57] For further information on gbXML see http://www.gbxml.org/

[58] New in Version 5.00

CeilingAir, UndergroundCeiling, RaisedFloor, SlabOnGrade, FreestandingColumn and *EmbeddedColumn.*

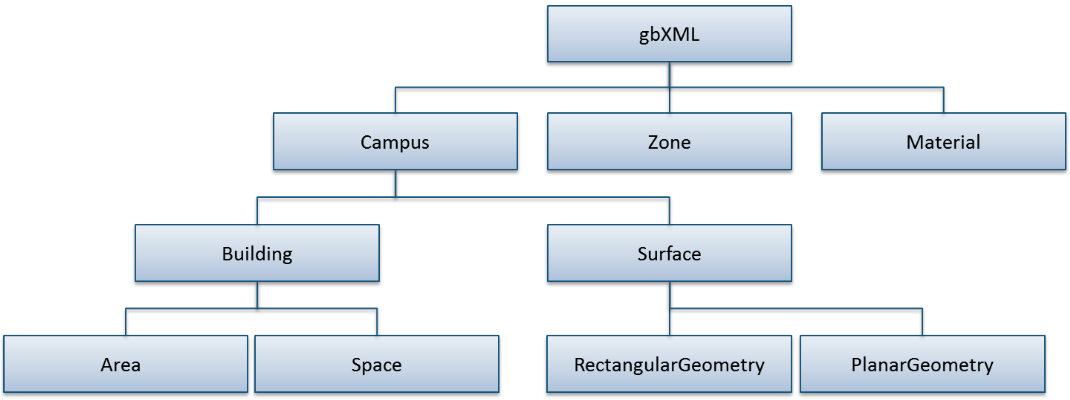


Figure 6-5 Part of the gbXML hierachy

The diagram shows part of the gbXML hierarchy: walls occur as an attribute of Surface as an enumerated type - either an InternalWall or ExternalWall.

The geometry of the *Surface* element can be recorded by use of two children, *RectangularGeometry* and *PlanarGeometry*. They contain the same data in slightly different format. The *RectangularGeometry* uses *a CartesianPoint* (three coordinates x, y, z) to position the element in space. The shape can be given using *Height* and *Width* children or as a *Polyloop*, a set of *CartesianPoints,* a list of coordinates that make up a polygon in three-dimensional space. *PlanarGeometry* only has one child, *Polyloop,* which gives the position of each point in space. There is redundancy in this data, the reason for this given by Dong et al is that it is a double check on the translation of the geometry from the CAD software (2007).

Figure 6-6 shows a curved surface converted into a series of facets or plans during the process of export to gbXML from BIM software. The use of either rectangular or planar geometry reflects the form used by simulation engines. EnergyPlus, the widely used building energy simulation engine, developed by the US Department of Energy, uses either rectangular shapes or sets of Cartesian coordinate points in its calculations (EnergyPlus Development Team, 2010). This use of points means that gbXML can utilise a very limited range of geometries in comparison with the IFC standard, essentially limited to faceted surfaces. This is a significant difference. It means that any design involving a geometry such as a curve, if converted to a gbXML format will have to become a series of planes. Although it would be relatively simple to add more geometric types to the standard this would not overcome the problem that the energy simulation engines require simplified models, with simple geometries.

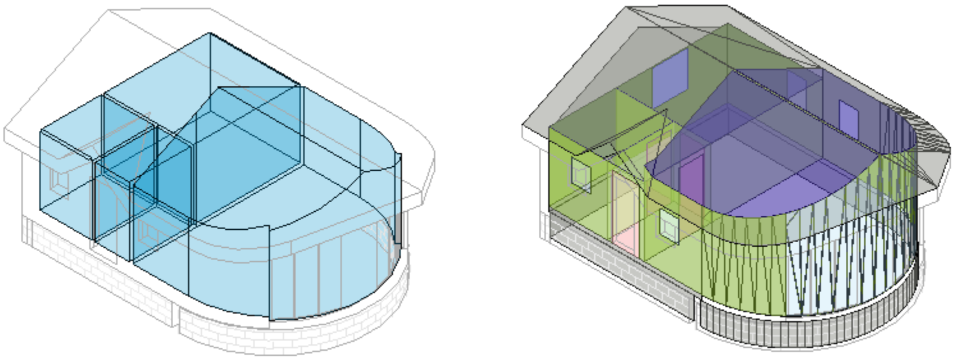


Figure 6-6 A building model of a small building with a curved wall.

The left hand image shows the small building with a curved façade, the right hand image shows the model converted to a series of planes as part of the export to gbXML process

Within the standard there are two branches in the hierarchical tree employed to describe building projects and building spaces: *Campus* and *Zone*, as illustrated in Figure 6-5. The *Zone* element contains data relating to thermal calculations and contains attributes and children such as *DesignHeatT* the design temperature, *AirChangesPerHour* and *IndoorAirQuality*. It also has an attribute of *CADObjectId*.

The *Campus* element is the base for all physical elements of the project, employed to contain data such as location and weather data. The *Building* element has a child element *Space*. The *Space* element represents a volume enclosed by surfaces and has attributes such as schedules for people, equipment and lighting. It references the *Zone* element through an attribute *zoneIdRef.* Children of the *Space* element include *PeopleNumber, Area, Temperature, Volume, and SpaceBoundary*. The *SpaceBoundary* element is employed to link the *Space* with *Surface,* discussed above, through the use of an attribute *surfaceIdRef.* The *SpaceBoundary* element has a child element *PlanarGeometry* that lists the Cartesian points of the space, defined as a loop.

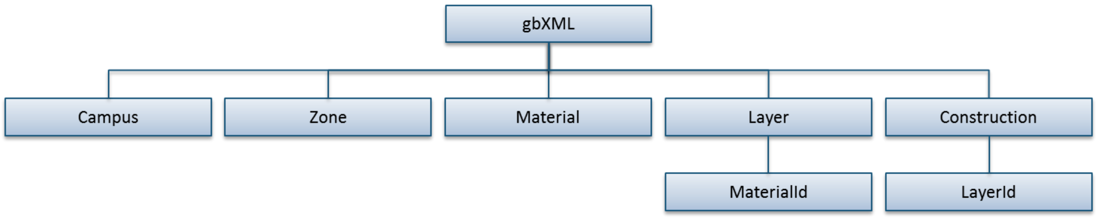


Figure 6-7 Part of the gbXML hierarchy showing the five children root node

Building elements, such as walls, floors and roofs, are recorded by in three elements: Materials; Layer and Construction, in the gbXML standard, all children of the gbXML root. As illustrated in Figure 6-7: a single building material is handled by the *Material* element. A combination of one of more building materials is handled by the *Layer* element. The Layer has 2 attributes materialIdRef and percentOfLayer. A Construction is a combination of layers, such as a wall or a roof. Each of these elements has attributes of *Id* and *DOELibIdRef* (used to reference objects in the DOE2 library[59]). The material element has children such as *R-value*, *Thickness*, *Conductivity*, *Density* and *SpecificHeat*, which are all used in calculations on the thermal performance of the material. A full list of children can be seen in a table in Appendix 4.

6.2 Comparison of IFC and gbXML

BIM and BES software tools generate building models differently and require different information. However, as discussed previously, there is a need to share data between the two types of software. This section compares the key elements relevant for energy modelling in IFC and gbXML.

The two standards have been designed and developed for very different purposes. IFC is large and complex and intended to cover all aspects of BIM. A goal from the developers, buildingSMART, is to extend processes and technology to “the whole built environment, over its lifecycle, and encompassing leadership, production, facilities management and

---

[59] For further information see http://www.doe2.com/download/Docs/22_Oview.pdf

engineering maintenance". The aim of IFC is to "contribute to sustainable built environment through SMARTER information sharing and communication" (Rooth, 2010, p.3). The aim of the developers of the gbXML, standard is to "*facilitate the transfer of building properties stored in 3D building information models (BIM) to engineering analysis tools*" (gbXML.org, 2010). As such, it has been designed to deal only with the data required by analysis tools. It is correspondingly smaller and more compact than IFC.

The two schemas handle data differently, which will partly explain the difficulties in creating translators between the two standards. As discussed in the previous chapter, in any simulation to predict the energy used in a building, there are many parameters to be considered. The number and interaction of these parameters can lead to a complex web of data. However, many of the parameters are discreet values that are can easily be stored, for instance design temperatures, occupancies and schedules for heating. The elements that reflect the richness of an architectural design relate primarily to the building geometry and the materials used. Table 6-1, located at the end of the chapter, gives a comparison of how these elements are stored by IFC and gbXML. The two standards use different languages and naming conventions. This can easily be overcome by the used of translators. However, as can be seen in Table 6-1, the geometries are handled very differently. In comparison, the materials appear to have common features, however as will be discussed, recording of material properties in the building model is problematic.

6.3 Improved methods for building model information exchange

As discussed earlier, IFC has been in development for a long time with the status and size of the standard representing the results of a significant collaborative endeavour. However, the implementation, particularly for interoperability, is far from perfect. Conversely gbXML is much smaller and more focussed than the IFC standard and has not had the commercial support of the IFC standard. The comparison of the two was important in confirming the need to examine in more detail the differing approaches to building geometries and recording of semantic data. This section will look in more detail at how IFC might be either refactored or implemented to support more effective data transfer between software types to support iterative building design and energy simulation.

The IFC model has been designed to be abstract, meaning that it can be used with multiple applications (Khemlani, 2004). In addition, it is highly redundant, meaning that there can be different ways to define objects, relations and attributes (Venugopal *et al.*, 2010). Abstraction and redundancy are discussed in terms of geometries and the materials of building models in the next sections.

6.3.1 Modelling a building design: abstraction and redundancy

Architects, during design, move from abstract concepts to more specific models by a process of refinement and addition of detail (Eastman & Siabiris, 1995). For example the concept BUILDING becomes DOCTORS' SURGERY which will include a WAITING AREA which will include either a PATIENTS or RECEPTIONIST AREA separated by a RECEPTION DESK. Relationships between spaces and artefacts make up the products that constitute the eventual building. As discussed earlier, at present, energy simulation generally occurs after the design is complete, but requires a simpler, more abstract model, giving rise to a progression from an abstract model to a detailed model and then another abstract model as shown below:

abstract	→	***detailed***	→	***abstract***
(sketch design)		*(building objects)*		*(performance simulation)*

The implication, or result of this process, is that the three model types are difficult to couple together, if not impossible. The IFC standard reflects the current method of post-design, with the derivation of zones from detailed building object models. The problems with working with this method, as discussed in Chapter 4, is that this computational derivation of zones can be inaccurate and requires manual checking. Also, it has proved impossible, to date, to facilitate the conversion of zone geometry back to the object form employed by BIM.

This thesis suggests that, in order to support iterative and reliable interoperability, the models for BIM (building object) and simulation would need to be coupled together. A new method is proposed here where the building model is structured around the concept of a common abstract model in order to achieve this closer coupling as illustrated by, where the arrows indicate iteration:

Abstract ⇆ ***detailed***

(sketch design and performance simulation) *(building objects)*

Within the IFC (proposed standard IFC 2x4 RC4) there already exist two entities that describe spaces:

> *IfcSpace* is a generic type of volume that can have a user-defined attribute, it was a introduced in IFC Release 1.0.
>
> *IfcSpatialZon*e can be used to represent a thermal zone, a construction zone, a ligh.ting zone or a usable area zone; it is a new entity with the proposed IFC Release 2x4.

As IFC entities these spaces are intelligent building objects. They can be employed to describe a building model, however, their position and geometry is recorded separately from the other building objects that comprise the building model. This independent recording of objects provides flexibility for software developers to provide for the creation and storage of building model information, with the majority of attributes made optional (BuildingSMART International Ltd, 2011a). However, this flexibility could also inhibit interoperability as building objects and spaces do not have to share the same positioning or location information.

The new method, proposed here involves an approach where the primary description of the building model is that of one composed of ‘Intelligent Spatial Entities’. Other building objects would be ‘related’ or ‘belong’ to one or more Intelligent Spatial Entity. The Intelligent Spatial Entity would still be an intelligent building object, in that it can have variable dimensions, assigned rules, complex geometric and functional relationships with other building elements. An Intelligent Spatial Entity would be:

- A 3D volume, defined by planar surface boundaries of zero thickness. Curves would be possible through the use of facetted boundaries.

- Either a part or the whole of the building model.

- Constructed so that the surface boundaries of neighbouring Intelligent Spaces are coplanar, that is with no gaps or left over voids in the building model.
- Attributed with experiential information, such as the design intent or rationale.
- Attributed with data, such as the function, type, energy targets, occupancy, occupancy schedules, comfort targets, etc.
- Able to link, by means of appropriate algorithms, to expert professional advice relating to energy targets and low energy building construction approaches/methods.

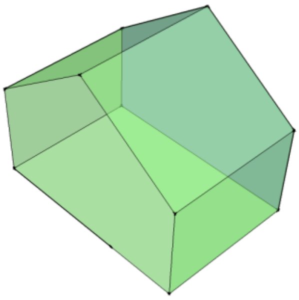
However, with this method the Intelligent Spatial Entity would act as a shell to which the building objects are ‘attached’, similar in many ways to how a setting out line is employed in the construction of a building [60].

Figure 6-8 c) illustrates a different relationship, where building objects such as walls are positioned or attached to surfaces of Intelligent Spatial Entities. The building could be designed as a series of volumes as shown in Figure 6-8 a) and b), that is in an abstract manner; the difference to current practice is that these volumes or spaces would persist throughout the design phases and thus could also serve as thermal simulation zones. The following sections explore two framings of how Intelligent Spatial Entities could be employed in an IFC model of a building based upon: an architectural hierarchy or a compositional approach.

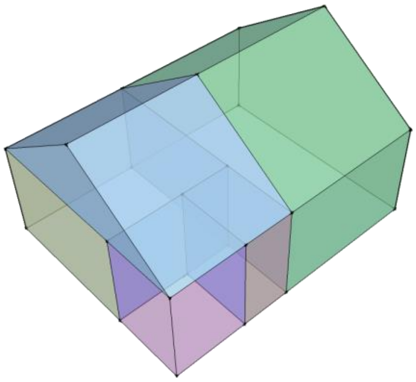
---

[60] Setting out is the accurate, temporary marking out of the position of a building or features (eg. building corners, wall line or boundary) in order that the feature can then be built in the correct location.

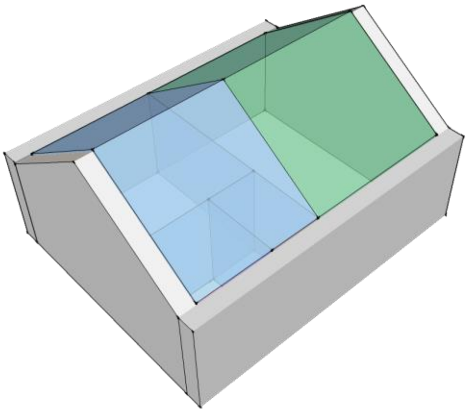
Figure 6-8 Assembly of a building model as a series of Intelligent Spatial Entities



a) shows how a building model is started with one Intelligent Space



b) shows how the building could be built up with multiple Intelligent Spaces



c) shows how the building could be built up with multiple Intelligent Spaces and the walls and enclosing elements added afterwards, attached to the surfaces of the space.

Modelling a building design using an architectural hierarchy of spaces

IFC is written in the EXPRESS language, an ‘object flavoured’ information modelling language. EXPRESS was developed to describe a product, for instance a car, throughout its lifecycle, from time of conception through its manufacture to its time of disposal (Wilson, 1998). However, Björk (1992) queried if material and construction method viewpoints (products) could be reconciled with that of an architectural space-centred one. Ekholm and Fridqvist have discussed what constitutes a space in a building; however, their work was aimed at user or facilities management, not at interoperability.

As discussed earlier spatial objects are included within IFC. Both the *IfcSpace and IfcSpatialZone* sit within the proposed (IFC 2x4 RC4) hierarchy as a types of *IfcSpatialElement* which is in turn a type of *IfcProduct*, see Figure 6-1, and inherits properties such as placement in the building model from that entity. However, a space is a conceptual 'thing'; it is not a physical 'object' like a wall, and as such the categorisation as a product is questionable.

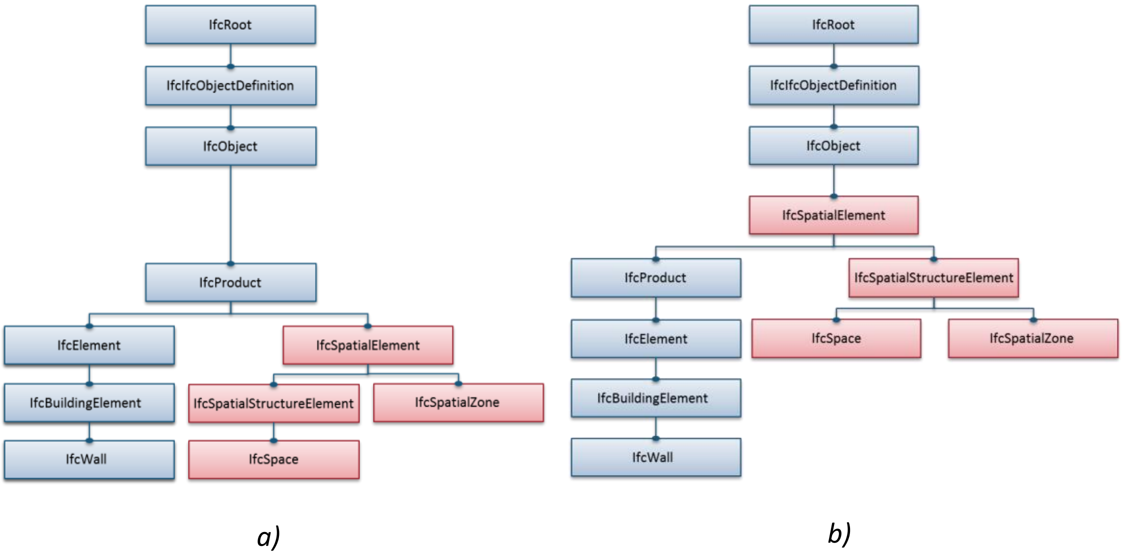


Figure 6-9 Initial proposal for a change in the IFC hierarchy

a) shows the hierarchy proposed under IFC2x4 and b) shows how the IFC hierarchy could be re-arranged with IfcSpatialElement moved above IfcProduct to enable inheritance of attributes.

In the early stages of this research a modification to the IFC hierarchy was initially proposed (Hetherington *et al.*, 2011) that would reflect a change in the relationship between building objects. This change in hierarchy is shown in Figure 6-9 where (a) shows the existing hierarchy and (b) shows the suggested change with the *IfcSpatialElement* moved higher up the hierarchy. This would mean that both spaces and walls would be subtypes of *IfcSpatialElement* and inherit properties such as positioning in space. The spatial element would be the equivalent of a surface in gbXML. It would be a planar geometry, akin to a 'setting out line' for a building object such as a wall, as discussed above.

This refactoring reflects more closely the way that a building is conceived and the design developed by an architect. All 'things' in a building relate to space, whereas all 'things' are not products. This, however, whilst more logical, does not reflect how elements in a building relate to each other. The next section explores a different approach to the problem, that of composition.

Modelling a building design as the composition of objects

The IFC standard provides for recording of the project with spatial structure elements, using *IfcSpatialElement,* to define a site, buildings, storeys and spaces as illustrated earlier in Figure 6-2. This works by composition which defines a relationship of one building object to that at a higher level for example a storey is part of a building. The IFC standard provides an order of spatial structure elements from high to low level as follows:

IfcProject > *IfcSite* > *IfcBuilding* > I*fcBuildingStorey* > *IfcSpace*[61].

A spatial structure element can only be part of an element at the same or higher level as depicted earlier in Figure 6-2 with multiple buildings and storeys. Composition is achieved by employing an *inverse attribute* by employing the following aggregation relationship:

I*fcRelAggregates*: composition of unordered parts

---

[61] This is claimed on BuildingSMART website, but is unclear how it is actually implemented, see http://www.buildingsmart-tech.org/ifc/IFC2x4/rc4/html/schema/templates/composition.htm

The IFC standard allows for the aggregation relationship to be applied to subtypes of *IfcObjectDefinition*, thus both *IfcSpace* and *IfcSpatialZone* entities inherits the following inverse attributes:

IsDecomposedBy:	SET OF IfcRelAggregates FOR RelatingObject;
Decomposes:	SET [0:1] OF IfcRelAggregates FOR RelatedObjects

However, by allowing a ‘0’ or ‘1’ composition, the standard enables the relationship to be optional. This optionality leads to redundancy in the model, increases the risk of errors and arguably inhibits interoperability. By making relationships compulsory between buildings, storeys and spaces, redundancy should be reduced. However, there would need to be strict rules regarding how the spaces are joined, that is where the Intelligent Spatial Entities would be germane. For instance if the space was a thermal space (or zone) a rule would need to be enforced that it would be required to be co-planar with adjacent thermal spaces. Interoperability would be further enhanced if the tighter coupling of spaces (building volumes) extended through to building components (walls, roofs, floors) with a relationship established as to belonging to a space or forming a boundary to a space (employed in thermal calculations). How this could be achieved, a clearer definition and the different types of Intelligent Spatial Entities, is discussed in greater detail in the following chapter.

Discussion

The problem of the development of standards for building models, because of its complex interdependencies, could be considered ‘wicked’. With such problems solutions are not right or wrong, some are just better (Rittel & Webber, 1973). Two framings of approaches to the tighter coupling of building models have been presented based upon an architectural hierarchy and one based upon composition. This section discusses which might be best.

The approach based on a refactoring of the standard based on an architectural hierarchy is attractive as it reflects how buildings are conceived and assembled in a spatial manner. This type of re-factoring could be considered radical and points towards a total re-think of the standard away from the application of an established product modelling language towards a bespoke building modelling language. Others have argued about the suitability of a product language, such as Express, to fully articulate the richness and complexity of buildings (Björk, 1992). However, the IFC standard has been a long time in development and represents a significant collaborative effort, which might be lost with this type of change. The compositional approach is less radical and could be achieved by minor modifications to the IFC standard and the creation of rules or protocols regarding model composition through the use of MVD's.

Strict rules for composition, employing Intelligent Spatial Entitles, would seem to be the best method to achieve closer coupling of both spaces within a building and of objects to spaces. The benefits of this approach are that through the application of Intelligent Spatial Entities, with rules as to the coplanar nature of assembly, the differences in geometric models required by BIM and BPS software would be accommodated. The more complex building objects with geometries, such as curves, if required by the designer, could be provided by BIM software and would inherit their position and control points from the planar geometry of the Intelligent Spatial Entities. This should ease many of the problems of geometric interoperability when moving data back from BPS to BIM and enable the identification of building objects affected by changes to the Intelligent Spaces in the BES environment. Furthermore it should avoid the difficulties with space boundaries as illustrated in Figure 6-3. The space boundaries would be created consistently with zero thickness surfaces.

A limitation of the proposal for tighter coupling of the building model is that it would alter how design software would assemble the building model. This in turn would affect the options offered to the architect by the software, principally in the design stages regarding spaces, in particular thermal spaces (or zones). This concept of how software would facilitate the design of a building as a series of adjacent thermal spaces (zones) will be further explored in the following chapter. The next section discusses how material properties are recorded to support heat transfer calculations.

6.3.2 Semantic data for thermal simulation

The IFC standard has a comprehensive range of material values, especially those required for thermal calculations. Comparison with those recorded within the gbXML standard, see Table 6-1, show that there are semantic differences such as *SpecificHeatCapacity* and *SpecificHeat*. There are some values missing in the IFC specification, such as the R-value and U-value, however these can be derived from first principles. With other values there are in-consistent or incomplete mappings. For instance albedo, the reflectance of solar radiation, used in gbXML, only maps onto translucent materials and there is no mapping for opaque materials.

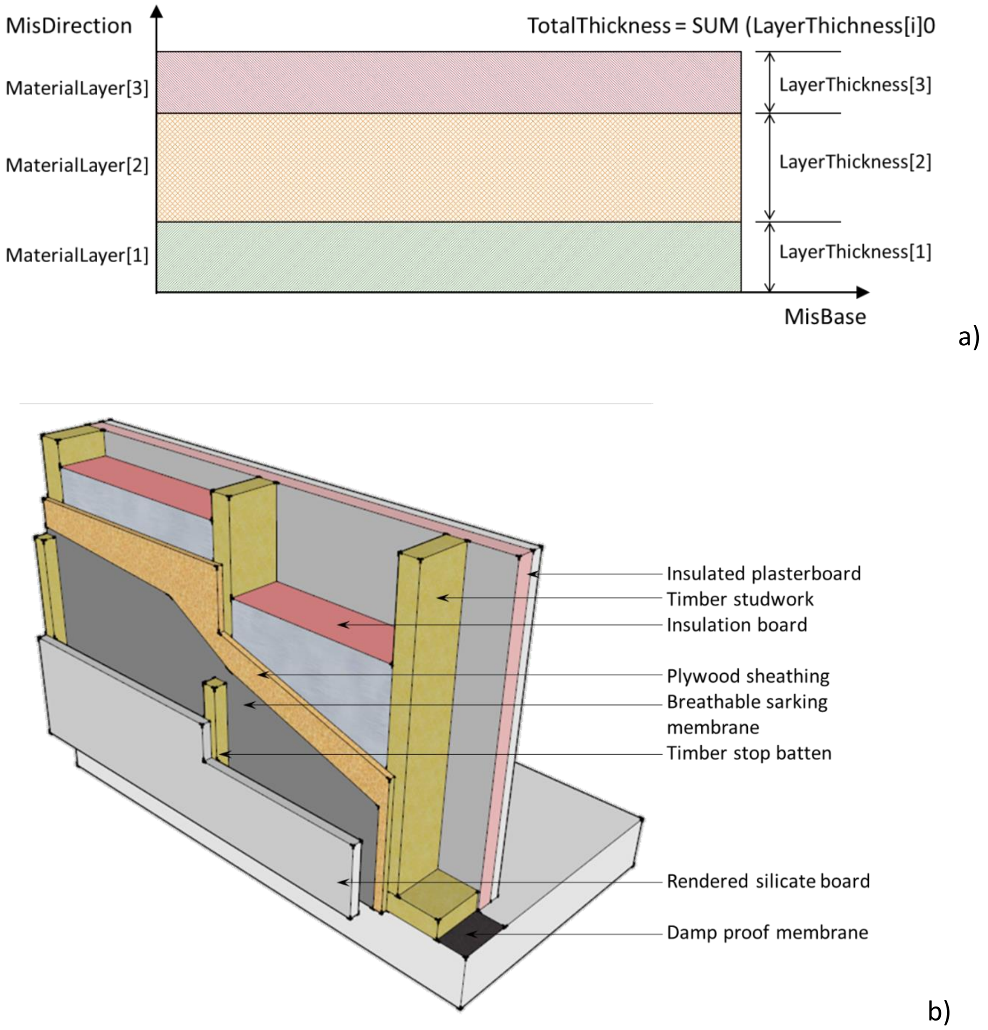


Figure 6-10 Depictions of materials as layers and a construction detail

(a) shows how layers combine into an IfcMaterialLayerSet (after BuildingSMART International Alliance for Interoperability, 2012) (b) shows a cutaway perspective of a 'real' construction detail with inconsistent cross section due to the presence od timber studs and battens, after (Kingspan, 2011). As can be seen the illustration in b) is considerably more complex than that of a) with differing consistency of materials across the cross-section of the wall that will affect the thermal performance of the construction.

However, the issue with both standards is the level of abstraction and lack of exemplars or rules for implementation. This is illustrated by a comparison of Figure 6-10 a) and b). Figure

6-10 a) shows diagrammatically how layers combine into an *IfcMaterialLayerSet*. Compare this with Figure 6-10 b) showing a 'real' example of a composite layer construction. As can be seen the illustration in b) is considerably more complex than that of a) with differing consistency of materials across the cross-section of the wall that will affect the thermal performance of the construction.

Changes that would facilitate better interoperability relating to the thermal performance of construction materials contained within the IFC standard are:

- The provision to enable demarcation of the inside and/or outside face of the material layers should be made explicit. Although each *IfcMaterialLayerSet* defines a material layer set base line (*MlsBase*), to which the start of the first *IfcMaterialLayer* is aligned it does not set out whether it is an inside or outside face. This information is crucial when taking into account a dynamic modelling of heat gain/loss through a building fabric.

- The provision of methods for dealing with inconsistent cross-sections as seen with the timber batten in Figure 6-10 b).

Although MVD's are currently under development, the one provided on the IFC Solutions Factory website for *Architectural Design to Building Energy Analysis* is very abstract (IFC Solutions Factory, 2011). It deals with the information required for exchange, does not deal the level of detail illustrated by the 'real' building construction as illustrated in Figure 6-10. A more thorough approach may be needed to supplement MVD's with the provision, analysis and rigorous use of examples of building constructions showing how materials are assembled. This being a different, but complimentary approach to the use of models of complete buildings used to test software. Comparisons could be drawn with the development of the X3D [eXtensible 3D] standard. Lessons learnt in the early development of VRML [Virtual Reality Modelling Language] led to a rigorous standardisation and testing of X3D with many code examples of model components freely available (Daly & Brutzman, 2007; Web3D Consortium, 2011).

6.4 Concluding remarks

Improved interoperable standards could enable the close linking of building design and energy analysis. This chapter has outlined what interoperability means in the context of the AEC industry. Current research in the area has been reported. The interoperable languages used for BIM and energy analysis have been described, compared and critically appraised in relation to modelling for thermal simulation. The different geometric approaches to creating a building model for BIM and BES have been analysed. Finally, recommendations have been made for possible future development of the IFC standard as follows:

- New rules for the composition to the building model through the use of Intelligent Spatial Entities are proposed to more tightly couple the relationship between building products and the spaces that they create.
- The provision of a library of building construction exemplars is proposed to enable the development of integrated BIM and thermal simulation software.

This study has been a speculative investigation, with the majority of the analysis carried out over the summer of 2011. It is “of the moment” as can be seen by the dramatic increase in interest in IFC in the last two years, as evidenced by the number of references in this thesis dated between 2010 and 2012. The interest and pace of research, particularly in the field of energy analysis and prediction of usage, is likely to increase significantly in the near future due to increased energy costs and the threat of climate change.

This study makes a contribution to knowledge in a number of ways. In addition to the recommendation of changes to the IFC standard that forms the most significant contribution, the analysis and comparison of the hierarchical structure and content of IFC and gbXML standard is unique. For instance Figure 6-1, Figure 6-5 and Figure 6-7 have been derived from on-line documentation of the standards. The analysis in Table 6-1 is unique and is important in providing an understanding of the standards.

This chapter has touched lightly on the practical details of how a building could be composed of Intelligent Spatial Entities. There would be significant issues such as how to deal with: different types of spaces, subdivision of spaces, elements such as staircases that may span multiple spaces, overlapping spaces and boundary conditions that would need to be dealt with in some depth. Some of this is already dealt with by the existing IFC standard, but may need re-visited in the light of a new approach to composition. The next chapter tackles this problem in a different manner; it will investigate how building design modelling and energy analysis software could be combined into one software tool. It will examine how the change in rules relating to building model composition proposed in this chapter would influence modelling styles and the effect this could have on the software functionality and design.

6.4.1 Related work published since this study was undertaken

This section details related work published since this study was carried out in the summer of 2011 which vindicate the approach proposed in this chapter.

The limitations of IFC and gbXML to support reliable, robust automated data exchange have been outlined by Hitchcock and Wong (2011), confirming the hypothesis in this study that interoperability is far from perfect. They do not, however, propose a solution; rather they discuss the problem in-depth. They outline the limitations and commercial pressures of existing software and the dichotomy between the users of architectural and simulation tools. They record that the development of MVD's has focussed primarily on the architectural view of the building model rather than transfer of the model to energy simulation tools. They note the use of default materials and properties in transformation from IFC to simulation as recorded earlier in this thesis in the case study. They call for more support in the form of libraries to record building construction and materials in the IFC standard to support simulation. They also identify the gap in recording shading devices such as overhangs and lightshelves, in IFC. They conclude that the principle limitation remains the transformation of thermal zone geometries.

A solution to the problem of interoperability has been proposed by the Lawrence Berkeley National Laboratory (O'Donnell *et al.*, 2011). Unlike this work, which suggests changes to the IFC and rules for implementation, they have developed a new data model, SimMode, with the ultimate objective that the SimModel will be absorbed into the IFC standard. SimModel is an XML-based model to support the building simulation process, aimed at preventing information loss. They discuss the limitations of both IFC and gbXML to support space boundaries and the specialised concepts used by simulation engines such as EnergyPlus. They also discuss the limitations of existing software. To overcome the problems with interoperability they have developed SimModel, to be closely aligned with IFC. This data model aims to provide mappings to and from exiting data models such as IFC and include tracking of design alternatives. This is part of a larger project with SimModel developed as the internal data model for the new EnergyPlus Graphical User Interface, also developed at Lawrence Berkeley National Laboratory (See *et al.*, 2011).

Table 6-1 A comparison of elements of the IFC and gbXML standards relevant to the storage of data relating to building geometries and materials employed in building energy simulation

	IFC	**gbXML**
Names	Entities	Elements
Language	STEP, with XML and zip encoding available	XML
Physical building enclosing object (such as a wall or floor)	3D 'intelligent' objects - entities such as Ifcwall or Ifcfloor,	No comparable objects – elements are zero-thick "Surfaces"
Physical positioning of objects	Inherited from parent entity IfcProduct	Surface with the position are given as a children elements using RectangularGeometry and/or PlanarGeometry
Geometry of objects	Wide range of geometric shapes	Restricted to planes, using either rectangles or a grid of points
Zones	Used to describe the type of zone: thermal, fire. Can have independent placing and shape representation from the main building objects.	Used to contain thermal data such as design temperatures and air changes
Shading devices	Treated as building objects	Only planes are available (surface element)
Material groupings	4 types: IfcMaterial IfcMaterialLayerSet IfcMaterialProfileSet IfcMaterialConstituentSet	3 types: Material Layer Construction
Material properties used in energy calculations	SpecificHeatCapacity	SpecificHeat
	No value	R-value
	LayerThickness	Thickness

	ThermalConductivity	Conductivity
	IfcMassDensityMeasure Note: designated a *general extended material property* definition rather than *extended thermal material properties*	Density
	SpecificHeatTemperatureDerivative	SpecificHeat
	VaporPermeability	Permeance
	Porosity Note: designated a *general extended material property* definition rather than *extended thermal material properties*	Porosity
	No value	U-value
	No value	Absorptance
	No value	Roughness
	SolarReflectanceBack SolarReflectanceFront Note: relevant to *general* optical properties and may not be relevant for opaque materials	Albedo
	VisibleReflectanceBack VisibleReflectanceFront	Reflectance Transmittance
	ThermalIrEmissivityBack ThermalIrEmissivityFront	Emittance

Chapter 7

The Integration of Architectural Design, Performance Simulation and Design Advice Software

The aim of this chapter is to propose a new approach to the integration of building modelling (BIM), energy simulation (BES) and decision support (DAS) software. Integrated software, or software that facilitated easy data movement between building design and simulation software, was recorded as a requirement in Chapter 4. The need for a system to provide advice in decision making was also outlined in Chapter 3. Chapter 5 discussed the three types of software, their very different origins and functions and the dissimilar requirements for recording building geometry in BIM and BES. One of the conclusions was that the differing methods for modelling a building need to be resolved to encourage regular application of BES. Chapter 6 concluded that new rules for the composition of building models as a set of spaces could solve the problem of the dichotomous view (building objects or thermal zones) of the building.

This chapter proposes integrated software based upon the concept of designing the building as an arrangement of 3D spaces, each with their own thermal targets. The chapter explores how applying the concept of creating a building model composed of connected Intelligent Spaces could be employed as the basis for the integration of the three functions into one software tool. The objectives are to:

1. Introduce, define and justify the concept of an Intelligent Spatial Entity.
2. Describe how the Intelligent Spatial Entity method enables the integration of the 3 components, BES, BIM and DAS.
3. Establish how the application of the software might relate to the stages/work flow employed by architects.

4. Outline the range of design and energy optimisation features that the integration of the software would provide throughout the design of a building.

This chapter corresponds to the *refine* phase of the Research Through Design approach of this thesis (Zimmerman & Forlizzi, 2008). The selection of the solution to the problem, the composition of a building model as a set of connected Intelligent Spaces, is outlined and justified. The form that the software will take is systematically described and illustrated. This description of the proposed, preferred state (of the integrated software) is achieved by stepping though the stages that an architect would take in the design of a building. It is a form of early prototyping with the implementation explored by means of the creation of a series of sketching and diagrammatic examples (Rogers *et al.*, 2011). Finally conclusions are drawn as to how this software might be developed.

7.1 Abstract spaces

Many of the features discussed in this chapter can be found in individual pieces of existing software, as discussed in Chapter 5. The novelty of this proposal is the combination of BIM and BES processes, supported by a DAS into one software tool. As discussed earlier in Chapter 4, recent developments in software where post design derivation of thermal zones from building geometries has been found to be unreliable and to require manual (visual) checking. Also the flow of data was uni-directional, only from BIM to BES. Any changes to the design resulting from modifications made in the BES environment had to be entered manually in the BIM tool thus giving rise to potential errors. The proposed software should enable the designer to move between abstract and detailed design models, to support iterative design and energy simulation, as introduced in the previous chapter. The basic principle is the use of a simple abstract model in both design and energy simulation to support iteration:

abstract ⇆ ***detailed***

(sketch design and performance simulation) *(building objects)*

The design of a building is about more than the assembly of physical objects, it also includes less tangible concepts such as space and boundaries (Eastman & Siabiris, 1995). Architects, through their practice and training, are familiar with working with spaces (van Nederveen *et al.*, 2009). Possibly this is one of the reasons why a design tool such as SketchUp is popular with architects, it is concerned primarily with the creation and manipulation of 3D volumes. This could also be a reason why BIM is believed to be unpopular with architects (Eastman *et al.*, 2011); even in the early stages of design it generally deals with physical objects rather than abstract conceptual forms. Spaces are components of BIM, as data about them can be a legal requirement, for instance in the US the Government Services Agency have set out requirements for the inclusion of space objects and associated occupancy in BIM models. However, they are derived from the physical objects of the BIM model. This work seeks to explore how this process might be reversed with the physical objects developed from the conceptual or abstract spaces. Rather than a space being perceived as a void resulting from enclosure by material objects such as walls floors and roofs, it is a positive entity with positioning, dimensions, properties and functions, that is a space to which intelligence has been attributed.

7.1.1 Intelligent Spatial Entities

Ekholm & Fridqvist (2000) discuss the nature of space in the context of the construction industry, they discuss factual (material) boundaries that may be enclosing or open, that is implied or imaginary. An example of an implied boundary might be a proscenium arch that separates a stage from the audience in a theatre. They introduce the term *shell* to denote the boundary surfaces and discuss the *construction space entity* as an aggregate of physical objects such as walls and floors along with the void that they create. The context of their discussion was to record user organisational information associated with the space. They describe the space as a *void* defined by the inner dimensions created by the facing structures.

This work is concerned with thermal spaces, or zones, that for calculation purposes must have planar surfaces of zero thickness. Basing these spaces on inner surface dimensions would create gaps between the spaces determined by the thickness of the walls and floors/ceilings between the spaces. Also the word *void* is not appropriate for this work; the space is perceived not as a negative, but a positive entity, as a volume of air that has properties, both physical and experiential. This is the basis for the concept of the Intelligent Spatial Entity.

The concept of Intelligent Spatial Entity is closely related to intelligent building objects that have been discussed in the literature, in that it can have variable dimensions, assigned rules, complex geometric and functional relationships with other building elements (Howell & Batcheler, 2005). An Intelligent Spatial Entity would be:

- A 3D volume, defined by planar surface boundaries of zero thickness. Curves would be possible through the use of facetted boundaries.
- Either a part or the whole of the building model.
- Constructed so that the surface boundaries of neighbouring Intelligent Spaces are coplanar, that is with no gaps or left over voids in the building model.
- Attributed with experiential information, such as the design intent or rationale.
- Attributed with data, such as the function, type, energy targets, occupancy, occupancy schedules, comfort targets, etc.
- Able to link to expert professional advice relating to energy targets and low energy building construction approaches/methods.

These points will be discussed in more detail with examples later in this chapter. There can be other types of space in the building model, for example those created by inner surfaces of enclosing objects such as walls and floors as discussed above, or circulation spaces. Whilst spaces have been included as intelligent building objects for some time in BIM and the IFC standard, the difference here is that they become the core modelling method for the proposed software. The rules for relationships and composition of the complete building model would need to be rigorous as will be discussed later in this chapter.

7.1.2 Energy efficient building design with Intelligent Spaces

The aim of software based upon Intelligent Spaces would be to provide better support to architects to design energy efficient buildings by providing a means for the architect to:

1. Visualise their building design as a set of interrelated thermal spaces.

2. Be more informed about the thermal properties and behaviour of the construction methods and materials they intend to employ in their designs through the use of the integrated expert system.

3. Design iteratively to achieve a balance between achieving a satisfactory appearance for their design whilst minimising the energy required both to build and run it.

This better understanding of the building in terms of thermal spaces would also enhance communications with thermal, energy and mechanical services consultants. However, and arguably more importantly, on smaller projects where there are insufficient funds to support the involvement of an external energy consultant throughout all stages of the design, it will assist the architect in the design of low energy buildings. For instance, in the UK where all buildings are to be zero carbon by 2019 (Great Britain, 2008a), concern has been expressed as to how smaller architectural practices will cope with limited access to tools and expertise. Many of the current tools are not seen to be accessible to professionals working in the “vast UK base of smaller practices” and hence there is a need for better design and decision tools (Technology Strategy Board, 2009, p.2).

7.1.3 Software components

There are three components to the proposed software that will provide:

- Building design functions, based upon Intelligent Spaces, with the existing (and sophisticated) features of current BIM software.

- Support for BES, by either:

    - The integration of existing algorithms programmed within the building design software.

    - The provision of a GUI to BES software such as Energy Plus (as illustrated previously in Figure 5-4) installed on the same computer, network or linked via the Internet to a server.

  - The ability to export and import data to and from free standing BPS software that has its own GUI, for instance Design Builder[62] or IES[63]. There will be functions such as CFD considered too specialist to be included in this proposed software as discussed in Chapter 5.

- A design advisor that would have two distinct features
  - A knowledge base and inference engine to provide information to assist the architect in making choices.
  - Targets and goal tracking to assist the architect in achieving very low energy buildings.

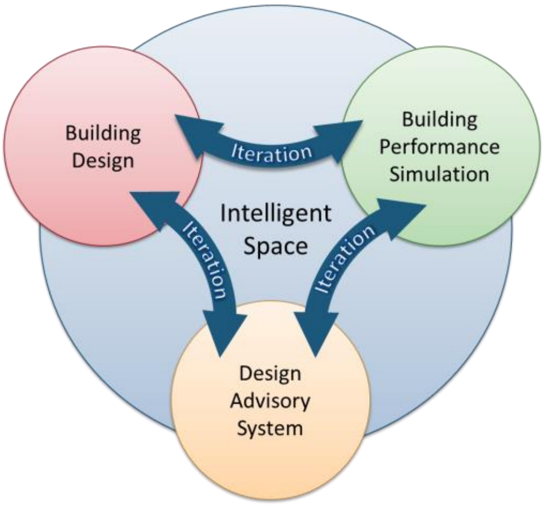


Figure 7-1 The Intelligent Spatial Entity and iterative building design process.

The Intelligent Spatial Entity facilitates the transfer of data between the 3 software components: Building Design; Building Performance Simulation and Design Advisory System

The three components of the software are shown in Figure 7-1. At the centre of this proposal is the concept of the Intelligent Spatial Entity to support iterative design. The Intelligent Spatial Entity would form the basis for architectural design and energy simulation and act as a ‘container’ for energy goals and targets within the design advisor component of the software.

---

[62] http://www.designbuilder.co.uk/

[63] http://www.iesve.com/software

Adapting an approach where the concept of the Intelligent Spatial Entity is a key design element offers a number of advantages for an integrated design approach. First, all building enclosing elements of the Intelligent Spatial Entity (walls, floors, ceilings, windows, etc.) can be related to the space. The extraction of a simplified model from the BIM component to the thermal simulation component, or an external package, would simply involve filtering data for that relevant to the simulation process. It would also be possible to transfer modified data back to the BIM from external simulation software following any changes made, for example alterations to the building proportions, in response to the results of simulation. The objects affected by the changes would then be identified by the computer and flagged for action by the architect.

Secondly, the process of compliance checking by independent consultants of building performance against specified standards will be made more efficient due to the ability to provide the consultants with an accurate thermal model mesh suitable for simulation.

Thirdly, the characterisation of the model in terms of a collection of unambiguously defined spaces would enable information required for an integrated DAS to be automatically updated as the thermal design evolved. Thus the DAS could monitor the results of any changes in thermal performance in relation to design targets and identify potential strategies for improving performance if required. This would enable the DAS to function in a very similar manner to that envisaged over 20 years ago by Pohl and Myers in their work on the ICADS system (Pohl *et al.*, 1992).

These advantages in composing a building model with Intelligent Spatial Entities are explored later in the chapter. The next section establishes how the software would operate throughout design stages typically employed by architects.

7.2 Steps in the building design using an integrated approach

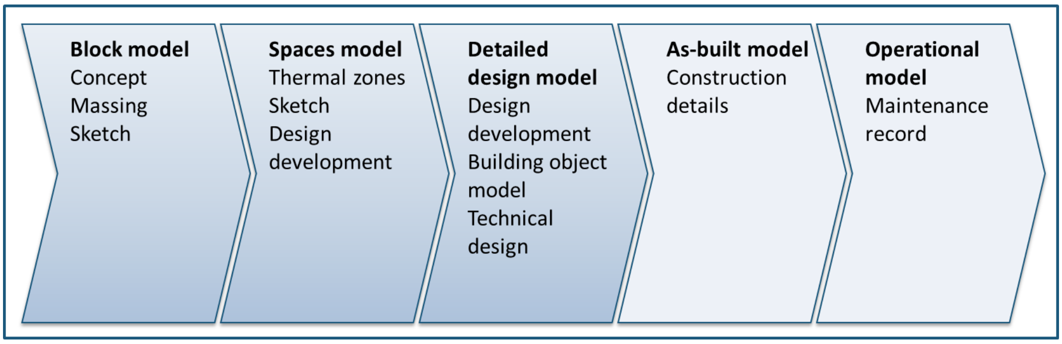


Figure 7-2 The five operation phases for the proposed software

The proposed software would provide five different phases: Block; Spaces; Detailed Design; As-built and Operational to support the different design or management functions typically found in a building project. This chapter deals in more depth with the first three phases as these are when energy simulation would be required

The proposed software described in this chapter is intended to cover the lifespan of the building from inception through to post occupancy. The proposal is for the software to support five distinct phases as illustrated in Figure 7-2. Any building design software must support the design and contractual processes required by the architectural profession. Figure 7-3 illustrates how this would be achieved with the stages in the RIBA Plan of Work (Royal Institute of British Architects, 2007) alongside the five phases for the proposed software. It is intended that, although there are these distinct phases, there should be fluidity between the stages to facilitate iterative design practises. This chapter deals in more depth with the first three phases, as that is when energy simulation is employed, however, the other two are covered briefly.

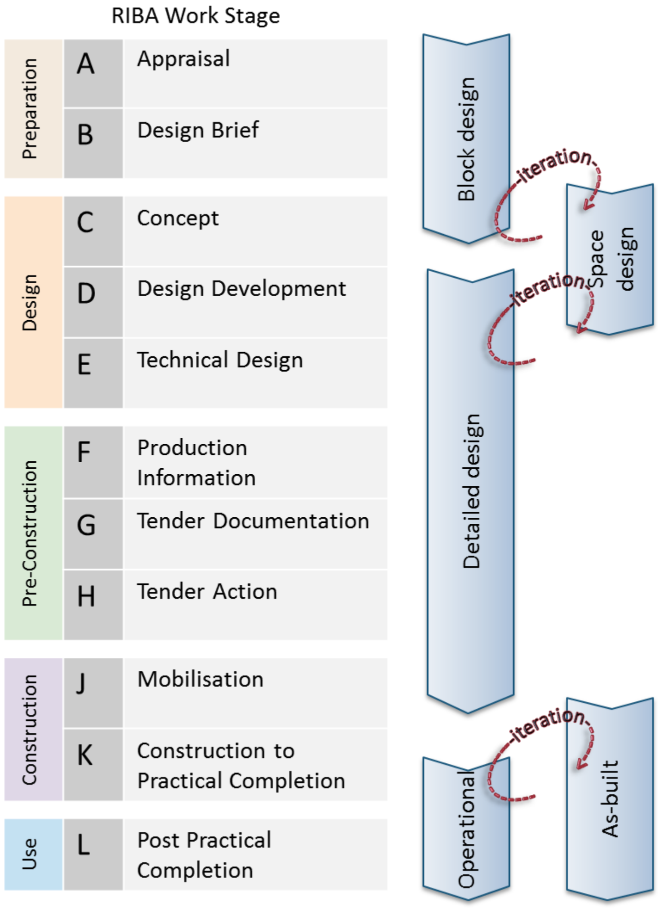


Figure 7-3 The RIBA Plan of Work and the five software phases

The diagram shows the relationship between the Plan of Work, currently employed in the UK (after Royal Institute of British Architects, 2007), and the five stages of the proposed software. It is intended that there would be the ability to move iteratively between the five stages in order to optimise the building form and construction.

The five discreet phases, or processes, shown in Figure 7-2 and 7-3, that the software would support are:

The *Block design* phase, which could also be called the concept, massing or sketch phase, it is when the overall 3D volume (mass) and footprint of the building is determined. As illustrated in Figure 7-3 this covers the RIBA work stages of Appraisal, Design Brief and Concept.

The *Space design* phase covers the development of the building into individual thermal spaces. This could also be called sketch or design development. This covers the RIBA work stages of Concept and Design Development. The overlap with the previous step, *Block*, reflects the iterative nature of the proposed software, whereby there would be fluidity between these steps as part of the optimization of the design.

The third stage of this proposal, when the design is developed, is called the *Detailed design*. This covers the RIBA work stages of Design Development, Technical Design, Production Information, Tender Documentation, Tender Action and Mobilisation. Again there is overlap with the previous stage.

The *As-built model* is a record of the building as constructed, recording any modifications to the design as a result of changes on site. As indicated in Figure 7-3 it would overlap with the following phase. Seldom does a building remain unaltered throughout its lifespan. However, often changes can be made without a sound understanding of the rationale of the original design, sometimes resulting in a detrimental effect on either the users or the running of the building. This facility would support the planning and recording of all changes to the building.

The *Operational model* would facilitate the running of the building based upon the design intent. It would also facilitate the recording of data from POE such that if the building performance differs from the design goals it should be possible to explore why. Recording of such data should be available to be feedback to: 1) improve design decisions, 2) improve thermal simulation engines and 3) improve knowledge about construction methods employed for low energy buildings.

7.3 Overview of the Intelligent Spatial Entity approach to the design of buildings

This section outlines how the composition of a building model as a set of connected Intelligent Spaces can be employed to design and manage a building. Core to the concept is that the Intelligent Spaces are 3D building volumes with consistent thermal design targets. As discussed earlier, most BIM software ‘fits’ or derives spaces after the design is complete and the enclosing building objects are in place in the model. The difference in approach is illustrated in Figure 7-4, the left hand image shows a simple small building modelled with building objects such as walls. The right hand image shows the same small building modelled as a series of thermal zones. The use of thermal zones as a design approach is not new; it is used in Ecotect (Marsh, 2006a) and more recently in Project Vasari. It is in many ways similar to the method of 2D extrusion used in SketchUp[64]. However, where this proposal varies from these types of software is that it extends past the early conceptual building design stage and is intended to act as the basis for iterative design, energy prediction and building management throughout the life of building project.

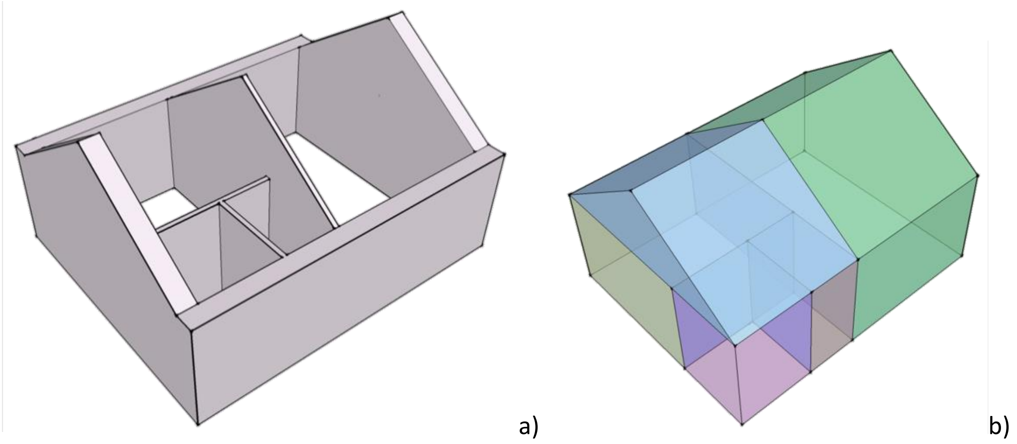


Figure 7-4 The differing approaches to modelling a building.

a) Shows how BIM software constructs a building model from objects such as walls with a finite thickness to make models of buildings as shown on the left. b) Shows a model of a building, suitable for thermal simulation, composed of zones; volumes of air in thermally consistent spaces.

As discussed earlier, iterative design, the ability move from the building conceptualisation to sketch and to detail phases and back again as required, is important in the design of low energy buildings. It will enable the optimization of the building form and envelope to enable the architect to balance the appearance of the building with the energy usage. With the proposed software it is planned that the modelling process starts with Blocks (3D volumes). In the next phase these volumes are subdivided into Thermal Spaces.

---

[64] http://www.sketchup.com/

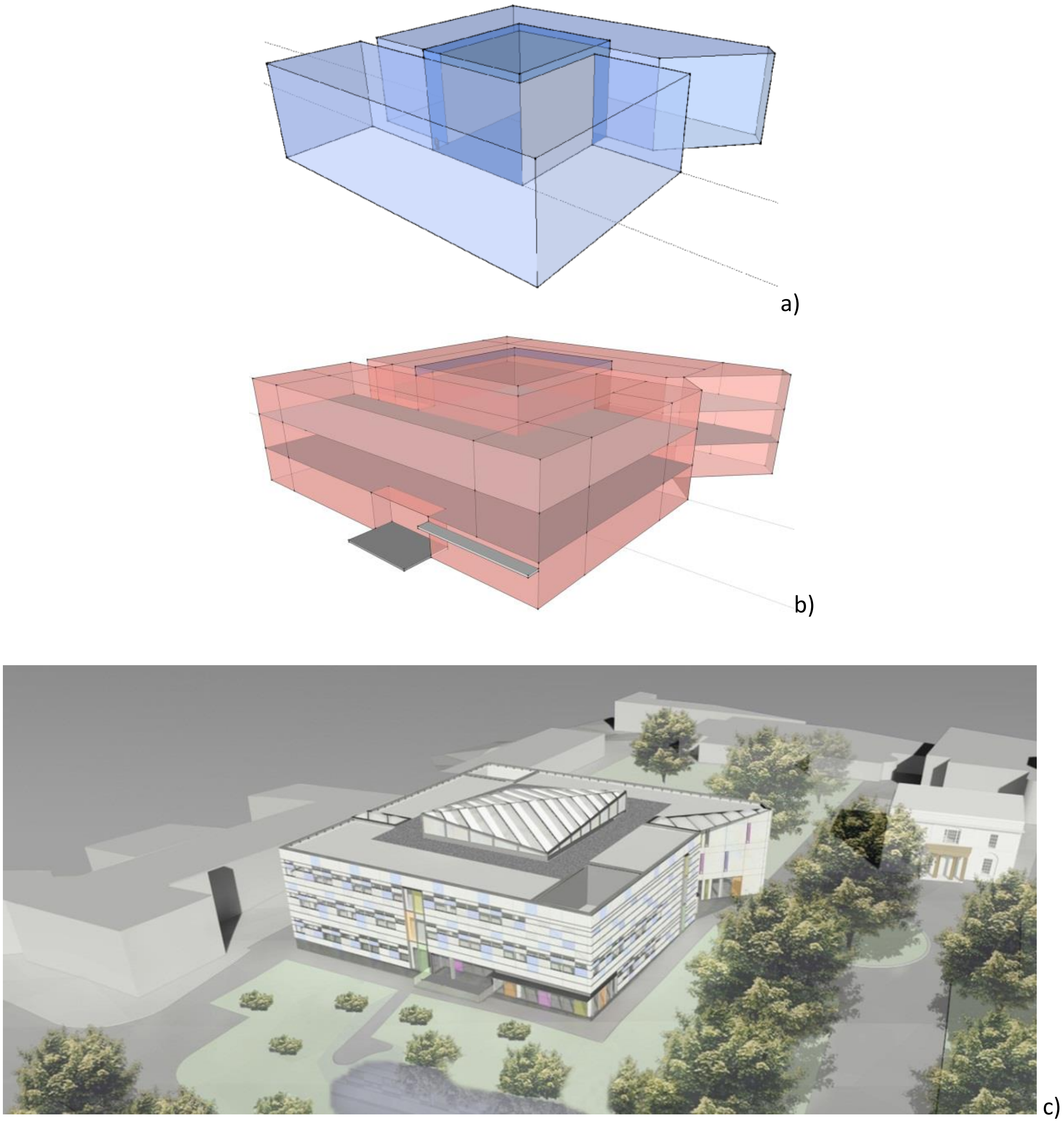


Figure 7-5 The different modelling stages in the building design process

a) Block design, the building as a number of blocks; b) Thermal Space design, the blocks broken down into a series of space zones an c) Detail design, the model with external finishes added[65]*.*

---

[65] Figure 4 a) and b) modelled in Sketchup and c) used with permission of Swanke Hayden Connell Architects

The surfaces used to form the Thermal Spaces then act as a frame or skeleton to which detailed objects of the building can be attached. The three stages are illustrated in Figure 7-5, using the example of an existing building, the Jennie Lee, The Open University, Walton Hall, Milton Keynes. Figure 7-5 c) is indicative of how a rendering of a BIM model might look.

This approach of starting with Intelligent Spaces is different to the current practice of either retro-fitting or completely re-modelling zones as part of a post-design energy analysis discussed in previous chapters. As argued earlier, there are dichotomous views of the building model. Architects start with simple sketch-type models that are developed into detailed views of the building, complete with moldings, profiles, structural elements and fittings. Although often the building concept has been simple, the building model becomes increasingly complex as the project is developed. Dynamic energy modelling typically simulates the response of a building to climate at regular time intervals over a year, for instance the default setting for EnergyPlus is 15 minutes. This is computationally demanding, hence the need to keep the model simple. To model, for instance, a door handle can use many polygons as it is usually a complex curved shape; however these polygons will not add significant accuracy to an energy model, but will significantly slow the modelling process down. The more complex the model mesh, the more time-consuming the simulation, with little improvement in the uncertainty of the simulation results (Hensen & Lamberts, 2011). The method described here effectively retains the simplicity (and intelligence) of the architect’s original concept within the building model and makes it visible and available for simulation as required during the design process.

As discussed earlier in section 7.1.3, the use of Intelligent Spatial Entities would also enable multi-criteria analysis of energy performance. Linkage of the simulation data with the DAS would enable the designer to be rapidly updated as to the effect of any changes in performance.

7.3.1 Types of Intelligent Spaces

The intelligence of the Spatial Entities lies in the associated attributes and rules. The method would allow for more than one type of Intelligent Spatial Entity as set out in Table 7-1 with the relationship between the types illustrated in Figure 7-6. *Buildings*, *BuildingBlock* and *ThermalSpace* make up the main elements as illustrated in Figure 7-7.

Table 7-1 Types of Intelligent Spatial Entities and Other Space types

Type	Examples of Rules	Examples of Attributes	Examples of Functions
Intelligent Spatial Entities			
Building	Surfaces of zero thickness There must be at least one Building	Building Blocks that comprise building [1 to many] Name Function Geometry Location Targets (Energy) Design intention	School Office building Hospital
BuildingBlock	Coplanar surfaces of zero thickness There must be at least one Building Block	Comprises a building [1 to 1] Spaces that comprise a Building Block [1 to many] Name Function Spaces that comprise the Block [1 to many] Geometry Targets Design intention	Science block Office block Hospital wing
ThermalSpace	Coplanar surfaces of zero thickness There must be at least one Thermal Space All of the Building Block volume must be accounted for by Thermal Spaces, there should be no ‘left over’ volumes No nesting of ThermalSpaces	Comprises a Building Block [1 to 1] Name Adjacency relationship to other Thermal Spaces Function Geometry Targets (comfort) Surfaces Associated Building Objects [many to many] Schedules Occupancy Courtyard (outside) Semi-enclosed space Design intention	Circulation Laboratory Classroom Offices Ward
Other Space types			
External Space	Not part of an Intelligent Spatial Entity	Name Area Function Design intention	Car park External circulation
Internal Space	Nesting of Spaces and ThermalSpaces allowed	Name Floor area Association to ThermalSpace [many to many] Function Design intention	Storey Room Circulation

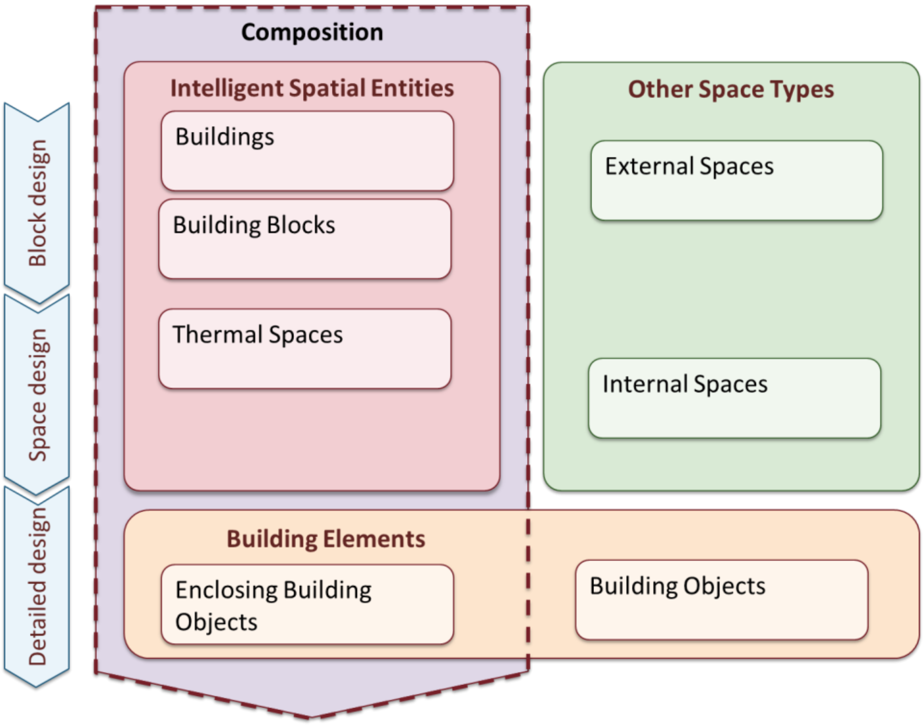


Figure 7-6 Types of Space

This diagram shows the relationship between stages in the software, the Intelligent Spatial Entities that would be employed to compose the building, along with Enclosing Building objects. Within the building model there would be other types of Space types employed to define building features such as car parks and building storeys.

The Block Design Stage of the software would offer two types of Intelligent Spatial entities; *Building* or *BuildingBlock,* as shown in Figure 7-6. There would be an attribute that would define how a *Building* would be composed of *BuildingBlocks*, with possible values ranging from one to many. The attributes for *Building* would include values such as: *Function*; *Geometry*; *Location*; *Targets for Energy Consumption* and *Design intention*. The roles of attributes such as *Function, Targets* or *Location* are discussed later. *BuildingBlocks* would have a one to one relationship with a *Building*, in that a *BuildingBlock* can only belong to one *Building.* At this stage the designer might want to add *External Spaces* to the scheme, for instance car parking areas or courtyards.

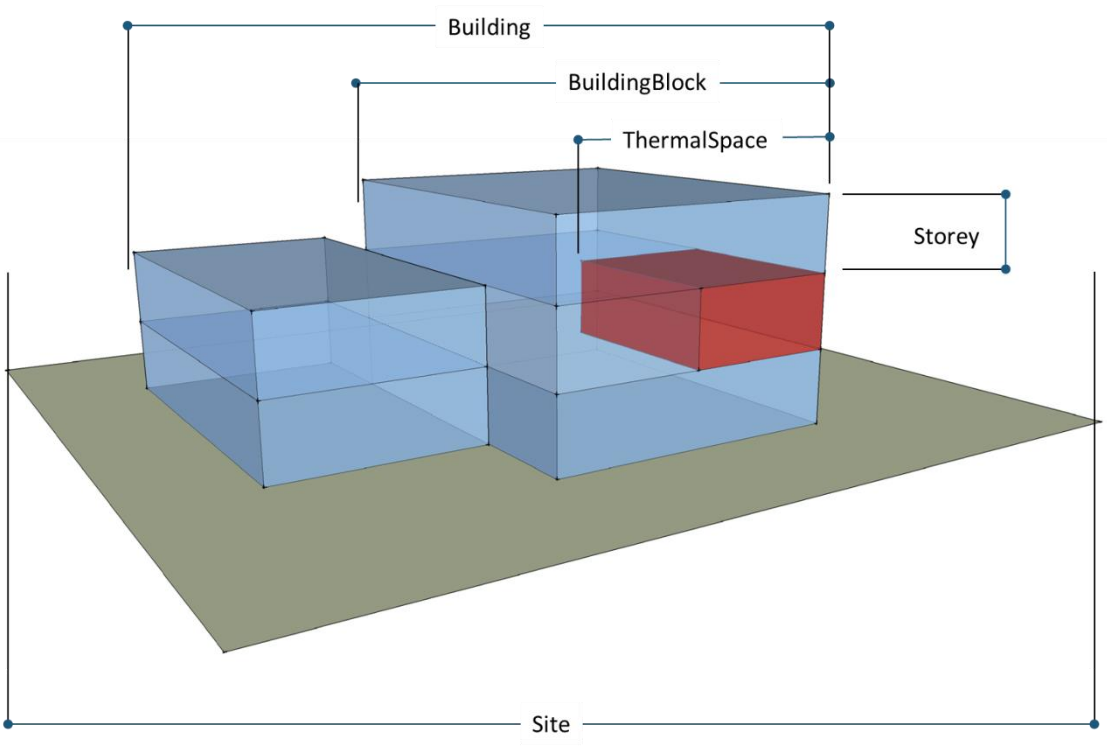


Figure 7-7 The naming convention for a building project employed in this study

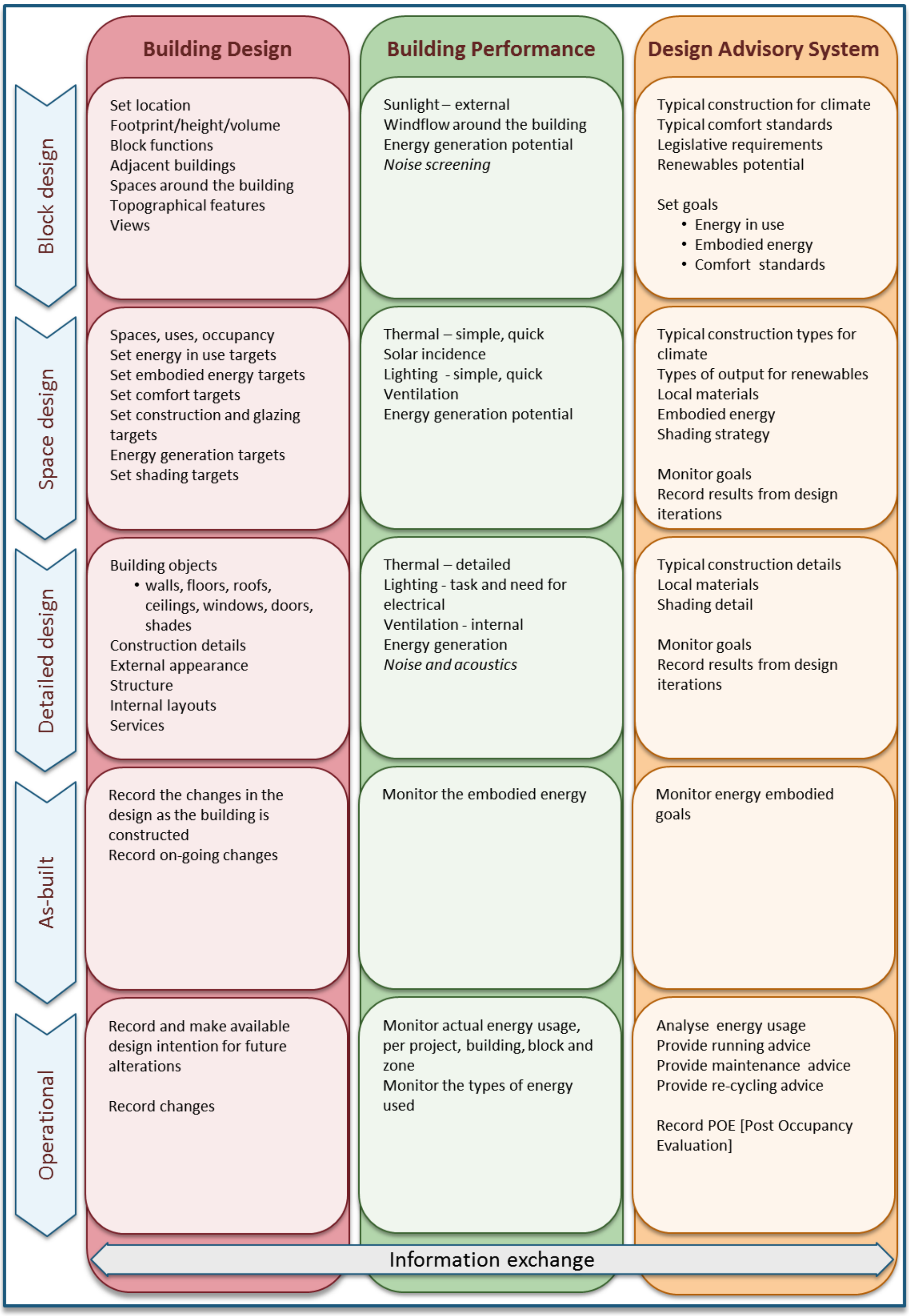
In this example there is a Building composed of two BuildingBlocks positioned on a Site. There are a number of Storeys (floors) and a number of Thermal Spaces (only one is highlighted red).

The Space Phase of the software would offer one type of Intelligent Spatial entities; *ThermalSpace*. A key feature of the method is that *Thermal Spaces* comprise *BuildingBlocks*, which in turn comprise *Building,* with no 'left over' volumes. Building features such as semi-enclosed spaces, that have an effect on the thermal performance of the building would all be types of *ThermalSpace,* for instance balconies. Every *ThermalSpace* would have a one to one relationship with a *BuildingBlock*. There could be no nesting (one inside another) of *ThermalSpaces*. In general a *ThermalSpace* would be a room or set of rooms, such as a run of offices or bedrooms.

In addition to the *ThermalSpaces* that are employed to comprise the building model in a consistent and non-redundant manner, that is with no over-lapping or nesting of volumes there would need to be other types of spaces. The *InternalSpace* type of volume could be employed in an organisational manner, to both nest and group other volumes. For instance an *InternalSpace* could be employed to group *Thermal Spaces* into a Storey as shown in Figure 7-7. Another example is a large *InternalSpace* with distinct thermal variations (for instance an exhibition room with a large expanse of glazing on one side) might contain two or more *ThermalSpaces*. The *InternalSpaces* could also be individual rooms and be employed to generate data such room schedules and floor areas, that is the space between walls.

7.3.2 Illustration of the Intelligent Spatial Entity approach

Building design involves different activities at different stages in the process, as shown in the matrix of Figure 7-8. The application of the Intelligent Spatial Entity method to support the design of a building as an arrangement of Thermal Spaces and thus enable the combination of BIM, BES and DAS functions through the building design steps is outlined. The following section discusses how the proposed combined software would operate at the various phases of the building design.



	Building Design	Building Performance	Design Advisory System
Block design	Set location Footprint/height/volume Block functions Adjacent buildings Spaces around the building Topographical features Views	Sunlight – external Windflow around the building Energy generation potential *Noise screening*	Typical construction for climate Typical comfort standards Legislative requirements Renewables potential Set goals • Energy in use • Embodied energy • Comfort standards
Space design	Spaces, uses, occupancy Set energy in use targets Set embodied energy targets Set comfort targets Set construction and glazing targets Energy generation targets Set shading targets	Thermal – simple, quick Solar incidence Lighting - simple, quick Ventilation Energy generation potential	Typical construction types for climate Types of output for renewables Local materials Embodied energy Shading strategy Monitor goals Record results from design iterations
Detailed design	Building objects • walls, floors, roofs, ceilings, windows, doors, shades Construction details External appearance Structure Internal layouts Services	Thermal – detailed Lighting - task and need for electrical Ventilation - internal Energy generation *Noise and acoustics*	Typical construction details Local materials Shading detail Monitor goals Record results from design iterations
As-built	Record the changes in the design as the building is constructed Record on-going changes	Monitor the embodied energy	Monitor energy embodied goals
Operational	Record and make available design intention for future alterations Record changes	Monitor actual energy usage, per project, building, block and zone Monitor the types of energy used	Analyse energy usage Provide running advice Provide maintenance advice Provide re-cycling advice Record POE [Post Occupancy Evaluation]

Figure 7-8 A matrix of building design, performance and design advisor activities

A matrix of the building design, performance and design advisor activities set against the stages of the proposed software of Block, Space, Detailed design, As-built and Operational

The Block Design stage

At the Block Design step the visualization of the building is of simple blocks that will be a *Building* composed of one or more *BuildingBlocks* as shown in Figure 7-7. Examples of possible rules and attributes for *Buildings* and *BuildingBlocks* are given in Table 7-1. The *Building* shown in Figure 7-7 is composed of two *BuildingBlocks*. The blocks could be generated from a palette of primitive volumes or extrusion from 2D shapes, which could be assembled and manipulated as required, with 'push-pull' of surfaces and vertices along with Boolean operations employed to combine volumes. The blocks could be coloured, translucent/transparent or wire-framed/solid as required. The principal rule is that surfaces between *BuildingBlocks* would be co-planar and that the *BuildingBlocks* are labelled.

The activities undertaken by the design team in the Block design stage are given in Figure 7-8. The first action on any project is to identify the building location which triggers the DAS to locate information regarding the climate. The effect of this is that the design advisor can give information on strategic options and types of construction appropriate for that region. The building function can be set; this will trigger the design advisor to supply information regarding legislation and comfort standards. In conjunction with the knowledge of the climate it could offer advice on possible plan forms. If for instance, the function of the *Building* is a school, the DAS would provide information such as: details of exemplar low energy buildings with similar function and location; requirements for means of escape in the case of a fire; disabled access requirements; car parking standards; costings and energy targets.

The design activities undertaken in this phase include an analysis of the site; adjacent buildings, topographical features and potential views. The design can then commence with visualisation of the concept as a group of *BuildingBlocks*. With a simple building it might be a single block; more complex projects may have multiple blocks and functions. These blocks would be Intelligent SpaceEntities and could then have goals established, based on their footprint or volume. The goals could be for energy in use, embodied energy etc.

At this stage simulations can then be run for relevant topics such as sunlight, windflow around the building and shadows, as shown in Figure 7-9[66]. The aim of these early stage simulations are to identify, by means of a visualisation, any problems such as permanent shadowing or wind canyoning created by the block forms and/or adjacent buildings. The potential for the use of renewable energy can be established based on the available area for GSHP [Ground Source Heat Pumps], the amount of incident solar energy for domestic hot water or electricity generation using PV [Photo Voltaic] and wind characteristics plus topographical features for wind turbine generation.

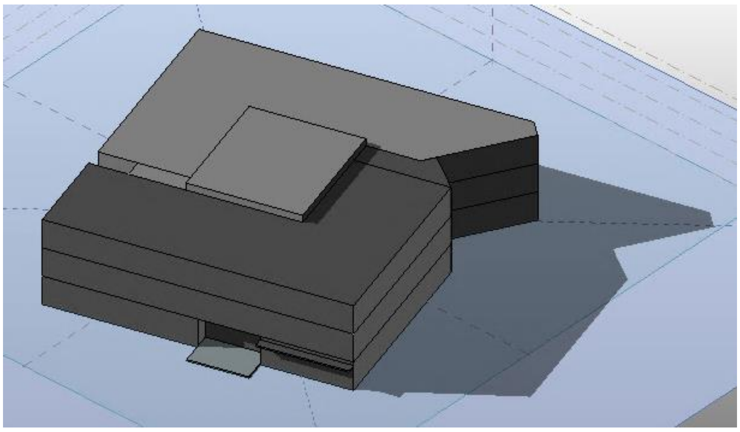


Figure 7-9 A Block model employed in a shadow prediction

The Space stage

The next step in the design process that the software would support is the subdivision of the Building Blocks into Spaces as shown in Figure 7-7, the default type would be *ThermalSpaces* in order to maintain the integrity of the building volume and avoid 'left-over' sections. The *ThermalSpaces* should be volumes that would be expected to have consistent thermal properties. Both *BuildingBlocks* and *ThermalSpaces*, as described in this section are types of Intelligent Spatial Entity. There could be instances of a simple project consisting of a

---

[66] Modelled in Project Vasari

Building, that is composed as a *BuildingBlock*, which is also a *ThermalSpace*, for example a small exhibition building, a café or shop.

A typical visualisation of the *BuildingBlock* composed of *ThermalSpaces* is shown in Figure 7-5 b). *ThermalSpaces* would be developed from the *BuildingBlock* volume, by splitting the blocks into a number of smaller units. This could be achieved automatically or by 'drawing' split lines. As with the *Block* phase the appearance - colour, transparency, solid/wireframe options could be applied. Dividing the *Block* into *ThermalSpaces* will require the designer to consider energy issues at this early design stage. As discussed above, with a very simple building the *Building, BuildingBlock and Thermal*Space meshes could be the same. However, to keep the simulation model simple and reduce computing time, in some cases groups of rooms with similar thermal requirements, for instance a row of cellular offices on one floor and on one side of a building, could be considered as one *ThermalSpace*. On the other hand one room, if expected to have significantly different thermal conditions, for instance, in a large, deep plan exhibition area that could be subject to varying thermal conditions due to the presence of windows along one wall might be subdivided into more *ThermalSpace*s.

The subdivision of the *BuildingBlocks* into *ThermalSpaces* is a very important step. In order to support reliable thermal modelling the building needs to be divided consistently with all volumes allocated to *ThermalSpaces*. *ThermalSpaces* would normally be storey height, however, this is not essential and they could span multiple stories. The DAS has an important role to play in the subdivision into *ThermalSpace*'s. It can provide advice to the designer regarding the optimum division. It can also verify that there are no left over volumes once the process is completed.

InternalSpaces could be either an individual room or groups of *Spaces* or groups of *ThermalSpaces*. These spaces would provide information about the building, for instance lists of rooms are often required, along with floor areas, for regulatory or organisational reasons. In addition they can be used for ventilation studies as discussed later in this section.

It has been argued that the definition of the thermal view of the building is better carried out by the building designer, rather than the current practice of an energy consultant, as they have a better understanding of the building (Bazjanac, 2008). This use of the concept of *ThermalSpaces* would also encourage the architect to visualize the building in terms of energy performance in addition to other aspects such as structural, organizational and aesthetics.

The *ThermalSpaces* would have specified functions which could be employed to set comfort standards using information provided by the design advisory system. Targets for energy, in-use and embodied, could then be 'attached' to the *ThermalSpaces*. These targets could be part of a graphical display, possibly through a 'dashboard' panel, and be continually updated as the design is developed. Individual surfaces of the *ThermalSpaces* could be selected within the model (highlighted) and targets set for construction, glazing, shading and PV/solar hot water. For instance the thermal resistance and thermal mass values of external walls and roofs could be set. The design advisor could be active in making suggestions at this stage. For instance, based on the orientation of the surface and the climatic data, it could advise on percentages of glazing, both in terms of heat loss/gain and possible need for shading. If the function of the Thermal Space was a classroom, the DAS would provide information regarding legal or advisory standards for the region, including space standards, day-lighting, allowable temperature ranges and ventilation requirements.

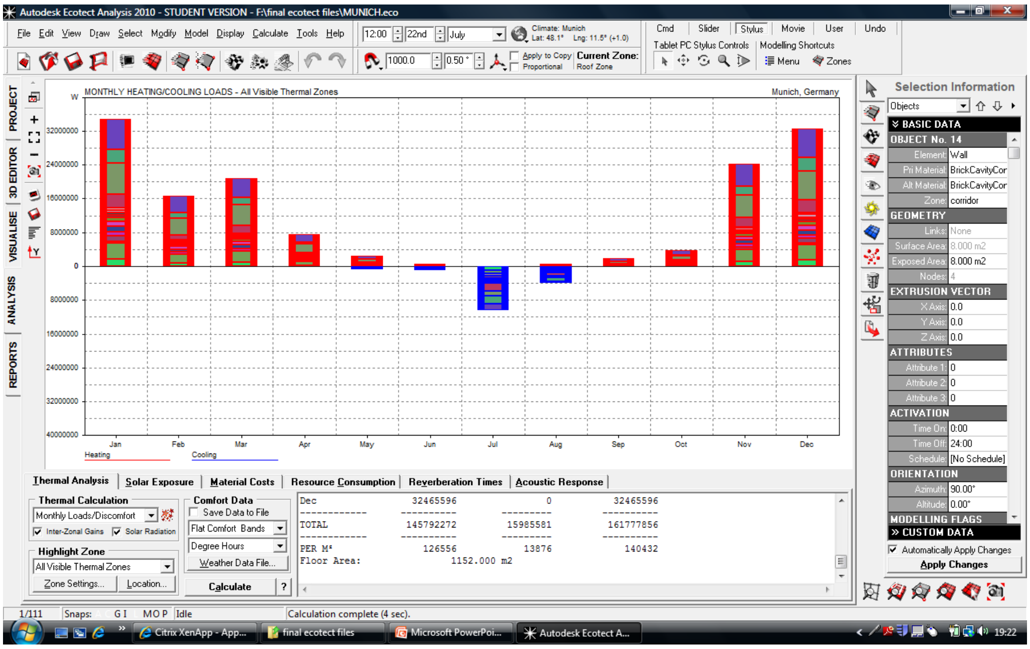
The range of planned simulations available at this stage is set out in Figure 7-8. Simulation and analysis would be rapid, comparable to the process of architectural sketching. This could be through the use of quick-to-run algorithms and enable 'what-if' scenarios to support the development and refinement of architectural concepts. Although the design advisor system might recommend a percentage of glazing for thermal reasons, the location and proportion of windows would affect the quality of light in the building. Thermal modelling could employ relatively simple algorithms such as those developed by ASHRAE[67] [American Society of Heating, Refrigerating and Air-Conditioning Engineers] or the CIBSE admittance method[68]. The need for such rapid, but quantified, 'performance sketching' is discussed by Donn et al (Donn *et al.*, 2012). They conclude that there is a priority for the much more widespread application of simulation in the early conceptual stages to facilitate design inquiry. The DAS could relate the results of any simulation to the energy

---

[67] http://www.ashrae.org/standards-research--technology/standards--guidelines

[68] http://www.edsl.net/main/Software/Designer/CIBSE.aspx

performance. As a result of these simulations it may be necessary to return to the Block model step and alter the overall form of the building.



Autodesk Ecotect Analysis 2010 - STUDENT VERSION - F:\final ecotect files\MUNICH.eco

Climate: Munich Lat: 48.1° Lng: 11.5° (+1.0)

Current Zone: Roof Zone

MONTHLY HEATING/COOLING LOADS - All Visible Thermal Zones

Munich, Germany

Thermal Calculation: Monthly Loads/Discomfort

☑ Inter-Zonal Gains ☑ Solar Radiation

Highlight Zone: All Visible Thermal Zones

Comfort Data: ☐ Save Data to File

Flat Comfort Bands

Degree Hours

```
Dec              32465596           0      32465596
-----------    ----------   ---------    ----------
TOTAL           145792272    15985581     161777856
-----------    ----------   ---------    ----------
PER M²             126556       13876        140432
Floor Area:             1152.000 m2
```

Calculation complete (4 sec).

Selection Information

OBJECT No. 14

Element: Wall
Pri Material: BrickCavityCor
Alt Material: BrickCavityCor
Zone: corridor

GEOMETRY

Links: None
Surface Area: 8.000 m2
Exposed Area: 8.000 m2
Nodes: 4

EXTRUSION VECTOR

X Axis: 0.0
Y Axis: 0.0
Z Axis: 0.0

ATTRIBUTES

Attribute 1: 0
Attribute 2: 0
Attribute 3: 0

ACTIVATION

Time On: 0:00
Time Off: 24:00
Schedule: [No Schedule]

ORIENTATION

Azimuth: 90.00°
Altitude: 0.00°

Figure 7-10 The monthly heating/cooling load for a complete building.

The positive bars indicate energy required for heating and the negative bars energy required for cooling. The different colours relate to different zones in the model[69].

Figure 7-10 shows an example of simulation result, the *Monthly loads/discomfort* chart which was reported as the most useful graph by students [98%] in their modelling study reported in Chapter 4. This chart identifies the months when heating or cooling would be required to maintain comfort. Plots such as these can be employed to inform the designer as to the proportion of energy needed to be spent on heating or cooling the space. From Figure 7-10 it can be deduced that in this case the majority of energy is required for heating the building in the colder months with little need for summer cooling. With this knowledge the designer would be advised to make modifications to the design such as: improvement of the insulation level, alteration of the type and proportion of fenestration, ventilation rates, heat recovery, etc. that would affect the more problematic heating months. As the need for

---

[69] Simulation run in Ecotect

cooling would be limited to only two months of the year and the chart indicates that only very little is required then natural ventilation strategies could be explored.

More detailed thermal modelling could be available at this stage, but it would be envisaged that it would actually be employed towards the end of the design stage, and perhaps left to run overnight, if necessary. Solar incidence data would be used to test out the need for shading and quantify the PV generation potential. Windflow studies would enable the development of a natural ventilation strategy.

Visualization of the simulation results at this early sketching of ideas stage is crucial. It requires comparison of the results with the goals and targets set within the design advisor component. At this stage the visualization could be very simple, aimed to illustrate how close the current design solution is to achieving a particular performance goal. Key to the iterative building design process is that the software should enable the designer to retrieve and compare previous design options/solutions and simulation results.

The Detailed Design stage

The detailed design stage involves using the *Thermal Space* mesh as a frame or skeleton to which building objects are attached or located within. At this stage the building objects represent 'real' or 'physical' building elements or products, such as external and internal walls, roofs, floors, ceilings, windows and doors.

Key to the operation of the software is a set of rules for the relationships of building objects within the building model. This affects the naming and connection of the building objects. A compositional relationship would be employed whereby all 'real' or enclosing building objects, such as external and internal walls, roofs, floors, ceilings, windows and doors are 'related' to at least one named, *ThermalSpace*. This can be seen in Figure 7-11 where Wall A relates to Thermal Space 1 and Wall D relates to Thermal Space 2. Both of these would be external walls and the construction details would be appropriate for their function. Building objects such as walls or floors that are positioned on surfaces between two *ThermalSpaces*, as shown by Walls B, C and E in Figure 7-11 would be related to both spaces. These walls will be internal partitions and the construction details would again be appropriate. Note that although Walls B and C are on the same plane and likely to be of identical construction, the software, because of the intersection of the surfaces of the adjoining Thermal Spaces would treat them as two distinct surfaces. Two building objects that are positioned on surfaces between possible adjoining *ThermalSpaces* such as Walls B and C, and Walls B and D would be related to each other in order to link them together. Where there are non-coplanar surfaces, such as the orthogonal configuration involving Walls A, B and D, these would again be related to each other with appropriate joint details specified.

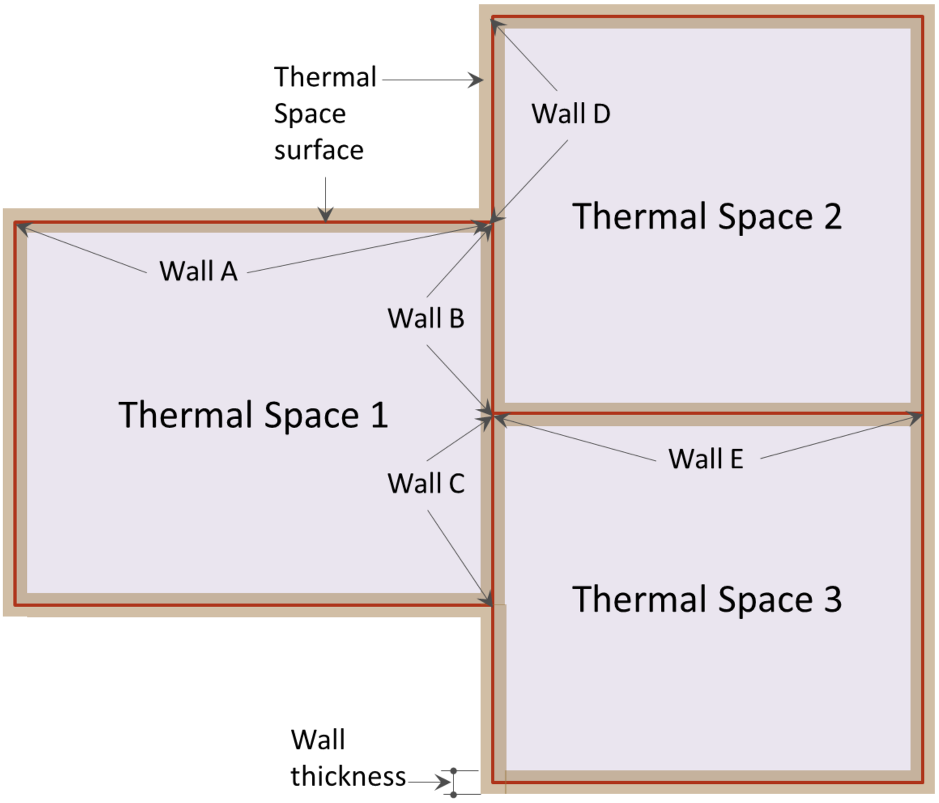


Figure 7-11 Enclosing Building Objects and Thermal Spaces

The diagram shows a plan of a notional building composed of three Thermal Spaces. Wall A is an external wall, 'attached' to the surface of the Intelligent Space that encloses Thermal Space 1. Wall A and D each relate only to one space. Wall B relates to two spaces, Thermal Space 1 and 2. Wall C relates to two spaces, Thermal Space 1 and 3. Wall E relates to two spaces, Thermal Space 2 and 3.

As with many types of design and visualisation software there would need for the facility to place objects, such as the Thermal Space meshes, onto an individual 'layer'. The feature would enable the isolation, visibility and manipulation of elements on that layer.

Curves can be an important design feature for architects. Figure 7-12 illustrates how a curved element is attached to an Intelligent Spatial Entity. It is proposed that curved primitives, such as spheres, cylinders and freeform curves would be available as part of palette of volumes available to the designer in the Block and Space modelling phases. However, they would be effectively planar. As buildings objects are attached to the Intelligent Spatial Entity surface they could take a curved form as required.

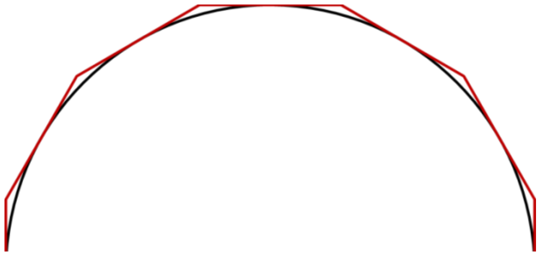
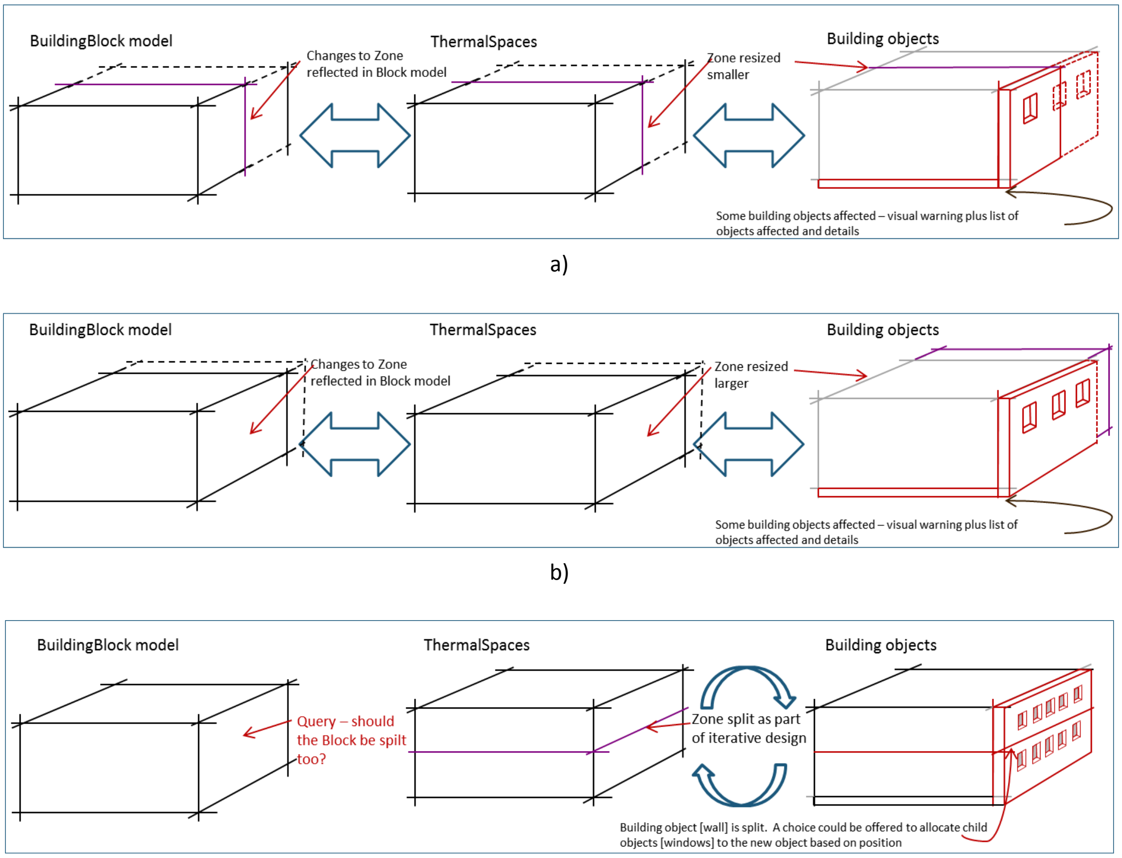


Figure 7-12 A curved surface

The drawing illustrates how a curved surface is dealt with by the software. The curve is 'attached' to the flat, segmented surface of the Intelligent Spatial Entity at a tangent (the attachment could be chosen from a series of options, such as tangential, nodal or on a vertex.

Rules for connections of building objects would be monitored and enforced by the software. The primary rule would be that *BuildingBlock* and T*hermalSpace* surfaces would be coplanar; this is to support reliable thermal analysis and inter-zone heat exchange calculations. All building objects would be related to at least one *ThermalSpace* and each *ThermalSpace* related to at least on *BuildingBlock*. Thus, as part of the iterative design process, if either the *BuildingBlock* or the T*hermalSpace* is resized the software will detect the changes. As shown in Figure 7-13 the building objects affected by these changes would be identified by the design advisory system and be both highlighted visually in the model and a list of affected objects given. The designer could then deal with the objects as they deemed necessary.

The rule for the 'attachment' of the building objects to the *ThermalSpaces* would be chosen from options offered by the software. For instance, with external walls, there could be a choice between whether the inner face, centre line or outer face of the wall would be coplanar with the *ThermalSpace* surface. Objects, such as internal walls, do not need be joined to the surface of the *ThermalSpace* in which they belong, but they would have a compositional relationship with the *ThermalSpaces* in which they are located. Rules or choices for junctions of building objects, such as internal walls joining external walls or the corners of external walls would be provided in a similar way to that already used in BIM software.



a)

b)

c)

Figure 7-13 The BuildingBlock, ThermalSpaces and BuildingObject models.

The software would support the viewing of the model three forms: BuildingBlock, ThermalSpaces and BuildingObjects. a) shows the effect to the model if the BuildingBlock is resized smaller, b) shows the ThermalSpace expanded and c) shows the ThermalSpace split. The software would re-size the BuildingBlock and ThermalSpace meshes to reflect changes made in the design as appropriate and give a visual warning and a list of the building objects affected by the change.

Simulation at this stage can include detailed thermal, daylighting, ventilation performance and energy generation characteristics. The model detail required for these types of analysis vary. Thermal simulation is likely to be a full dynamic analysis, taking into account direct and indirect solar gains, internal gains, inter-zonal heat flow, occupancy schedules and internal comfort requirements. At this stage, the *ThermalSpace* mesh will be suitable for inter-zonal studies, but additional data would be required to model solar overhangs and shading devices as shown in Figure 7-14.

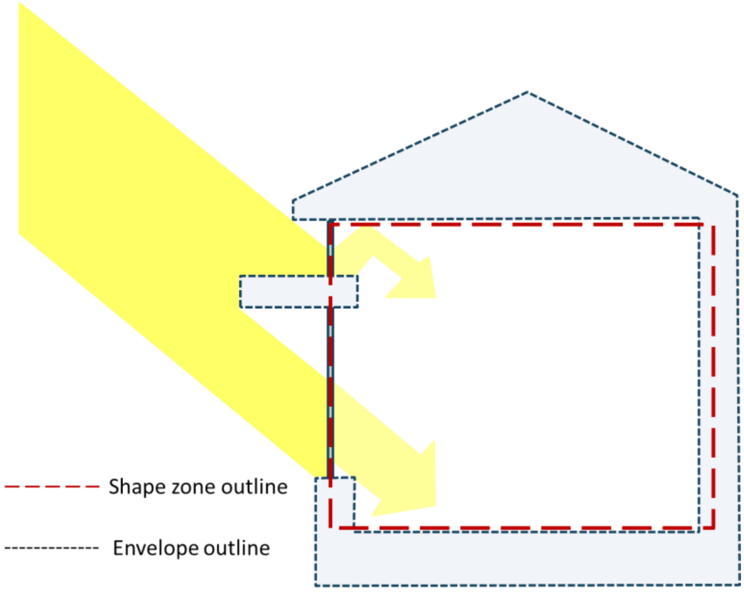


Figure 7-14 Profile required for lighting modelling.

A diagrammatic section through a building showing the profile required for daylight modelling. The Thermal Space boundary is shown as a red dashed line. The envelope outline necessary for sunlighting and daylighting studies is shown as a blue dotted line. Penetration of sunlight is restricted by the overhang, the thickness of the external wall and the light shelf, and light is shown reflected from the light shelf and ceiling.

Daylight studies predict the internal natural lighting levels on a working plane or surface to determine if they will be sufficient for occupants of the space to carry out their normal duties. Effective use of natural daylight means that the use of electrical lighting, and hence energy used, can be reduced. Accurate daylight modelling only requires a relatively simple model, however unlike a thermal model, external wall thicknesses, overhangs, light-reflectors and shading devices become important as shown in Figure 7-14. To enable this type of simulation the automatic generation of an additional mesh could be provided within the software, called the *external envelope*. It would be generated from Cartesian coordinates obtained from the zone data and the known thicknesses of the walls and the dimensions of overhangs and shading devices. This mesh would reside on a bespoke layer.

Ventilation simulation, as discussed in Chapter 5 can use two methods. *Multi-zone airflow networks* rely on the subdivision of a building into a number of zones (normally rooms). These are different from *ThermalSpaces* (that may span a number of rooms) as wall dividers will affect the air movement. It would require the *ThermalSpaces* to be further subdivided into volumes that relate to rooms, with the position of openings, such as doors and windows detailed. An example is a row of offices. Thermally they could be treated as one *ThermalSpace*, but for ventilation purposes they would need to be treated as individual rooms, *InternalSpaces*. CFD would require a similar model, with the addition of obstructions, such as internal partitions and furniture, and in certain conditions occupants, which affect the flow of air are important features to model. However, they also need to be modelled in a simplified ‘block’ manner. This data could be generated from the geometry of the model and reside on a separate layer.

Detailed predictions would be provided for energy generation by the input of specific product details to the model and the results fed through to the energy goals calculations.

The DAS could monitor the outputs of the different simulations and where these indicate a failure to achieve targets it would propose alternative approaches. The design advisor would provide typical construction details and the embodied energy of materials along with an option to supply data on local materials (to reduce transport costs). It could provide data and options on how shading could best be provided. The monitoring of goals would be ongoing, but due to the time taken to carry out the more detailed analysis at this stage might be restricted to an overnight run.

At this detailed design stage the software would provide a range of building model visualisation, rendering and printing options, as typically found in BIM software.

The As-built stage

The importance of this step is to provide the facility to record what is actually built, and the reasons for any deviations from the original plan. This extends to any changes in materials and associated embodied and transport energy. The DAS would monitor these changes and be used to provide alternative suggestions. During the design stages the designer would have the opportunity to record experiential data to the building model, that is to record the design intent. This would become part of the *As-built* model and could be taken into account when possible changes in the building are considered. As the building is modified and altered during its lifespan, changes could be dated stamped and recorded in the building model.

The Operational stage

The Operational step would support a number of functions relating to the day to day use of the building. It would provide scheduling for both the running and maintenance of the building and equipment. It would enable monitoring of actual energy usage, both per volume, *Building*, *BuildingBlock* and *ThermalSpace* and also by usage, for instance, heating, or cooling, lighting and equipment. The DAS would analyse this usage against design targets and flag significant anomalies and assist identification of the discrepancies against the design predictions. The *Intelligent Spatial Entities* could be employed to record POE, for instance in the tracking of occupant satisfaction/comfort and any necessary interpretation of results relating to each thermal zone.

The model could also be used strategically to record changes to the building. It would provide information regarding the original design intent that could be used to inform decision making when planning or designing alterations.

7.4 Discussion

The novelty of the proposal is that it maintains both an abstract and detailed version of the design within the building model. The abstract view of the building would be composed of *Intelligent Spatial Entities*, and would be available both for design visualisation and performance simulation throughout all stages of the design and operational phases. This concept for the proposed software offers a number of advantages over that currently available. The same model can be used from early sketch design to completion, operation and possible re-modelling. The early sketch modelling in 3D, through the use of primitive block shapes, should make the software attractive to architects as it could overcome some of the concerns regarding inhibition of early design processes through the use of high precision tools (Kalay, 2006) such as BIM. This sketching of the building form, coupled with rapid 'sketch' type analysis, should support the architect in the optimisation of both the aesthetics and the performance of the building. This would enable the rapid comparison of early design concepts and provide flexible integration within the iterative design process as discussed by Donn et al (2012), Schlueter and Thesseling (2009) and Gething (2011). It should also obviate or reduce the necessity of multiple tools to design low energy buildings as outlined by Attia and De Herde (2011).

The software would place the determination of the thermal view back into the hands of the architect, who understands the building, as opposed to an external consultant. This should help avoid the arbitrary decisions and assumptions associated with the creation of thermal zones used in simulations as discussed by Bazjanac (2008). Because of this the architect, with the support of the design advisor system, would potentially be better able to conceptualise the building in terms of thermal comfort zones and energy targets. This should partly address concern about 'black box' results where the computer delivers a set of incomprehensible numbers. The proposed software will potentially enhance dialogue between the architect and energy consultant or enable the architect to undertake building performance simulation. Possible adaption to changed climate could also be modelled with the inclusion of future weather data now being developed (Eames *et al.*, 2010).

As discussed by Attia et al., the provision of information to assist the design optimization process is vital (2009). The use of Intelligent Spatial Entities would allow the integration of the DAS with the building model at all stages of the design process. This would avoid the problems with standalone design advisory systems where the model data has to be input manually. The inclusion of the DAS would probably be the most challenging component of the proposed software, as a successful, comparable system has yet to be fully developed. The closest in aspirations is the ICADS system discussed earlier. The used of intelligent spatial entities will overcome the issue with geometry as expressed by Pohl and Myers (1992).

To enable the composition of the building model as a series of intelligent spatial entities the software would need to operate in a well-defined manner, with choices offered to the user in a predetermined order. However, restricted methods of working are common in 3D modelling software, for instance SketchUp works by the extrusion of 2D shapes and it is not possible to start with a 3D volume as would occur for example in 3DS max. Work involving architectural students working with Ecotect and designing with zones (thermal spaces) suggests that such restrictions should not be a problem (Hetherington *et al.*, 2011). It should be noted that learning 3D building modelling software and the principles of building performance simulation is non-trivial. Working with Intelligent Spatial Entities should reduce anomalies in boundaries and thermal spaces as reported in the literature (Bazjanac, 2010).

The term Intelligent Spatial Entities was arrived at after some deliberation. Initially the term ‘zonal mesh’ was considered, however, it is a technical term, used by heating and mechanical services engineers and upon some reflection, was not an appropriate term for architects. Also as discussed earlier there may be more than one type of ‘zone’. The term ‘mesh’ can have different meanings. In the context of this work a *mesh* is a collection of vertices, edges, and faces that describe the shape of a *3D* object. However, in CFD the term ‘mesh’ is used to describe the discrete cells (or subdivisions) that makes up the volume being modelled. However there are still difficulties with naming conventions, some are cultural, for instance floors or storeys, buildings or blocks. An appropriate naming convention would need to be established as the software was developed through detailed requirements analysis.

7.5 Conclusion

This chapter has outlined a method for the integration of BIM and BES processes, supported by a DAS into one software tool through the use of Intelligent Spatial Entities. The concept of an Intelligent Spatial Entity has been defined as 3D volumes with coplanar surfaces, with attributes, rules and functional relationships with other spaces and physical building objects. The building model would need to be assembled in a particular manner composed of Intelligent Spatial Entities. The phases, or work flow, that the software would provide has been outlined and related to existing professional stages employed by UK architects. The integration and functions of the 3 components, BES, BIM and DAS by use of the Intelligent Spatial Entity method has been described. Finally the range of design and energy optimisation features that proposed software would provide throughout the design of a building has been demonstrated.

This chapter has been a sketch design for the proposed software. It has attempted create a vision of how the software might be employed. The software, with the support of the integrated design advisory system, would be a significant improvement on existing, separate tools. The major benefit would be that it would allow the architect to think about the building in terms of thermal comfort spaces. Further work would yet be necessary to establish detailed software requirements and design the software architectures to enable the development of a product. The next chapter outlines the future development and research work necessary to develop this novel approach.

Chapter 8

Conclusions

The motivation for the research was a concern regarding how architects, especially those working in small practices, will have the correct tools to help them deal with the changes that will occur to the design of buildings as a result of policies arising from the Climate Change Act of 2008. The research started by looking at the synergies between software, energy and architecture. Initial scoping of the problem was established in two short papers, one concerned with achieving zero carbon buildings by 2019 (Hetherington *et al.*, 2010a) and the second with the need for changes in building modelling practices (Hetherington *et al.*, 2010b). An empirical study, reported in Chapter 4, carried out early in the development of the thesis, investigated existing software approaches and led to the framing of the research question:

How could software be better designed with the integration of design, energy simulation and knowledge systems to support architects in the design of low energy buildings?

This was broken down into a number of related questions, the following sections describe how the questions have been answered and conclusions drawn.

8.1 The problem domain

What are the problems with existing building design and simulation methods with respect to supporting the iterative and holistic design of low energy buildings?

The analysis of the problem domain has formed a significant part of this thesis. According to Kalay (2004), problem analysis forms a major part of the process of architectural design. In the field of software engineering, Jackson stresses the necessity of starting development with a focus on the 'problem world' (2005, p.6). Chapter 2, *Influences on Software to Design Low Energy Buildings,* contains a review of the literature. In addition to academic research, governmental policy, professional processes and proprietary software development have all influenced the problem space. The reasons for building design practices and software tools needing to change to cope with legislative changes was reviewed. The types of software to design buildings, simulate their energy performance and support decision making were discussed. The current barriers to integrated design and simulation software were outlined. A number of problem areas were established: the need for improved building design, simulation and decision advisory tools, the need for the architect to develop a better understanding of building physics and the need for better interoperability of data to support an iterative design process.

The growing awareness of the importance of energy in buildings in contributing to the threat of Climate Change has led to a dramatic increase in the number of relevant academic publications produced over the period of this research. It should be noted that government policy in the UK towards the AEC industry has changed radically since the beginning of 2010 when this research started. This thesis seeks to respond to two major challenges to the building design profession arising from legislative requirements, detailed in Chapter 2: (1) all buildings should be ‘zero carbon' and (2) the use of BIM is to be mandatory for all public projects.

Chapter 3, *The Problem Domain: Low Energy Buildings*, established the reasons for the importance of dynamic building performance simulation for the design of low energy buildings. The meaning of low energy building design for the architect in the context of zero carbon legislation was discussed. An overview of the physical parameters involved in relation to energy and buildings was provided. The importance of employing performance simulation as part of an iterative building design and optimisation process was discussed. The need for improved information support in decision making in the light of the rapidly changing legislative environment has also been highlighted.

Chapter 4, *Empirical Studies into Software to Design Low Energy Buildings,* reported on two case studies. Both studies addressed the problems associated with using existing software tools to design and model low energy buildings. The first study, using BIM and BES software to model a small low energy building, identified significant limitations. A further study, involving a group of architectural students using BES software, confirmed many of the initial findings and was used to establish early software requirements. Themes established in this chapter were the need for:

1. Improved modelling processes – this theme contained requirements for simulation software, such as either more intuitive modelling techniques similar to that found in design software and/or software combining both building design and simulation functions.

2. Visualisation of data – this theme included the need for improved display of both the input values and the results of simulation, recording and display of multiple sets of data and the tracking of design evolution.

3. Design decision support and knowledge systems – this theme included the need for calculation support, error messages and information regarding local materials.

The problem domain was further explored in Chapter 5, *Domain Requirements for Software to Model and Simulate Low Energy Buildings*, with the methods employed by current BIM and BES software analysed. The differing, dichotomous, approaches to the creation of a model of a building design by BIM and BES processes was investigated. BIM software is concerned with the assembly of the model with detailed building objects, whereas BES software primarily employs more abstract models of building volumes. Themes established in this chapter were the need for:

1. Resolution of the different requirements for geometric modelling, between BIM and BES software.

2. The design of an interface to accommodate both BIM and BES functions.

3. The different requirements for recording materials for both design and BES software.

4. Interoperability of data between BIM and BES software environments.

The chapter ended with the conclusion that if BES and BIM processes are to be more closely integrated, either by improved interoperability or integrated software, the requirement for a common approach to geometric representations has to be resolved.

This work is opportune in that it associates two contemporary legislative developments affecting the AEC industry by making an original linkage between government policy on BIM and energy usage in new buildings. It articulates the issues and problems facing architects in the UK caused by proposed legislative changes. It established the need for improved software tools to support architects in dealing with the challenges created by rapidly changing policies.

8.2 Interoperability

What are the interoperable languages currently in use and could they be modified to better support the reliable transfer of data between design and simulation environments?

Chapter 6, *The Building Model and Interoperability,* discussed the importance of interoperability in the AEC industries and discussed current research. The predominant, current interoperable languages, IFC for BIM and gbXML for energy analysis, were described, compared and critically appraised in relation to modelling for thermal simulation. The relationship between building objects and spaces was examined. New rules for the composition of the building model were proposed to couple more tightly the relationship between building products and building spaces to improve interoperability. The provision of a library of building construction exemplars is proposed to enable the development of integrated BIM and thermal simulation software.

This chapter provided an original analysis of the key interoperable languages for low energy buildings: IFC and gbXML. It makes recommendations for the improvement to interoperable standards relating to the data requirements necessary for building energy analysis for both geometric and semantic data exchange. Again this work is timely; as discussed in Chapters 2 and 6, there is a relatively small amount of published information about the workings of IFC, yet the key objective of the UK Government policy for BIM Level 3 is for a *single project model* (Sinclair, 2012, p.6). As discussed in the chapter, interoperability, especially for building performance simulation and optimisation, is currently perceived to be inadequate. The method proposed in this chapter of tighter coupling of elements within the building model through composition of Intelligent Spatial Entities, if adopted, should significantly improve interoperability.

8.3 Integrated software

Could an approach based upon intelligent spatial entities be employed to enable the integration of building modelling, energy simulation processes and a design advisory system into one software tool?

Chapter 7, *The Integration of Building Design and Simulation Software,* proposed a new approach to the integration of building modelling and simulation software. The approach outlined is the combination of BIM and BES processes, supported by a DAS integrated into one software tool through the use of Intelligent Spatial Entities. The Intelligent Spaces would be abstract volumes that have data and rules attached. The abstract volumes then: act as a skeleton or frame to attach building objects to facilitate BIM; act as a thermal zone to enable regular performance simulation and optimisation and act as a container for the setting and monitoring of energy targets, thus facilitating a design advisory system. The application of the software to professional work stages employed by architects was outlined and the range of design and energy optimisation features that the integration of the software would provide was discussed.

The novelty of the proposal is that it maintains both an abstract and detailed version of the design within the building model through all stages of the building design and operational phases. The integrated software would be a significant improvement on the separate tools and processes currently employed in the design of low energy buildings. With the support of the integrated design advisory system the software would enable the architect to conceptualise the building in terms of thermal comfort spaces and energy targets. The *Intelligent Spaces* could also be employed to support energy usage monitoring and evaluation against predictions during the operation, maintenance, and future possible alterations of the project once built.

8.4 Evaluation

During the course of this work the UK government declared the intention to make BIM mandatory for all major construction projects. Concurrently, legislation is being introduced in both the UK and the EU to reduce energy used in new buildings, thus the work is timely. The challenges facing the AEC industry in responding to these two developments are profound. The software, as proposed, will not solve these problems, but would constitute a valuable tool to enable architects to: experiment with building form and construction, test alternatives, optimise their building for energy use and monitor actual final energy use and occupant satisfaction. The principal objective in this process is not to produce completely 'green' or 'sustainable' buildings; it is about fine-tuning designs to use as little energy as possible whilst maintaining aesthetics standards. The software is primarily concerned with the design of new, non-domestic, buildings; however, it could be used for both domestic and existing buildings. The retrofitting of the existing building stock presents significant opportunities for savings in CO_2.

The approach has been to develop a strategic view of how the software could be employed to predict and iteratively reduce energy demand of a building whilst maintaining occupant comfort. However, it may lead to a method of designing a building that is more intuitive for an architect. BIM, although recognised to be much more versatile than conventional CAD, nevertheless evolved from the need to add semantic data to groups of lines intended to model an object in a building such as a window or door. Albeit a very sophisticated tool, BIM remains a computer science response to a problem. Much of the criticism of BIM lies with the perception that it is a documentation tool rather than a design environment (Lévy, 2012). Simpler tools, such as SketchUp, are seen by designers as more suitable for conceptual design (Salman, 2011).

Kalay (2004) discusses how early computer-aided design approached the problem from an intuitive, architectural design viewpoint. However, this approach was lost as software was developed primarily to support drafting and rendering requirements through the development of CAD. The method proposed in this thesis of Intelligent Spaces employed to provide and maintain an abstract version of the building model, although initially conceived as a response to issues of interoperability between BIM and BES, could also satisfy Kalay's description of earlier concepts of architectural design software.

Although not one of the research objectives, it may be that this suggestion for a space based approach to the software could provide a tool that would provide a 'designerly' front to the sophisticated processes of a BIM database-supported environment. This is because it would present the architect with a toolkit of 3D primitive forms in the early stages of the design process, rather than the building objects offered by contemporary BIM products. This would enable a more abstract approach in the early building design stages. This addresses a concern expressed by Kalay (2006) regarding the use of precise tools employed too early in the design process that can give the illusion of more precision in the design than it deserves or is desirable. It should also overcome unease expressed by Gething (2012, p.13) regarding the design becoming 'frozen' too early in the design process before it has been fully evaluated.

The staged approach of *Block* > *Space* > *Detailed Design* as proposed in Chapter 7 could be reflected in the design of the software interface with options offered to the architect/contractor/building operator reflecting the task in hand. This should support a better understanding of separation between the "divergent, open-ended, and often erratic processes of design exploration" as provided by the *Block* and *Space* stages, and the later processes of assembling "intelligent geometrical objects in 3D" in the *Detailed Design* stage, as discussed by Holzer (2011, p.468). The method would restrict the architect, if they choose to use the software, to a particular mode of working, conceiving the building as a collection of 3D spaces. However, as discussed by Holzer, architects already think in spaces; 2D plans, elevations and sections are abstractions used to communicate their ideas to others.

At present, in general, architects do not use building performance simulation tools, they either use rules of thumb, employ energy experts, or a mixture of both. This thesis has argued that the radical change required to design buildings with very low energy demands will require them to either develop good working relationships with energy experts or learn how to use the tools. Crawley (2008, pp.1–6) in his thesis on BPS tools for policymaking states that "designers *must have and use* building performance tools to address the complexity of today's buildings". This thesis has proposed a method to make such tools more available and usable by the architect, especially those working in small practices with limited access to outside expertise.

8.5 Future work

In order to meet the challenge of designing to very low energy standards, architects will need the right software. The development of the type of software as proposed in this thesis is non-trivial, because of the scope of such a project and is beyond the capabilities of one person. Development of these software tools would need support from both policy making bodies and those planning to market the technology. Relative to: (1) projected savings from the adoption of BIM and (2) the cost of adaptation to climate change, funding the design and creation of such tools would seem an obvious choice for decision makers. The Technology Strategy Board in the UK state that a collaborative approach to the development of design and decision tools is required but that it may not occur readily in response to market forces (2009). Because of the scale of the project it would require a large and skilled team with new techniques to be researched and developed as outlined below.

8.5.1 Overall development of the software - Open Source approach

Concern regarding the role that buildings have to play in the mitigation of climate change may mean that the time is now right for a collaborative and open approach to the development of new software tools. The vision for this software is for the core to be developed under an Open Source Licence and to be freely available. An Open Source software license makes the source code available freely with relaxed or non-existent copyright restrictions[70]. Open Source is more of a philosophy rather than a prescribed method of working. Wikipedia lists a number of different models and examples[71]. In view of the scope and scale of the project a 'patron' type of approach is envisaged, with funding from either governmental or philanthropic sources for the core software. The Open Source approach would challenge the current market that creates commercial BIM software, which can be too expensive for small architectural practices to purchase (National Building Specification, 2012; Jamieson, 2011) and is argued to inhibit interoperability (Jardim-Goncalves & Grilo, 2010).

The software should be built upon regulated interoperable standards with a freely available knowledge base. It would be capable of utilising a range of underlying thermal simulation engines. Thermal engines, such as DOE2 and EnergyPlus, developed by the U.S. Department of Energy, are already freely available[72]. Commercial opportunities lie with the ability to add value through additional proprietary features as illustrated in Figure 8-1. This is a similar

---

[70] See http://opensource.org/

[71] See http://en.wikipedia.org/wiki/Open_source and http://en.wikipedia.org/wiki/Business_models_for_open-source_software

[72] http://www1.eere.energy.gov/analysis/tools.html#1

model to that employed with SketchUp[73]. These features could include facilities such as advanced rendering and visualisation, scheduling and costing. In addition, as part of the Open Source approach, there would be the opportunity for the development of plugins by others to extend the functionality of the core software.

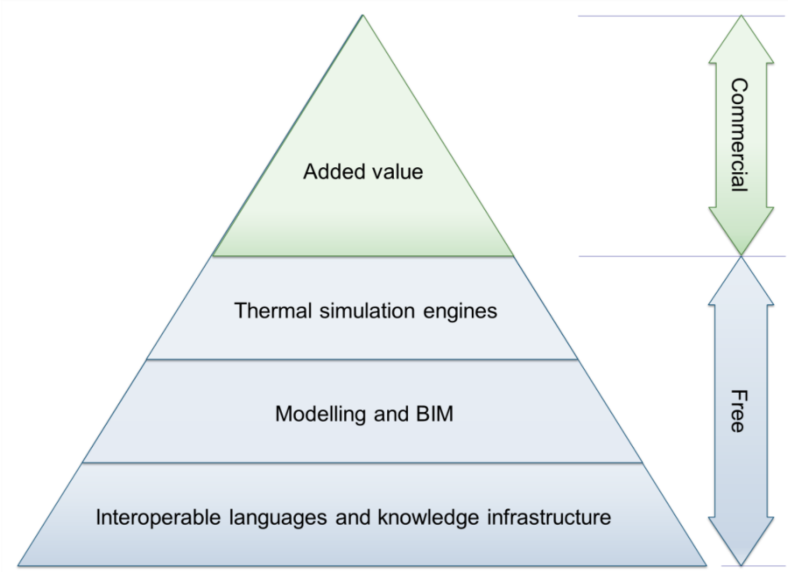


Figure 8-1 The commercial development of the software.

The bottom layer is interoperable languages, the second layer from the bottom is the geometric modelling, the third layer is thermal simulation. The software to provide these functions would be free and based on open standards. Commercial development opportunities, as represented by the top layer of the triangle, could include the provision of additional functionality such as advanced rendering and visualization, costing and scheduling.

Key to the integration of all three software functions is the adoption of the approach to the design of buildings based upon the concept of spaces. The adoption of the Intelligent Spaces design method would facilitate a collaborative approach to the population of the knowledge base element of the DAS. Previous attempts to produce a DAS generally have been abandoned as the work could not be easily integrated into a variety of architectural design

---

[73] http://www.sketchup.com/

software systems or a particular funding stream came to an end. An approach to the sketch design of 3D spaces specified with a common format would enable appropriately designed DAS software to be applied to all such models.

8.5.2 Research directions arising from this thesis

This work concentrated on resolving the geometric disparities between BIM and BES, once these are resolved the main technical obstacle to the development of integrated software is removed. The development of the combined software would result in opening up a number of research areas.

The design of the GUI [Graphical User Interface] for the combined software would need to facilitate the display of the three components: the building model design, input and output information from the BES and information from the design advisor. A particular challenge would be to make the GUI appear simple and intuitive to use and yet provide access to information from detailed simulation results and deliver sophisticated BIM operations. As discussed above, the early design modelling should be seen as a separate operation to the detailed BIM modelling process. In addition the design of a suitable interface for both designing and analysis would be challenging given the multiple devices and display types that are currently available, ranging from handheld tablets to arrays of large high definition monitors.

The BES component of the software also presents significant challenges. Both the input and output of data requires attention. As highlighted by Jankovic (2012), thermal algorithms frequently have default values included to enable them to run; if left blank the software will crash. However, default values may result in inaccurate calculations. A method would need to be developed to make these values either specifically chosen or altered by the user of the software. The DAS would have a role in advising on these choices. The outputs also need consideration. This was one of the requirement themes from the case studies described in Chapter 4. To support design decisions the results from simulations need to be presented in a visually meaningful and communicative manner. This would probably be through the use of graphical techniques, but other methods could be explored. For instance it could involve a visual link with the building model. The presentation of targets and goals linked to the simulation would be important. The concurrent display of inter-related data would need to be explored including the display of simulation results from iterations, to support design experimentation and to enable the comparison of different approaches.

The DAS would involve three components; the knowledge base, the inference engine and the goal tracking systems. Compilation of a knowledge base that covers an extensive range of topics such as rules of thumb advice, construction details relative to the geographical location, embodied energy, comfort and user standards and patterns, local and transport details, etc. is a significant task. In addition the knowledge base would require constant updating with POE data and new building product details. The energy goal or target tracking system, linked to the Intelligent Spaces, would require collecting the output from a number of analytical engines to calculate and compare predicted energy required along with potential energy generated. It would have to provide warnings on concepts such as comfort conditions, potential thermal difficulties with the construction and high embodied energy. The use of cloud technologies for storage and retrieval of data would need to be explored.

The combination of the three components of the proposed software, building design, BES and the design advisor, relies on the successful exchange of data as shown in Figure 8-2. The input data for the various BES algorithms and external software would need to be established and cross referenced to check that, in particular, the geometries meet the various requirements. Export and input of data by way of interoperable languages would also require further investigation.

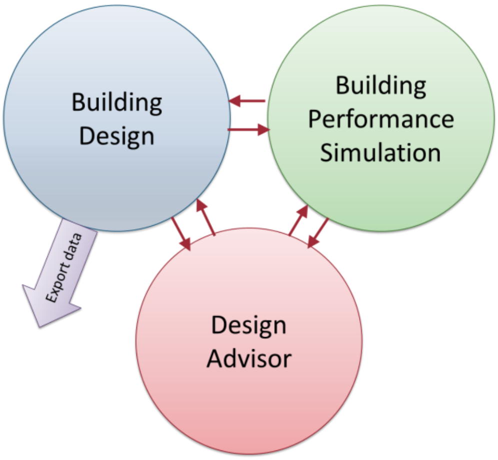


Figure 8-2 Data flow between the three components of the proposed software.

The components are: Building Design; Building Performance Simulation and the Design Advisory System, plus the export of data.

The challenges of a rapidly changing legislative environment regarding energy usage in buildings leads to more research questions than to those specifically relating to the new software tool explored in this thesis. For example, how architects will respond to these challenges and how might the implementation of BIM technologies and low energy legislation buildings affect the appearance of buildings?

8.6 Reflection

The design of buildings is a multifaceted process, dealing with externally imposed constraints, such as the site, costs and building codes, and internally drawn inspirations. Kalay (2004, p.1) describes architectural design problems as both ‘ill-structured’ (Simon, 1996) and ‘wicked’ (Rittel & Webber, 1973). In addition, the urgent need to ‘decarbonize the built environment’ in the next 20-30 years (Oreszczyn & Lowe, 2010, p.108), adds another layer of complexity to the design of buildings. The development of software to support the architect in the design of buildings, particularly when they are intended to be largely self-sufficient in energy, will probably also be multifaceted. This diversity is reflected in the coverage and spread of this thesis as illustrated by the petals in Figure 8-3.

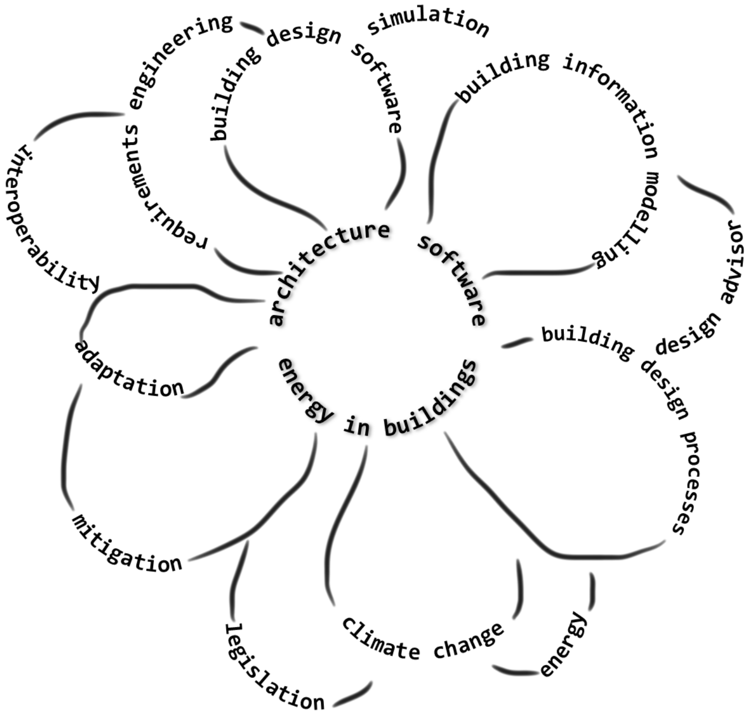


Figure 8-3 A visualisation of the problem space.

At the centre are the central themes of the thesis: architecture, software engineering and energy in buildings. The petals represent the multi-faceted, ill-structured, overlapping relationship of the elements that constitute the problem domain.

The topics, represented by petals, fan out from the central themes of architecture, energy in buildings and software engineering. The random and arbitrary size and order of the petals illustrates the lack of structure of the problem and the diversity of the issues involved.

Working in such a trans-disciplinary manner brings challenges and frustrations. Thorpe expressed difficulties in finding reviewers with knowledge that covered the disciplines that she covered. She talks of feeling “homeless” in disciplinary terms (2010, p.314). However, this detachment can bring new insights or observations into the other disciplines that have influenced this work.

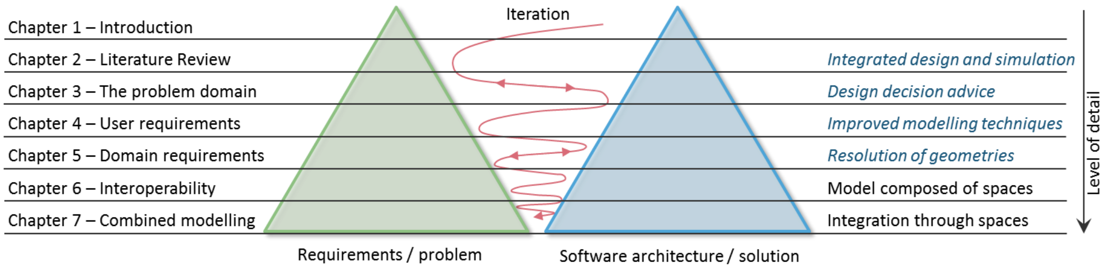


Figure 8-4 The Twin Peaks model for software development.

The Twin Peaks of 'requirements and software architecture' as outlined by Nuseibeh (2001) and/or 'problem and solution' as re-named by Hall et al (2002). The development of detail within both concepts is developed with equal status.

Software Engineering sits at the centre of the flower in Figure 8-3; however, the research has not been into SE methods. The focus of the work has been on how to integrate BES with BIM software. Procedures from Requirements Engineering have been employed in Chapters 4 and 5 as a method to assist in the framing and synthesis of the problem. My experience in applying RE techniques to a complex problem has given rise to an observation on the widely cited Twin Peaks diagram (Nuseibeh, 2001; Hall *et al.*, 2002) as shown in Figure 8-4. The diagram shows the Twin Peaks with equal status given to *requirements* (or *problem structures* as relabelled by Hall et al.) and *architectures* (*solution structures*) with both developed concurrently. An attempt to relate this work to the Twin Peaks concept by overlaying the structure of the thesis over the diagram is shown in Figure 8-4. It proved difficult however to justify the annotation of the solution peak. Reflection on the process of the development of the proposed software in this thesis led to the proposal for a different relationship of the solution to the problem as illustrated in Figure 8-5.

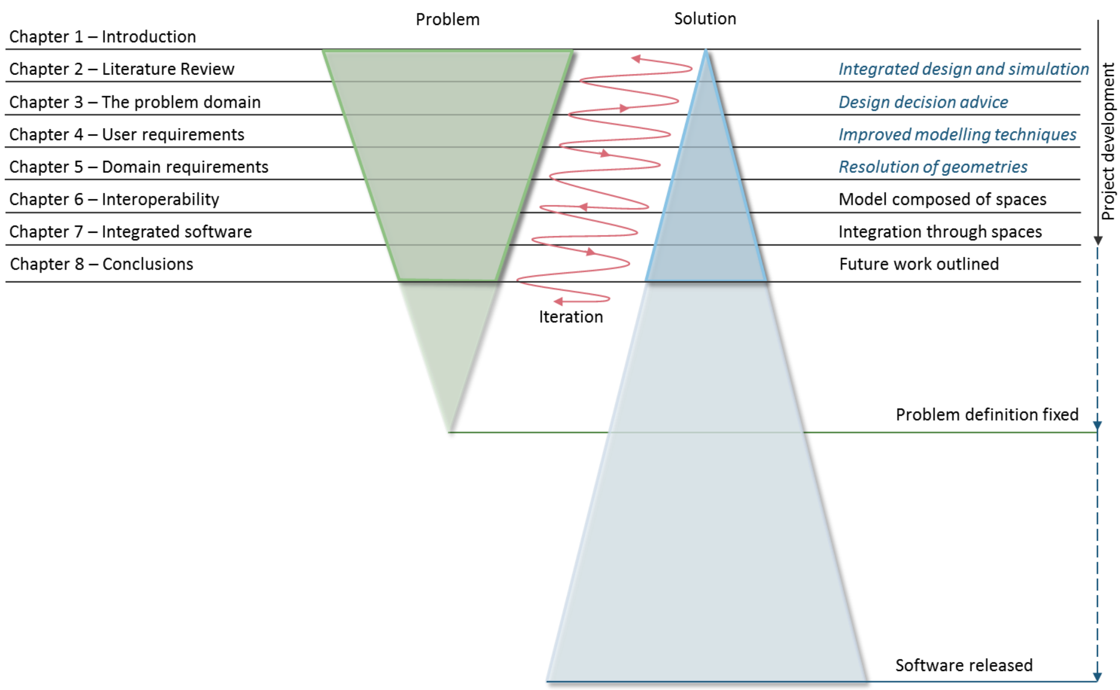


Figure 8-5 An alternate version of the Twin Peaks model.

This illustration is based upon the experience of dealing with the relationship between the Problem and Solution domains in this thesis. The problem peak has been flipped vertically, the solution peak extends past the problem peak and the vertical access is labelled 'project development'

The reasons for the modifications to the Nuseibeh diagram are:

1. It was difficult to justify the development of the solution in early stages as equal to that of the problem. As indicated by the blue italic text in both figures; at the early stage the solution was vague and tentative, conversely the problem domain was detailed. Although developed iteratively, much more time and effort was expended on problem definition in the early chapters. That level of detail and time decreased as the solution began to evolve in the later chapters, hence the flipping of the problem triangle.

2. The vertical axis has been relabelled from 'Level of detail' to 'Project development'. This reflects the nature and development of the project and the differing level of focus between the problem and solution. There was significant

iteration between the chapters, but there was still a progression in development of the solution.

3. Both the problem and solution peak extend beyond the timeline of the thesis, however the problem peak is shown stopping earlier than the solution peak. It is common practice in any commercial project, be it architectural or software, that the problem definition needs to stop (or become fixed) in order to allow the project to be developed through to completion. Continual revision of the brief/requirements can lead to delays and cost penalties.

Although the thesis was initially motivated by proposed regulatory changes and the effect that they would have on the type of small practices that I used to work in, the extent of coverage on energy policy on new buildings has also been relatively limited. The intention of the UK government that all new buildings will be 'zero carbon' by 2019 (Department for Communities and Local Government, 2008), could significantly affect architectural working practices and potentially the quality of the built environment. As discussed in Chapter 3, the policy is arguably confused, and already there has been a reduction in the standard for domestic housing with non-regulated energy removed from the calculation. During the early part of the first year of the thesis, 2010, consultations were held on the meaning of 'zero carbon' for non-domestic buildings [74], however, a definition of both carbon compliance and allowable solutions has yet to be made, some three years later.

Although BIM is now featuring heavily in the architectural press, energy in building seems a less prevalent topic. There is a solid core of academics and practitioners working in the field of sustainable design as evidenced by the Passivhaus[75] movement and the on-going success of EcoBuild[76]. However, in a report on the future of the profession published by the RIBA, looking forward to 2025, the word *carbon* appeared only once and *energy*, *green* or *sustainable* did not feature at all. This is a time when architects worry about their financial future. In August 2012 more than one in four British architecture firms were predicting an empty order book within the next 12 months (Wilding, 2012). In a profession where sole

---

[74] See https://www.gov.uk/government/consultations/zero-carbon-for-new-non-domestic-buildings

[75] http://www.passivhaus.org.uk/

[76] http://www.ecobuild.co.uk/

principals earn on average just over £30,000 pa, with one quarter earning less than £20,000 pa (Mirza & Nacey Research Ltd, 2013), the year 2019 can seem a long time in the future.

Given the current difficult economic conditions (2013), it is probable that the UK government will come under significant pressure from the construction industry for a further weakening of the policies. However, concurrently, the European Union is now legislating for minimum energy performance requirements for new and existing buildings[77] and this may also affect UK policy. Analysis of contemporary global zero and low carbon/energy policies is a complete area of study in its own right and a difficult topic as they are continually evolving. Hence the stance taken in this thesis is that all buildings need to consume as little energy as possible and architects need good tools to achieve the best designs possible.

8.6.1 Closing thoughts

This thesis has peered into the future for architects. In many ways it has been blue sky thinking; of the software that I, both as an architect and an architectural educator, would like to help with the design of very low energy buildings. There are challenges to the development of this type of software. The building design software market is dominated by large companies with vested interests in tying customers into their suite of software. Architects may not be open to new ways of working, having invested time to get familiar with working with one particular type of software. There is also a culture of passing the responsibility for calculations to consultants.

The opportunities exist to develop new software that is fit for purpose; both to design buildings and predict energy usage. Software engineering, hardware and HCI principles have developed amazingly during my time of using computers and I believe that there is now the knowledge to take BIM, BES and DAS to another, integrated, user-friendly, level. This thesis has presented a vision of how such software might work.

---

[77] See http://ec.europa.eu/energy/efficiency/buildings/buildings_en.htm

References

AECOM (2011) *Zero Carbon Non-Domestic Buildings Phase 3 Final Report*. London, United Kingdom: Department for Communities and Local Government.

Ahmad, M., Demian, P. & Price, A. (2012) Creativity with Building Information Modelling Tools. In: *First UK Academic Conference on BIM: Conference Proceedings*. 2012 Northumbria University, UK: pp. 152–163.

Amor, R. & Dimyadi, D. (2010) An Open Repository Of Ifc Data Models And Analyses To Support Interoperability Deployment. In: *Proceedings of the CIB W78 2010: 27th International Conference*. 2010 Cairo: pp. 1–10.

Anderson, R.J. (1994) Representations and Requirements: The Value of Ethnography in System Design. *Human-Computer Interaction*. 9 (2), 151–182.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C. & O'Reilly, K. (2011) Technology adoption in the BIM implementation for lean architectural practice. *Automation in Construction*. 20 (2), 189–195.

Arup (2012) *UK Energy Legislation timeline, European and UK energy policy, electricity market reform consultation (EMRC)| Arup*. Available from: http://www.arup.com/Publications/UK_Energy_Legislation_Timeline.aspx [Accessed: 22 June 2012].

Attia, S., Beltrán, L., De Herde, A. & Hensen, J.L.M. (2009) 'Architect Friendly': A Comparison Of Ten Different Building Performance Simulation Tools. In: *Proceedings of 11th International IBPSA Conference. Glasgow. Scotland*. 2009 pp. 1–8.

Attia, S. & De Herde, A. (2011) Early Design Simulation Tools for Net Zero Energy Buildings: a Comparison of Ten Tools. In: *Proceedings of Building Simulation 2011*. 2011 Sydney, Australia: pp. 94–101.

Augenbroe, G. (2011) The role of simulation in performance-based building. In: *Building Performance Simulation for Design and Operation*. London, United Kingdom: Spon Press.

Augenbroe, G. (2002) Trends in building simulation. *Building and Environment*. 37 (8-9), 891–902.

Autodesk (2011) *Conceptual Design and Analysis in Autodesk Revit Architecture 2011*. [online]. Available from: http://images.autodesk.com/adsk/files/revit_architecture_2011_whitepaper_conceptual_design.pdf [Accessed: 30 October 2012].

Autodesk (2012) *Revit – Architectural Design Software – Autodesk*. Available from: http://usa.autodesk.com/revit/architectural-design-software/ [Accessed: 30 October 2012].

Azhar, S., Carlton, W.A., Olsen, D. & Ahmad, I. (2011) Building information modeling for sustainable design and LEED® rating analysis. *Automation in Construction*. 20 (2), 217–224.

Barnaby, C.S. & Crawley, D.B. (2011) Weather data for building performance simulation. In: *Building Performance Simulation for Design and Operation*. London, United Kingdom: Spon Press.

Bazjanac, V. (2002) Early lessons from deployment of IFC compatible software. In: *EWork and eBusiness in architecture, engineering and construction: proceedings of the fourth European Conference on Product and Process Modelling in the Building and Related Industries, Portorož, Slovenia, 9-11 September 2002*. 2002 pp. 1–10.

Bazjanac, V. (2008) *IFC BIM-Based Methodology for Semi-Automated Building Energy Performance Simulation*. [online]. Available from: http://www.escholarship.org/uc/item/0m8238pj.

Bazjanac, V. (2010) Space Boundary Requirements for Modeling of Building Geometry for Energy and Other Performance Simulation [online]. *CIB W78 2010 - Applications of IT in the AEC Industry*. Available from: http://itc.scix.net/cgi-bin/works/Show?w78-2010-127.

Björk, B.-C. (1992) A conceptual model of spaces, space boundaries and enclosing structures. *Automation in Construction*. 1 (3), 193–214.

BuildingSMART International Alliance for Interoperability (2011a) *IFC Overview summary — Welcome to buildingSMART-Tech.org*. Available from: http://buildingsmart-tech.org/specifications/ifc-overview [Accessed: 14 June 2011].

BuildingSMART International Alliance for Interoperability (2012) *IFC4 RC4 Documentation*. Available from: http://www.buildingsmart-tech.org/ifc/IFC2x4/rc4/html/index.htm [Accessed: 7 January 2013].

BuildingSMART International Alliance for Interoperability (2011b) *News release - Clear comprehensive overview of IFC-compliant software*. Available from: http://buildingsmart.com/resources/publications/newsletters-magazines/20111005%20-%20bSInternational%20news%20release.pdf [Accessed: 17 October 2011].

BuildingSMART International Alliance for Interoperability (2010) *Start Page of IFC2x4 RC2 Documentation*. Available from: http://buildingsmart-tech.org/ifc/IFC2x4/rc2/html/index.htm [Accessed: 8 July 2011].

BuildingSMART International Ltd (2011a) *faq specific ifc spec — Welcome to buildingSMART-Tech.org*. Available from: http://www.buildingsmart-tech.org/implementation/faq/faq-specific-ifc-spec [Accessed: 27 February 2012].

BuildingSMART International Ltd (2011b) *Model View Definition Summary*. Available from: http://buildingsmart-tech.org/specifications/ifc-view-definition/summary [Accessed: 20 October 2011].

BuildingSMART International Ltd (2011c) *Summary of IFC Releases — Welcome to buildingSMART-Tech.org*. Available from: http://buildingsmart-tech.org/specifications/ifc_specification/ifc-releases [Accessed: 27 April 2011].

Bunker, G., Wright, A., Greenough, R., Shao, L., Hernandez, J., Wheatley, C. & Hardy, K. (2011) Low Energy and Sustainable Solutions Online Knowledge System. In: *Proceedings of Building Simulation 2011*. 2011 Sydney, Australia: pp. 1313–1319.

Cabinet Office (2011) *Government Construction Strategy*. London, United Kingdom: The Stationery Office.

Cabinet Office (2012) *Government Construction Strategy: One Year On Report and Action Plan Update*. [online]. p.1–69. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61151/GCS-One-Year-On-Report-and-Action-Plan-Update-FINAL_0.pdf [Accessed: 24 June 2013].

Cerovsek, T. (2011) A review and outlook for a Building Information Model (BIM): A multi-standpoint framework for technological development. *Advanced Engineering Informatics*. 25 (2), 224–244.

Chappell, D. (2010) *The Architect in Practice*. 10th ed. Chichester, West Sussex, U.K.: Wiley-Blackwell.

Clarke, J. (2001) *Energy simulation in building design*. 2nd ed. Oxford: Butterworth-Heinemann.

Cohn, M.L., Sim, S.E. & Dourish, P. (2010) Design methods as discourse on practice. In: *Proceedings of the 16th ACM international conference on Supporting group work*. 2010 Florida, USA: ACM Press. pp. 45–54.

Construction Skills (2011) *UK Carbon Reduction Target - Countdown Timetable | cutcarbon.info*. Available from: http://cutcarbon.info/what-do-i-need-know/whats-timetable-year [Accessed: 29 May 2012].

Construction Users Roundtable (CURT) (2004) *Collaboration, Integrated Information, and the Project Lifecycle in Building Design,. Construction and. Operation*. [online]. Available from: www.gnycuc.org/media/curt.pdf [Accessed: 30 May 2012].

Crawley, D.B. (2008) *Building Performance Simulation: A Tool for Policymaking*. PhD thesis. Glasgow, UK: University of Strathclyde.

Crawley, D.B., Hand, J., Kummert, M. & Griffith, B. (2008) Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*. 43 (4), 661–673.

Crawley, D.B., Lawrie, L.K., Winkelmann, F.C., Buhl, W.F., Huang, Y.J., Pedersen, C.O., Strand, R.K., Liesen, R.J., Fisher, D.E., Witte, M.J. & Glazer, J. (2001) EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*. 33 (4), 319–331.

Cross, N. (2001) Designerly Ways of Knowing: Design Discipline Versus Design Science. *Design Issues*. 17 (3), 49–55.

Dado, E., Beheshti, R. & van de Ruitenbeek, M. (2009) Product Modelling in the Building and Construction Industry: A History and Perspectives. In: Jason Underwood & Umit Isikdag (eds.). *Handbook of Research on Building Information Modeling and Construction Informatics*. IGI Global.

Daly, L. & Brutzman, D. (2007) X3D: Extensible 3D Graphics Standard [Standards in a Nutshell]. *IEEE Signal Processing Magazine*. 24130–135.

Davies, M.G. (2004) *Building heat transfer*. Hoboken, NJ, USA: J. Wiley & Sons.

Davis, A., Overmyer, S., Jordan, K., Caruso, J., Dandashi, F., Dinh, A., Kincaid, G., Ledeboer, G., Reynolds, P., Sitaram, P., Ta, A. & Theofanos, M. (1993) Identifying and measuring quality in a software requirements specification. In: *Proceedings First International Software Metrics Symposium*. 1993 Baltimore, MD, USA: IEEE Comput. Soc. Press. pp. 141–152.

DECC (2012) *Energy consumption in the United Kingdom - Department of Energy and Climate Change*. Available from: http://www.decc.gov.uk/en/content/cms/statistics/publications/ecuk/ecuk.aspx [Accessed: 24 April 2012].

Department for Business, Innovation and Skills (2012) *Building Information Modelling, Industrial strategy: government and industry in partnership*. [online]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/34710/12-1327-building-information-modelling.pdf [Accessed: 11 February 2013].

Department for Business, Innovation and Skills (2010) *Executive Summary; Low Carbon Construction Innovation & Growth Team*. HM Government.

Department for Business, Innovation and Skills (2011) *Report to the Government Construction Clients Board on Building Information Modelling and Management | Policies | BIS*. Available from: http://www.bis.gov.uk/policies/business-sectors/construction/research-and-innovation/working-group-on-bimm [Accessed: 2 September 2011].

Department for Communities and Local Government (2007) *Building a Greener Future: policy statement*. [online]. Available from: http://www.communities.gov.uk/documents/planningandbuilding/pdf/building-greener.pdf [Accessed: 3 February 2010].

Department for Communities and Local Government (2008) *Definition of zero carbon homes and non-domestic buildings: consultation.* London, United Kingdom: Department for Communities and Local Government.

Digital Building Lab (2010) *BIM Resources @ Georgia Tech*. Available from: http://bim.arch.gatech.edu/app/bimtools/tools_list.asp?id=521 [Accessed: 23 August 2010].

Digital Building Lab (2012) *BIM Resources @ Georgia Tech - BIM Tools*. Available from: http://bim.arch.gatech.edu/app/bimtools/tools_list.asp?id=521 [Accessed: 7 June 2012].

Dong, B., Lam, K., Huang, Y. & Dobbs, G. (2007) A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments. In: *Tenth International IBPSA Conference*. 2007 Beijing: IBPSA China: pp. 1530–1537.

Donn, M., Selkowitz, S. & Bordass, B. (2012) The building performance sketch. *Building Research & Information*. 40 (2), 186–208.

Dyckhoff, T. (2011) Home [online]. *The Secret Life Of Buildings*. 1 August. Available from: http://www.channel4.com/programmes/the-secret-life-of-buildings/episode-guide/series-1/episode-1 [Accessed: 28 March 2012].

Dykes, T.H., Rodgers, P.A. & Smyth, M. (2009) Towards a new disciplinary framework for contemporary creative design practice. *CoDesign: International Journal of CoCreation in Design and the ArtsCoDesign*. 5 (2), 99–116.

Eames, M., Kershaw, T. & Coley, D. (2010) On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology*. 32 (2), 127–142.

Easterbrook, S., Singer, J., Storey, M.A. & Damian, D. (2008) Selecting Empirical Methods for Software Engineering Research. In: Forrest Shull, Janice Singer, & Dag I. K. Sjøberg (eds.). *Guide to Advanced Empirical Software Engineering*. London: Springer London. pp. 285–311.

Eastman, C., Jeong, Y.-S., Sacks, R. & Kaner, I. (2010) Exchange Model and Exchange Object Concepts for Implementation of National BIM Standards. *Journal of Computing in Civil Engineering*. 24 (1), 25.

Eastman, C. & Siabiris, A. (1995) A generic building product model incorporating building type information. *Automation in Construction*. 3 (4), 283–304.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. (2011) *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors*. 2nd ed. Hoboken, NJ: Wiley.

Ekholm, A. & Fridqvist, S. (2000) A concept of space for building classification, product modelling, and design. *Automation in Construction*. 9 (3), 315–328.

EnergyPlus Development Team (2010) *Input Output Reference: The Encyclopedic Reference to EnergyPlus Input and Output*. [online]. Available from: http://apps1.eere.energy.gov/buildings/energyplus/pdfs/inputoutputreference.pdf [Accessed: 7 July 2011].

Estrada, S.M. (2002) *Environmental Design & Sustainability: Strategies for Teaching and Learning in UK Schools of Architecture.* PhD thesis. UK: University of Sheffield.

European Commission Legal Service (2007) *T-201/04 Microsoft v Commission, judgment of 17 September 2007 Competition - Microsoft – abuse of a dominant position*. Available from: http://ec.europa.eu/dgs/legal_service/arrets/04t201_en.pdf [Accessed: 1 April 2011].

Fallman, D. (2003) Design-oriented human-computer interaction. In: *Proceedings of the SIGCHI conference on Human factors in computing systems*. 2003 ACM Press. pp. 225–232.

Feigenbaum, E.A. (1982) *Knowledge Engineering in the 1980's*. Dept. of Computer Science, Stanford University, Stanford, CA, USA.

Ferrari, P., Silva, N. & Lima, E. (2010) Building Information Modeling and Interoperability with Environmental Simulation Systems. In: Tarek Sobh (ed.). *Innovations and Advances in Computer Sciences and Engineering*. Dordrecht: Springer Netherlands.

Franconi, E. (2011) *RMI's Building Energy Modeling Innovation Summit*. [online]. Available from: http://www.youtube.com/watch?v=VQVx3khPqRg [Accessed: 25 June 2012].

Frary, R. (1996) Hints for designing effective questionnaires. Frary, Robert B. *Practical Assessment, Research & Evaluation*. 5 (3), 1–3.

Galasiu, A.D. & Reinhart, C.F. (2008) Current daylighting design practice: a survey. *Building Research & Information*. 36 (2), 159–174.

Gallaher, M.P. & Chapman, R.E. (2004) *Cost analysis of inadequate interoperability in the US capital facilities industry*. US Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.

gbXML.org (2010) *Welcome - Green Building XML Schema*. Available from: http://www.gbxml.org/index.php [Accessed: 15 June 2011].

GbXML.org (2010) *Current Schema - Green Building XML Schema*. Available from: http://www.gbxml.org/currentschema.php [Accessed: 27 April 2011].

Génova, G. (2010) Is computer science truly scientific? *Communications of the ACM*. 53 (7), 37.

Gething, B. (2011) *Green Overlay to the RIBA Outline Plan of Work*. London, United Kingdom: RIBA.

Gething, B. (2012) *Presenting the 'green overlay' to the RIBA plan of work*. [online]. Available from: http://www.ecobuild.co.uk/presentations/download/3718.html [Accessed: 30 May 2012].

Giarratano, J.C. & Riley, G. (1989) *Expert systems : principles and programming*. Boston: Boyd & Fraser.

Goh, A., Hui, S. & Song, B. (1996) An integrated environment for product development using STEP/EXPRESS. *Computers in Industry*. 31 (3), 305–313.

Goulding, J., Lewis, J.O. & Steemers, T. (1992) *Energy conscious design: a primer for architects*. London: Batsford for the Commission of the European Communities.

Great Britain (2008a) *Budget 2008 : stability and opportunity: building a strong, sustainable future : economic and fiscal strategy report and financial statement and budget report*. London: The Stationery Office.

Great Britain (2008b) London : HMSO. *Climate Change Act 2008: Elizabeth II. Chapter 27*. London: The Stationery Office.

Great Britain (2009) *Definition of zero carbon homes: Impact assessment*. London: Department for Communities and Local Government.

Grilo, A. & Jardim-Goncalves, R. (2010) Value proposition on interoperability of BIM and collaborative working environments. *Automation in Construction*. 19 (5), 522–530.

Gu, N. & London, K. (2010) Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*. 19 (8), 988–999.

Hall, J.G., Jackson, M., Laney, R.C., Nuseibeh, B. & Rapanotti, L. (2002) Relating software requirements and architectures using problem frames. In: *Proceedings IEEE Joint International Conference on Requirements Engineering*. 2002 Essen, Germany: pp. 137–144.

Hamil, S. (2011) *The rapid acceleration of BIM*. [online]. Available from: http://www.thenbs.com/topics/BIM/articles/rapidAccelerationOfBIM.asp [Accessed: 24 June 2013].

Hamza, N. & Horne, M. (2007) Building Information Modelling: Empowering Energy Conscious Design. In: *3rd Int'l ASCAAD Conference on Em'body'ing Virtual Architecture*. [online]. 2007 Alexandria, Egypt: .Available from: http://www.ascaad.org/conference/2007/052.PDF.

Hartman, H. (2012) *Sustainable design is difficult both to do and to talk about*. Available from: http://m.architectsjournal.co.uk/8637635.article [Accessed: 25 October 2012].

Harty, J. & Laing, R. (2011a) *BIM as a mindset*. [online]. Available from: http://www.thenbs.com/topics/bim/articles/bimAsMindset.asp [Accessed: 24 June 2013].

Harty, J. & Laing, R. (2011b) Trust and Risk in Collaborative Environments. In: *15th International Conference on Information Visualisation (IV)*. July 2011 London: IEEE. pp. 558–563.

Hellman, L. (2001) *Architecture A to Z: a rough guide*. Chichester West Sussex: Wiley-Academy.

Hensen, J.L.M. (2004) Towards more effective use of building performance simulation in design. In: *Proc. 7th International Conference on Design & Decision Support Systems in Architecture and Urban Planning*. 2004 pp. 2–5.

Hensen, J.L.M. & Lamberts, R. (2011) *Building performance simulation for design and operation*. Abingdon Oxon; New York NY: Spon Press.

Hetherington, R., Laney, R. & Peake, S. (2011) Integrated Building Design, Information and Simulation Modelling: The Need for a New Hierarchy. In: *Building Simulation 2011*. 14 November 2011 Sydney, Australia: pp. 1430–1450.

Hetherington, R., Laney, R. & Peake, S. (2010a) Software engineering challenges: Achieving zero carbon buildings by 2019. In: *ACM-BCS Visions of Computer Science 2010*. [online]. 13 April 2010 Edinburgh University, UK: .Available from: www.ukcrc.org.uk/grand-challenge/gccr10-sub-9.cfm.

Hetherington, R., Laney, R. & Peake, S. (2010b) Zero and Low Carbon Buildings: A Driver for Change in Working Practices and the Use of Computer Modelling and Visualization. In: *2010 14th International Conference Information Visualisation*. July 2010 London, United Kingdom: pp. 590–596.

Hietanen, J. (2006) *IFC Model View Definition Format*. Helsinki: IAI.

Hitchcock, R.J. (2003) Software interoperability for energy simulation. *ASHRAE Transactions*. 109.

Hitchcock, R.J. & Wong, J. (2011) Transforming Ifc Architectural View Bims for Energy Simulation: 2011. In: *Proceedings of Building Simulation 2011*. 2011 Sydney, Australia: pp. 1089–1095.

HM Government (2011) *Low Carbon Construction Action Plan*. [online]. Available from: http://www.bis.gov.uk/assets/BISCore/business-sectors/docs/l/11-976-low-carbon-construction-action-plan.pdf [Accessed: 12 July 2011].

HM Treasury & Department for Business Innovation and Skills (2011) *The plan for growth*. [online]. London: HM Treasury. Available from: http://cdn.hm-treasury.gov.uk/2011budget_growth.pdf [Accessed: 18 June 2012].

Holzer, D. (2011) BIM’s Seven Deadly Sins. *International Journal of Architectural Computing*. 9 (4), 463–480.

Hong, T., Chou, S. & Bong, T. (2000) Building simulation: an overview of developments and information sources. *Building and Environment*. 35 (4), 347–361.

Howard, R. & Bjork, B. (2008) Building information modelling – Experts’ views on standardisation and industry deployment. *Advanced Engineering Informatics*. 22 (2), 271–280.

Howell, I. & Batcheler, B. (2005) *Building Information Modeling Two Years Later – Huge Potential, Some Success and Several Limitations*. [online]. Available from: http://www.laiserin.com/features/bim/newforma_bim.pdf.

IEEE Computer Society, Standards Coordinating Committee (1991) *IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*.

IFC Solutions Factory (2011) *IFC Solutions Factory - Architectural Design to Building Energy Analysis*. Available from: http://www.blis-project.org/IAI-MVD/ [Accessed: 20 October 2011].

IPCC (2007a) *Climate change 2007 : mitigation of climate change : contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge; New York: Cambridge University Press.

IPCC (2007b) *Climate change 2007 : the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge; New York: Cambridge University Press.

Jackson, M. (2001) *Problem frames : analysing and structuring software development problems*. Harlow England: Addison-Wesley.

Jackson, M. (2005) Problem frames and software engineering. *Information and Software Technology*. 47 (14), 903–912.

Jamieson, C. (2011) *RIBA: The Future for Architects*. London, United Kingdom: Building Futures.

Jankovic, L. (2012) *Designing zero carbon buildings using dynamic simulation methods*. Abingdon, Oxon [England]; New York, NY: Earthscan.

Jardim-Goncalves, R. & Grilo, A. (2010) Building information modeling and interoperability. *Automation in Construction*. 19 (4), 387–387.

Jung, Y. & Joo, M. (2011) Building information modelling (BIM) framework for practical implementation. *Automation in Construction*. 20 (2), 126–133.

Kalay, Y.E. (2004) *Architecture's New Media: Principles, Theories, and Methods of Computer-aided Design*. Cambridge, Mass.; London: MIT Press.

Kalay, Y.E. (2006) The impact of information technology on design methods, products and practices. *Design Studies*. 27 (3), 357–380.

Khemlani, L. (2004) *The IFC Building Model: A Look Under the Hood*. Available from: http://www.aecbytes.com/feature/2004/IFCmodel.html [Accessed: 28 April 2011].

Kibert, C.J. & Fard, M.M. (2012) Differentiating among low-energy, low-carbon and net-zero-energy building strategies for policy formulation. *Building Research & Information*. 1–13.

King, D. & Royal Academy of Engineering (Great Britain) (2010) *Engineering a low carbon built environment: the discipline of building engineering physics*. London: Royal Academy of Engineering.

Kingspan (2011) *Kooltherm K12 Framing Board*. [online]. Available from: http://www.kingspaninsulation.co.uk/getattachment/fd77d557-97b0-47c1-b0e9-5c12eb237861/Kooltherm-K12-Framing-Board.aspx [Accessed: 12 December 2012].

Krygiel, E. & Nies, B. (2008) *Green BIM : successful sustainable design with building information modeling*. Indianapolis, USA: Wiley.

Lane, M. (2011) *BBC News - How warm is your home?* Available from: http://www.bbc.co.uk/news/magazine-12606943 [Accessed: 15 March 2011].

Laudon, K.C. & Laudon, J.P. (2012) *Management information systems : managing the digital firm*. Boston: Prentice Hall.

Lawson, B. (2005) Oracles, draughtsmen, and agents: the nature of knowledge and creativity in design and the role of IT. *Automation in Construction*. 14 (3), 383–391.

Leon, M.A. & Laing, R. (2012) The Review of BIM as an Effective Tool for Collaborative Design During the Early Design Stages. In: *First UK Academic Conference on BIM: Conference Proceedings*. 2012 Northumbria University, UK: pp. 109–117.

Lévy, F. (2012) *BIM in small-scale sustainable design*. Hoboken, N.J.: Wiley.

Liebich, T. (2010a) *Newsletter • No 1 • August 2010*. Available from: http://buildingsmart.com/news/resources/publications/newsletters-magazines/bSI_Newsletter_no_1.pdf [Accessed: 4 April 2011].

Liebich, T. (2010b) *Unveiling IFC2x4: the Next Generation of openBIM Interoperability*. [online]. Available from: http://buildingsmart-tech.org/downloads/accompanying-documents/presentations/ [Accessed: 15 June 2011].

Lipman, R., Palmer, M. & Palacios, S. (2011) Assessment of conformance and interoperability testing methods used for construction industry product models. *Automation in Construction*. 20418–428.

MacKay, D. (2009) *Sustainable energy--without the hot air*. Cambridge England: UIT.

Mahdavi, A. (2011) People in building performance simulation. In: *Building Performance Simulation for Design and Operation*. London, United Kingdom: Spon Press.

Maile, T., Fischer, M. & Bazjanac, V. (2007) Building energy performance simulation tools-a life-cycle and interoperable perspective. *Center for Integrated Facility Engineering (CIFE) Working Paper*. 107 (-), 1–49.

Malone, A. (2013) *Realising the potential of BIM*. [online]. Available from: http://www.thenbs.com/topics/BIM/articles/realisingThePotentialOfBIM.asp [Accessed: 24 June 2013].

Marsh, A. (2006a) *CAD Geometry vs Performance Analysis, Natural Frequency*. Available from: http://naturalfrequency.com/articles/cadanalysis [Accessed: 24 August 2010].

Marsh, A. (2006b) *Thermal: Analysis Methods*. Available from: http://wiki.naturalfrequency.com/wiki/Thermal_Analysis_Methods [Accessed: 24 July 2012].

McGraw-Hill Construction (2008) *Building Information Modeling (BIM) SmartMarket Report: Transforming Design and Construction to Achieve Greater Industry Productivity*.

Mirza & Nacey Research Ltd (2013) *The Fees Bureau - Architects Earnings Summary*. Available from: http://www.feesbureau.co.uk/Earns2012-1.asp [Accessed: 10 February 2013].

National Building Specification (2012) *NBS National BIM Report 2012*. [online]. Available from: http://www.thenbs.com/pdfs/NBS-NationalBIMReport12.pdf [Accessed: 19 October 2011].

Van Nederveen, S., Beheshti, R. & Gielingh, W. (2009) Modelling Concepts for BIM. In: Jason Underwood & Umit Isikdag (eds.). *Handbook of Research on Building Information Modeling and Construction Informatics*. IGI Global. [Accessed: 20 February 2012].

Nicholls, R. (2008) *The green building bible Volume 2*. 4th ed. Keith Hall (ed.). Llandysul, UK: Green Building Press.

Nuseibeh, B. (2001) Weaving together requirements and architectures. *Computer*. 34 (3), 115–119.

O'Donnell, J.T., Garr, M., See, R. & Bazjanac, V. (2011) Simmodel: A Domain Data Model for Whole Building Energy Simulation. In: *Proceedings of Building Simulation 2011*. 2011 Sydney, Australia: pp. 382–389.

Offen, R. (2002) Domain Understanding is the Key to Successful System Development. *Requirements Engineering*. 7 (3), 172–175.

Oppenheim, A. (1992) *Questionnaire design, interviewing and attitude measurement*. 2nd edition. London, United Kingdom: Continuum.

Oreszczyn, T. & Lowe, R. (2010) Challenges for energy and buildings research: objectives, methods and funding mechanisms. *Building Research & Information*. 38 (1), 107–122.

Oxman, R. (2008) Digital architecture as a challenge for design pedagogy: theory, knowledge, models and medium. *Design Studies*. 29 (2), 99–120.

Papamichael, K. (1997) Building Design Advisor: automated integration of multiple simulation tools. *Automation in Construction*. 6 (4), 341–352.

Papamichael, K. & Pal, V. (2002) *Barriers in developing and using simulation-based decision-support software*. [online]. Available from: http://www.escholarship.org/uc/item/2q52c7rq [Accessed: 19 January 2011].

Pazlar, T. & Turk (2008) Interoperability in practice: geometric data exchance using the IFC standard. *ITcon*. 13362–380.

Penttilä, H. (2006) Describing the changes in architectural information technology to understand design complexity and free-form architectural expression. *ITcon*. 11 (Special Issue The Effects of CAD on Building Form and Design Quality), 395–408.

Perry, D.E., Sim, S.E. & Easterbrook, S. (2006) Case studies for software engineers. In: *Proceeding of the 28th international conference on Software engineering - ICSE ’06*. 2006 Shanghai, China: pp. 1045–1046.

Pohl, J., Chapman, A. & Pohl, K. (2000) Computer-Aided Design Systems for the 21st Century: Some Design Guidelines. In: *Fifth International Conference on Design and Decision-Support Systems for Architecture and Urban Planning*. 2000 Nijkerk, The Netherlands: pp. 1–18.

Pohl, J., Myers, L. & Chapman, A. (1992) The ICADS Model in Retrospect. *CIB Report*. 369–369.

Prazeres, L. & Clarke, J. (2005) Qualitative Analysis On The Usefulness Of Perceptualization Techniques In Communicating Building Simulation Outputs. In: *Building Simulation 2005*. 2005 Montréal, Canada: pp. 961–968.

Preston, C. & Colman, A. (2000) Optimal number of response categories in rating scales: reliability, validity, discriminating power, and respondent preferences. *Acta Psychol (Amst)*. 104 (1), 1–15.

Punjabi, S. & Miranda, V. (2005) Development Of An Integrated Building Design Information Interface. In: *Building Simulation 2005*. 2005 Montréal, Canada: pp. 969–976.

Raslan, R. & Davies, M. (2010) Results variability in accredited building energy performance compliance demonstration software in the UK: an inter-model comparative study. *Journal of Building Performance Simulation*. 3 (1), 63–85.

Reinhart, C.F. (2011) Daylight performance predictions. In: *Building Performance Simulation for Design and Operation*. London, United Kingdom: Spon Press.

Revelation Research LLP (2009) *2008 Architectural CAD User Survey Summary Report*. [online]. Available from: www.revresearch.co.uk [Accessed: 29 January 2010].

Rittel, H.W.J. & Webber, M.M. (1973) Dilemmas in a general theory of planning. *Policy Sciences*. 4155–169.

Robertson, S. & Robertson, J. (2006) *Mastering the requirements process*. 2nd ed. Upper Saddle River NJ: Addison-Wesley.

Rogers, Y., Sharp, H. & Preece, J. (2011) *Interaction design : beyond human-computer interaction*. 3rd edition. Chichester; UK: Wiley.

Rooth, Ø. (2010) *Strategic Plan 2010-2011*. [online]. Available from: http://buildingsmart.com/about-us/buildingsmart-international/IC%2010015%20Strategic%20Plan%2020100506.pdf [Accessed: 1 May 2011].

Ross, D.T. & Schoman, K.E. (1977) Structured Analysis for Requirements Definition. *IEEE Transactions on Software Engineering*. SE-3 (1), 6–15.

Royal Institute of British Architects (2008) *Architect's job book.* 8th ed. London: RIBA.

Royal Institute of British Architects (2007) *RIBA Outline Plan of Work*. London, United Kingdom: RIBA.

Royce, W.W. (1987) Managing the development of large software systems: concepts and techniques. In: *ICSE '87: Proceedings of the 9th international conference on Software Engineering*. 1987 Los Alamitos, CA, USA: IEEE Computer Society Press. pp. 328–338.

Salman, H. (2011) *The impact of CAAD on design methodology and visual thinking in architectural education*. PhD thesis. Aberdeen, Scotland, UK: Robert Gordon University.

De Saulles, T. (2012) *Thermal Mass Explained (2012 update)*. [online]. Available from: http://www.concretecentre.com/technical_information/performance_and_benefits/thermal_mass.aspx [Accessed: 19 July 2012].

Schlueter, A. & Thesseling, F. (2009) Building information model based energy/energy performance assessment in early design stages. *Automation in Construction*. 18 (2), 153–163.

Schön, D.A. (1983) *The Reflective Practitioner : How Professionals Think in Action.* New York: Basic Books.

See, R. (2011) *IFC Solutions Factory - Home*. Available from: http://www.blis-project.org/IAI-MVD/ [Accessed: 20 October 2011].

See, R., Haves, P., Sreekanthan, P., O'Donnell, J.T., Basarkar, M. & Settlemyre, K. (2011) Development of a User Interface for the Energyplus Whole Building Energy Simulation Program. In: *Proceedings of Building Simulation 2011*. 2011 Sydney, Australia: pp. 2921–2926.

Simon, H.A. (1996) *The sciences of the artificial*. Cambridge, Mass.: MIT Press.

Sinclair, D. (2012) *BIM Overlay to the RIBA Outline Plan of Work*. London, United Kingdom: RIBA.

Singh, V., Gu, N. & Wang, X. (2011) A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction*. 20 (2), 134–144.

Somboonwit, R. (2011) Modeling for Building Energy Performance Improvement in Accordance with the Local Climate Settings: A case of Generalisable Building Design of Intermediate Health Care Facilities in Thailand. In: *Building Simulation 2011*. 14 November 2011 Sydney, Australia: pp. 1623–1630.

Sommerville, I. & Sawyer, P. (1997) *Requirements engineering: a good practice guide*. Cichester, UK: John Wiley & Sons.

Spitler, J.D. (2011) Thermal load and energy performance prediction. In: *Building Performance Simulation for Design and Operation*. London, United Kingdom: Spon Press.

Srebric, J. (2011) Ventilation performance prediction. In: *Building Performance Simulation for Design and Operation*. London, United Kingdom: Spon Press.

StatPac Inc (2010) *Survey Sampling Methods*. Available from: http://www.statpac.com/surveys/sampling.htm [Accessed: 7 January 2011].

Steel, J., Drogemuller, R. & Toth, B. (2010) Model interoperability in building information modelling. *Software & Systems Modeling*. 11 (1), 99–109.

Stein, Z. (2007) Modeling the demands of interdisciplinarity: Toward a framework for evaluating interdisciplinary endeavors. *Integral Review*. 491–107.

Succar, B. (2009) Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction*. 18 (3), 357–375.

Sullivan, L. (2012) *The RIBA Guide to Sustainability in Practice*. London, United Kingdom: RIBA.

Survey Monkey (2010) *Smart Survey Design*. [online]. Available from: http://s3.amazonaws.com/SurveyMonkeyFiles/SmartSurvey.pdf [Accessed: 9 January 2011].

Suwa, M., Gero, J. & Purcell, T. (2000) Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies*. 21 (6), 539–567.

Szokolay, S. (2008) *Introduction to architectural science: the basis of sustainable design*. 2nd ed. Amsterdam; Boston; London: Elsevier/Architectural Press.

Technology Strategy Board (2009) *Design & Decision Tools for Low Impact Buildings*. [online]. Available from: http://www.innovateuk.org/_assets/pdf/tsb_ddtoolforlowimpactbuildcompflyer.pdf [Accessed: 8 November 2011].

The American Institute of Architects (2012) *The American Institute of Architects - AIA Facts and Figures, Background on the AIA*. Available from: http://www.aia.org/press/kit/background/AIAS077761 [Accessed: 8 February 2013].

The European Parliament and the Council of the European Union (2010) Directive 2010/31/EC of The European Parliament And Of The Council. *Official Journal of the European Communities*.

The Fees Bureau (2009) *Architects' Earnings. How do you compare?* Arundel, United Kingdom: Mirza & Nacey Research Ltd.

Thoo, S. (2008) *Interoperability and Sustainable Design: AECbytes Feature Article*. Available from: http://www.aecbytes.com/feature/2008/Interoperability_SustainableDesign.html [Accessed: 20 August 2010].

Thorpe, A. (2010) *Design and Political Resistance: Tactics, Power, and Transformation*. PhD thesis. Milton Keynes, UK: The Open University.

Tupper, K., Franconi, E., Chan, C., Hodgin, S., Buy, A. & Jenkins, M. (2011) Building Energy Modeling: Industry-wide Issues and Potential Solutions. In: *Proceedings of Building Simulation 2011*. 2011 Sydney, Australia: pp. 734–742.

U.S. Department of Energy (2011) *Building Technologies Program: Building Energy Software Tools Directory*. Available from: http://apps1.eere.energy.gov/buildings/tools_directory/ [Accessed: 27 April 2011].

U.S. Department of Energy (2012) *Buildings Energy Data Book 2011*. Available from: http://buildingsdatabook.eren.doe.gov/default.aspx [Accessed: 7 February 2013].

U.S. Department of Energy (2010) *EnergyPlus Energy Simulation Software: Learn More About OpenStudio*. Available from: http://apps1.eere.energy.gov/buildings/energyplus/openstudio.cfm [Accessed: 10 November 2010].

Underwood, J. & Isikdag, U. (2009) *Handbook of Research on Building Information Modeling and Construction Informatics*. IGI Global. [Accessed: 20 February 2012].

Urban, B. & Glicksman, L. (2006) The MIT Design Advisor – a Fast, Simple Tool for Energy Efficient Building Design. In: *SimBuild 2006*. 2006 Cambridge, Massachusetts, USA: pp. 270–276.

Venugopal, M., Eastman, C., Sacks, R., Panushev, I. & Aram, V. (2010) Engineering Semantics Of Model Views For Building Information Model Exchanges Using Ifc. In: *CIB W78 2010: 27th International Conference*. 16 November 2010 Cairo: pp. 1–10.

Vidler, A. (2000) Diagrams of Diagrams: Architectural Abstraction and Modern Representation. *Representations*. (72), 1–20.

W3C (2008) *Extensible Markup Language (XML) 1.0 (Fifth Edition)*. Available from: http://www.w3.org/TR/REC-xml/#sec-origin-goals [Accessed: 21 June 2011].

web3D consortium (2011) *X3D Resources*. Available from: http://www.web3d.org/x3d/content/help.html#Examples [Accessed: 11 July 2011].

Web3D Consortium (2011) *Web3D Consortium - Royalty Free, Open Standards for Real-Time 3D Communication*. Available from: http://www.web3d.org/ [Accessed: 3 February 2010].

Webb, T. & Harvey, F. (2011) *Budget 2011: Zero-carbon homes plan 'watered down' | UK news | guardian.co.uk*. Available from: http://www.guardian.co.uk/uk/2011/mar/23/budget-2011-zero-carbon-homes [Accessed: 18 June 2012].

Wilding, M. (2012) One in four architects expects empty order book within a year [online]. *Building Design*. 14 August. Available from: http://www.bdonline.co.uk/5041033.article?origin=BDdaily [Accessed: 14 August 2012].

Wilson, P.R. (1998) *STEP and EXPRESS*. Available from: http://deslab.mit.edu/DesignLab/dicpm/step.html [Accessed: 12 December 2012].

Wong, K. (2010) *Computer-Aided EcoDesign | Cadalyst*. Available from: http://www.cadalyst.com/aec/computer-aided-ecodesign-13162 [Accessed: 20 August 2010].

Young, N., Jones, S. & Bernstein, H.M. (2008) Building Information Modeling (BIM)-Transforming Design and Construction to Achieve Greater Industry Productivity. *SmartMarket Report, McGraw Hill Construction, Bedford, MA, USA*. 1–48.

Zero Carbon Hub (2011) *Allowable Solutions for Tomorrow’s New Homes*. [online]. Available from: http://www.zerocarbonhub.org/resourcefiles/Allowable_Solutions_for_Tomorrows_New_Homes_2011.pdf [Accessed: 18 June 2012].

Zimmerman, J. & Forlizzi, J. (2008) The Role of Design Artifacts in Design Theory Construction. *Artifact*. 2 (1), 41–45.

Zimmerman, J., Forlizzi, J. & Evenson, S. (2007) Research through design as a method for interaction design research in HCI. In: *CHI ’07 Proceedings of the SIGCHI conference on Human factors in computing systems*. 2007 ACM Press. p. 493.

Appendix 1 – Nomenclature

	Built environment	*Software engineering*	*This thesis*
Architecture	The art or practice of designing and constructing buildings. *Oxford Dictionary*[78]	The structure or structures of the system, which comprise software components, the externally visible properties of those components, and the relationships between them. *Wikipedia*[79]	Both meanings are employed.
Design	The art or action of conceiving of and producing a plan or drawing of something before it is made. *Oxford Dictionary*	The process of problem-solving and planning for a software solution. *Wikipedia*	
Sketch design	*Sketch*: a rough or unfinished drawing or painting, often made to assist in making a more finished picture *Design*: a plan or drawing produced to show the look and function or workings of a building *Oxford Dictionary*		A drawing, model or description illustrating the key concepts, functions and relationships of a design: applicable to both architectural and software engineering
Abstraction	Schematic evocations of space, of a building's principal element …abstraction was registered as a primary aesthetic quality, one that allowed for the proportional systems and historical styles formerly making up the aesthetic content of the "art" of architecture, to be superseded by its own constructive and space-enclosing elements expressed in the pure geometries... (Vidler, 2000)	The process by which data and programs are defined with a representation similar in form to its meaning (semantics), while hiding away the implementation details. Abstraction tries to reduce and factor out details so that the programmer can focus on a few concepts at a time. *Wikipedia*	
Abstract space			A space or volume representing the essence of part, or whole of a building. It is a simplified three-dimensional form without detail, employed to illustrate proportions of spaces and relationships between spaces.

---

[78] http://www.oxforddictionaries.com/

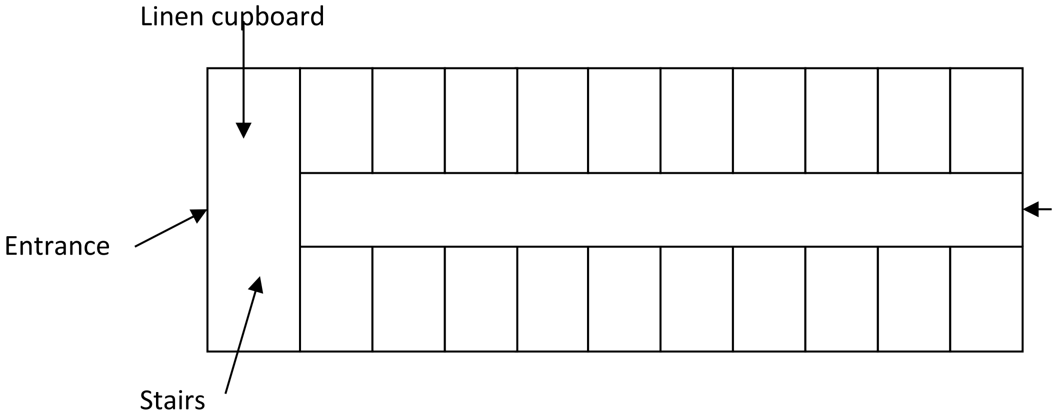
[79] http://en.wikipedia.org/wiki/

Intelligent spaces			Intelligent Spatial Entity: a building volume that can have variable dimensions, assigned rules, complex geometric and functional relationships with other building elements. The entities would be the vehicle for linkage between architectural design, building energy simulation and design decision support systems with intelligence incorporated by means of algorithms governing the interaction between these three elements.
Brownfield development	Refers to the development of brownfield sites: land previously used for industrial purposes or some commercial uses. *Wikipedia*	A term commonly used in the IT industry to describe problem spaces needing the development and deployment of new software systems in the immediate presence of existing (legacy) software applications/systems. *Wikipedia*	

Appendix 2 – The Student Project

An Investigation into Design Strategies for a Low Carbon Building

Specification: two storey accommodation block (motel) with a pitched roof consisting of 20 double rooms with en suite bathrooms on each floor with 10 rooms each side of a central corridor. There is an entrance at one end with a staircase and linen storage room and an external emergency staircase accessible via a door at the other end. This is illustrated in the following schematic diagram.



Note: no dimensions are given, this is left as an exercise for you but bear in mind that this is simple low cost accommodation. It is not necessary to model the en suite bathroom as this can be considered to be part of the same zone as the bedroom.

The weighting for this assignment is 50% of the total available for the module and as such is a substantial piece of work. The submission should be in the form of a PowerPoint presentation consisting of approximately 50 slides in which the results of a systematic investigation of the effect of different strategies on the energy requirements of the building are presented.

Objectives:

1. To try to achieve satisfactory thermal comfort in Winter and Summer whilst minimising the consumption of energy and emission of carbon dioxide.
2. To ensure the provision of an adequate supply of domestic hot water heated by solar energy.
3. To ensure the provision of adequate electrical energy generated by solar radiation.

Strategies for achieving optimum performance at two locations, Munich and Sydney, are to be investigated and comparisons drawn regarding the different strategies required for each location. The accommodation block will be aligned with the central corridor along the West-East axis i.e. with half the rooms on the south facade and half the rooms on the north facade. When the appropriate strategies for the initial orientation have been established the effect on performance resulting from alignment of the central axis in NW-SE and NE-SW directions will be investigated (NB no further modifications are required – this is a check on the sensitivity of the building performance to orientation.

Marking Scheme

Aspect	Mark Available
Establish performance requirements: comfort standards; domestic hot water, electrical power.	5
Construction of the basic model including zone simplification	5
Analysis of performance of building for location in Munich using Ecotect default construction details. This will include identification of most promising modifications to the construction based upon the results obtained.	8

Systematic modification of the constructional details, justified above, and recording of the resulting variation in performance in terms of potential energy consumption and comfort conditions until an optimum standard has been achieved.	25
Investigate the effect on performance of modifying the building alignment to NW-SE and NE-SW.	2
Estimation of potential to satisfy domestic hot water and electrical power requirements.	5
Analysis of performance of building for location in Sydney using Ecotect default construction details. This will include identification of most promising modifications to the construction based upon the results obtained.	8
Systematic modification of the constructional details, justified above, and recording of the resulting variation in performance in terms of potential energy consumption and comfort conditions until an optimum standard has been achieved.	25
Investigate the effect on performance of modifying the building alignment to NW-SE and NE-SW.	2
Estimation of potential to satisfy domestic hot water and electrical power requirements.	5
Summary and discussion of results	10

Appendix 3 –
Questions and Results from the Student Survey

This survey forms the final part of the elective, Modelling the Environmental Performance of Buildings. Please complete every question in this survey, unless marked optional.

The survey is to support a research project into the design of improved thermal modelling software. The aim is to establish the deficiencies of current software, test attitudes to possible alternative approaches to improving software and to solicit any additional suggestions from you.

All questions are compulsory, unless marked optional. Your replies will be treated anonymously, please give honest answers; they will not in anyway affect your grade for this module.

Previous computer experience

This section aims to establish your level of experience in using computers to provide background information to the survey.

Are you confident in using computers?				
Yes	96%	No	4%	

Are you confident in modelling building designs in three dimensions using computer software?				
Yes	87%	No	13%	

Have you used any of the following software to model a building design (you can select more than one)?									
Sketchup	92%	AutoCAD	69%	Revit	15%	ArchiCAD	15%	Bentley MicroStation	6%
Other		Please specify							

Before this module have you used software to carry out a thermal analysis of a building project?				
Yes	31%	No	69%	
If yes	What was the software? Ectoect 27% One student had used Ecotect, SBEM, ENVEST,			

How would you assess your level of knowledge relating low energy building design before taking this module?									
Very poor	6%	Poor	13%	Average	50%	Good	31%	Excellent	0%

Creation of the thermal zone model

Thermal zones are used in thermal simulations to enable calculations of internal temperatures and heat loads. Each zone should represent an enclosed volume of relatively homogeneous air. This section is aimed at establishing how easy it was for you create your zone model and how the process might be improved.

Did you find creating the zone model with Ecotect difficult?				
Yes	12%	No	88%	

Was it more difficult to model with Ecotect compared with modelling with other 3D building modelling or CAD software?				
Yes	52%	No	48%	

Optional - can you suggest any ways in which the zone modelling could be improved?
63% replied

Would you like to be able to export a zone model from a 3D model created in conventional modelling software, such as Sketchup, AutoCAD, Revit, ArchiCAD, Microstation, and then import it into the thermal analysis software?

Yes	77%	No	2%	Not sure	10%

Establishing performance criteria

Before running a thermal analysis it is important to establish the performance requirements for your building; these include setting thermal comfort standards and domestic hot water and electrical power requirements. This section aims to determine how much the software assisted this process and how it might be improved.

How often did you use the Ecotect Help system to establish performance requirements?					
Never	38%	Sometimes	52%	Frequently	10%

How often did you use books to establish performance requirements?					
Never	25%	Sometimes	62%	Frequently	13%

How often did you use the Internet (The World Wide Web) to establish performance requirements?					
Never	4%	Sometimes	29%	Frequently	67%

How often did you consult with fellow students to establish performance requirements?

Never	12%	Sometimes	56%	Frequently	33%

How often did you use journals to establish performance requirements?					
Never	69%	Sometimes	25%	Frequently	6%

Did you use the software default settings for the comfort temperature range?			
Yes	58%	No	40%

What was the lowest bedroom air temperature you allowed in the analysis for comfort in ^{o}C?

16	17	18	19	20	21	22	23
2%	0%	63%	17%	8%	0%	0%	4%

What was the highest bedroom air temperature you allowed in the analysis for comfort in ^{o}C?

21	22	23	24	25	26	27	28	29	30	31	32
4%	4%	6%	12%	27%	42%	0%	4%	0%	0%	0%	2%

What did you calculate as the total energy required to heat domestic hot water for the building for the year in MWh?

35.778, 0659, 132.4, 160, 167, 3066, 3.28, 35, 4200 (J) mass specific heat of water * number of days * number of months)/1000000 for MWh, 2.772, 4500l per day Munich= 45mwh Sydney = 32mwh, 158, I did not calculate this number in my assignment., 170, 715, 7.012, 183,000,000, 12096000, 500, 54.684, 419, Temperature difference between mains water (5 degrees C) , 33.264 MWh, 40.88mwh, Sydney: 67435200(W), Munich: 94953600(W), <Unanswered>, 80.64, NA, 40.880 MWh, 120.925MWh, 66.226, 46.08, 13490.4, 1960, 54.6MWh, 220 MWH, 649.9MW, 144, 500.78 MWh, 40.88MWh, 6.7MWh, 715.4MWh per year, 0.000752 MWh, 152.935 MWh, 146Mwh, 13490.4, 657, 64.15, 337.26 MWh, 58.2 MWh, 221MWh

What did you calculate as the total electrical energy required for the year MWh?

13.56704, 25477, 33.2, 58, 54, 40.004, 1.774, 24, (power appliance (kW) * duration of time used (hr))/10000 for Mwh, 14.46, 106mwh, 59, I did not calculate this number in my assignment., 80, 730, 7.608, 18,000,000, 15096090, 40, 43.41686, 63.2, 50.749 KW/h, 10.368 MWh, 1.34mwh, Sydney: 133034950 (W), Munich: 160934494 (W), <Unanswered>, 21.6, NA, 1.3435 MWh, 760.468MWh, 84.06, 39.478, 175.93, 41.58, 26.8MWh, 90MWH, 146.8MW, 48, 0.783, 1.3687MWh, 9.4MWh, 730MWh per year, 40.44MWh, 0.5767 MWh, 189.2Mwh, 175.93, 3080, 93.32, 175.93 MWh, 31808100 kWh = 31.8 MWh, 16MWh

Optional - Any other comments on how software might be improved to assist in establishing performance criteria?

21% replied

Interpretation and implementation of energy analysis data

Various options are provided by Ecotect for plotting results from the energy simulation. This section of the questionnaire seeks to establish how useful you found this information, how easy it was to use this information when trying to reduce the predicted energy demand of your design and how the visualisation of data might be improved to enable holistic decision making.

There are various standards which set targets for the energy consumption of buildings. For example, the Passivhaus standard requires that the total energy demand for space heating and cooling is less than 15 kWh/m^2 per year. This value corresponds to a very energy efficient building and could be used to help you to assess the relative performance of your designs.

Would you find it useful to have an energy target, displayed by the software alongside your results, to act as a target for the building thermal design?

Yes	90%	No	0%	Not sure	8%	*Note, one student did not answer,*

How would you rate the solar exposure calculation feature of Ecotect?

Did not use it	2%	Poor	8%	Adequate	40%	Good	44%	Excellent	2%

Would you find it useful to have the ability to 'place' and visualise solar collectors for hot water and photo voltaic panels for electricity generation on your model together with the option to display their output?

Yes	87%	No	4%	Not sure	10%	Yes	87%	No	4%

Optional - Any comments as to how the software could have assisted more in determining potential for renewable energy provision?

27% replied

Ecotect offers the option of examining a large number of parameter obtained from energy simulations in the form of graphs or tables. The number may be excessive.

Which of the following graphs or results did you use in your thermal analysis?

~Monthly loads/discomfort	98%
~Passive gains breakdown	79%
~Hourly temperature profile	69%
~Direct solar gains Qg	27%
~Temperature distribution	21%
~Temp/gains comparison	13%
~Monthly degree days	12%
~Fabric gains – Qc + Qs	10%
~Indirect solar gains – Qs	6%

~Ventilation gains – Qv	4%
~Passive adaptivity index	4%
~Internal gains – Qi	2%
~Inter-zonal gains – Qz	2%

Have you confidence in the results of the thermal simulation?					
Yes	37%	No	15%	Not sure	48%

Would it have been useful for you to see multiple graphs on the screen next to the 3D model to enable the direct comparison of different sets of results?					
Yes	71%	No	10%	Not sure	17%

Would you have found it useful to be able to track (or record) automatically the results of changes in energy performance as you altered the building model?					
Yes	94%	No	4%	Not sure	2%

Would you have found it useful to be able to see a summary of the currently set input parameters, such as ventilation rates, heating systems, occupancy, etc., displayed alongside the analysis?					
Yes	92%	No	4%	Not sure	4%

A dashboard display, resembling an automobile's dashboard, is sometimes used in computer software to display information relating to a number of parameters in a way that makes it easy to read and compare sets of information. Would you think a 'dashboard' display, showing both current input parameters and analysis results, would be a useful feature?					
Yes	67%	No	12%	Not sure	21%

Rank in order of preference those items that you think would be useful to see in the dashboard, with 1 as the most preferred.

Answers	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
An overall energy target	51%	17%	9%	9%	2%	2%	4%	6%
Potential for renewable energy sources such as solar or wind	11%	6%	19%	9%	19%	8%	15%	13%
Energy usage	34%	40%	6%	6%	6%	2%	4%	4%
Passive gains	6%	13%	34%	17%	11%	11%	4%	4%
Ventilation settings	4%	6%	9%	15%	9%	30%	19%	8%

A breakdown of construction (fabric) heat losses in terms of different elements (wall, windows, roof, etc.)	13%	13%	15%	32%	13%	6%	6%	2%
Selected heating system	4%	4%	8%	9%	13%	21%	28%	13%
Conflicts and errors	6%	6%	9%	2%	15%	9%	6%	47%

Optional - Comment on how the visualisation of data might be improved to assist your design process?

37% replied

Modifying **the construction**

In the project you were expected to reduce energy demand by making systematic modifications to the constructional details. There are various strategies that you might have explored, including improving insulation, use of thermal mass, control of the ventilation of occupied zones, ventilation of the roof space and utilisation of direct solar gain. The aim of this section is to determine how easy it was to use the software for this iterative process.

Rate the level of support that the software provided to enable you to formulate a strategy for energy reduction?									
Very poor	8%	Poor	15%	Neutral	38%	Good	38%	Excellent	0%

Optional - Any suggestions as to how the software could give you more support to enable you to formulate a strategy for energy reduction?

31% replied

How difficult did you find changing the construction details?

Very difficult	2%	Difficult	15%	Neutral	33%	Easy	42%	Very easy	8%

Rate the assistance given by the software in making decisions about modifying construction details in order to improve the energy performance?

Very poor	10%	Poor	37%	Neutral	25%	Good	27%	Excellent	0%

How useful would the availability in the software database of high performance standard construction details have been for making decisions?

Not at all useful	0%	Not very useful	4%	Undecided	21%	Somewhat useful	38%	Very useful	37%

In the 3D model, how useful would it have been to select and visualise all elements with the same construction, for instance, use different colours for each construction type?

When changing the constructional details of elements such as walls or windows in the 3D model how useful would it have been as a check that all elements have been assigned the revised constructional specification to be able to visualise all elements coloured according to their constructional specification. For example, the colour blue might identify glazing with different shades of blue indicating different specifications e.g. single and double glazed windows.

Not at all useful	0%	Not very useful	10%	Undecided	10%	Somewhat useful	37%	Very useful	44%

The appearance of your building

It is fully understood that all marks for this module were given for the energy study and none were allocated for building aesthetics, however, one of the objectives of improved software would be to enable buildings to be designed holistically so that they are both energy efficient and aesthetically pleasing. This section aims to establish your opinions as to how the software might be improved to facilitate design decisions to be made by balancing both energy and aesthetic aspects.

How difficult did you find it to achieve a low energy building?									
Very difficult	4%	Difficult	44%	Neutral	40%	Easy	12%	Very easy	0%

How would you rate the appearance of your proposed building?									
Very poor	23%	Poor	27%	Neutral	31%	Acceptable	17%	Very good	0%

If you tried to make the building more aesthetically pleasing, how would you expect the energy usage to increase?

No increase	21%	A slight increase	52%	A considerable increase	27%

Window areas are an important feature that affects the quality of light and enjoyment of buildings. How does Ecotect assist in making decisions about window area sizes?									
Not at all	19%	Not much	31%	Neutral	27%	Well	17%	Very well	0%

How important do you think the availability of thermal analysis software integrated with conventional 3D modelling software might be for enabling the design of aesthetically pleasing low energy building?									
Not important	0%	Little importance	0%	Neutral opinion	12%	Important	50%	Very important	33%

How much do you think it would improve your holistic design process to have energy simulation functions integrated into standard design software (CAD or BIM)?					
A significant improvement	50%	Some improvement	42%	No improvement	8%

Optional - How do you think energy simulation software could be improved to enable design decisions to be made in which aesthetics could be considered?

37% replied

Using Ecotect

This section aims to establish how you learnt how to use Ecotect and located information relating to your project. The aim of the questions is to establish your views as to how the low energy design process might be improved with the use of computerised support systems.

How difficult was it to learn the software?									
Very difficult	6%	Difficult	17%	Okay	58%	Easy	17%	Very easy	2%

If you did not know how to do something with the software, which of the following methods did you employ to solve your problem?

Ecotect's Help system	Never	Rarely	Sometimes	Frequently	A lot
	21%	38%	21%	15%	4%
The Internet (The World Wide Web)	Never	Rarely	Sometimes	Frequently	A lot
	6%	13%	27%	40%	13%
Your tutor	Never	Rarely	Sometimes	Frequently	A lot
	12%	19%	44%	21%	4%
Fellow students	Never	Rarely	Sometimes	Frequently	A lot
	6%	6%	27%	38%	23%

Books	Never	Rarely	Sometimes	Frequently	A lot
	48%	21%	17%	6%	8%

Were there some questions regarding the use of the software for which you could not find an answer?

Yes	46%	No	54%

Optional - What were the questions?

19% replied

How good did you find the Ecotect Help system?									
Very poor	4%	Poor	12%	Neutral opinion	54%	Good	23%	Excellent	8%

Computerised systems such as ‘Expert Systems’ and ‘Decision Support Systems’ can be developed to provide expert knowledge and aid decision making in specialised professional fields such as architectural design. This is different from a traditional Help system in that in addition to containing a knowledge base, it aims to apply rules to interpret information relating to the design and to provide recommendations to aid decision making. Ideally it is similar to having an expert permanently on hand to answer your questions. Such systems are frequently stand alone programmes, but it is envisaged that it could be integrated within a software package that provided combined 3D building modelling and thermal simulation functionality.

Would you find such a system, integrated with 3D modelling and thermal simulation software, useful for making decisions about performance criteria?					
Yes	77%	No	8%	Undecided	15%

Would you find such a system, integrated with 3D modelling and thermal simulation software, useful for making decisions about construction details?					
Yes	73%	No	10%	Undecided	17%

Would you find such a system, integrated with the 3D modelling and thermal simulation software, useful for making decisions about the provision of renewable energy devices?					
Yes	71%	No	8%	Undecided	21%

Would you find such a system, integrated with 3D modelling and thermal simulation software, useful for informing decisions as part of your iterative design process?					
Yes	71%	No	8%	Undecided	19%

Optional - Comment on any other aspects relating to how an Expert or Design Support System could assist your design process?

17% replied

Rank in order of difficulty the tasks you found hardest in this project with 1 as the most difficult..

Answers	**Most difficult**			**Least difficult**
Creating the thermal zone model	6%	8%	15%	72%
Establishing the performance criteria	11%	28%	53%	8%
Interpreting the energy analysis data	47%	30%	17%	6%
Modifying the construction to reduce energy demand	26%	30%	32%	11%

And finally

Are you:

Optional - if you would you be prepared to take part in a focus group to discuss the form of future software Please give your name and email address (both Liverpool University and another)?

Thank you for completing this survey.

Responses to optional questions

Optional - can you suggest any ways in which the zone modelling could be improved?

Dimensioning of zone boundaries was quite difficult and normally would spawn from an origin (0,0). It may be simpler to create a point then type the dimension you want, click enter and a new point would be created (like sketchup) - although Ecotect could think that by pressing enter, that this is the limits of the zone.It is much easier to draw a zone in plan.

making it more explorable in terms of been able to grab zones, windows and objects and move them with a snap tool helping you position them to other nodes. Nodes are not very clear so highlighting of corners which cud me snaped to an moved would make it more flexable in modelling.

allow importing of models from programs such as sketchup and autocad architecture

Import models from sketch up or 3D MAX

Add copy button for building identical zones

When drawing the zone next to each other, they should only have combine the wall as this could be confusing. Due to when I was doing this project and someone asked me that do we have to delete one wall so that there will be only one wall not two wall next to each other.

Possibly make i easier to distinguish to touching zones.

zone modelling could be improved to be more dynamic currently you create to primitives next to each other meaning that each zone has a overlapping surface. if ecotect worked on faces and defined boundary condition then this overlap could be removed. similar to how hatching working in cad.

The hight set is a little bit inconvenience in each different zones.

It will be better if the height of the zone could be edited flexibly

maybe a seperation between materials and zones would make it easier to edit

Sometimes the colors of difernent zones are similar.

Just not very comfortable to built a model in 3D perspective. And it's not very convenient to change each the position of the object(for example, light).

Clearer icons on toolbars

n/a i though tit was fine.

I think a view-history box, like the one you see on adobe photoshop, would be very useful. Allowing you to revert easily to a previous design; making the undo tool more accessible.
Sometimes it can be difficult to differentiate between zones in the plan or elevation view, especially windows e.t.c within the zone. when making amendments, this can be a little confusing. Perhaps a solution would be for the zone to be obviously highlighted over those you are not working on, or it could perhaps be turned off, so you cannot accidentally change the wrong zone.

It should be more flexible with colours and shapes

The ability to change the height of the zone easier. The way zones conflit with each other when two faces from seperate zones are touching.

The modelling in Ecotect has very limited options and i think there should be more flexibility in the modelling tools which can help to model more complex and curvilinear forms.

make it easier to edit after creating the zone, make zone complete rather than individual planes

Change parameters by right clicking, or the same way as Sketchup does when I create models, the coincident surface can not be deleted automatically.

hot keys? for section or something like that.

Be able to put all three X,Y and Z dimensions rather than just drawing X and Y dimensions and then changing Z after to change the height

It could be made more flexible because as it is it comfortably accommodates square and rectangular structures. It is more difficult to model circular forms.

if i can draw the 3D model in sketch and directlly tranform to zoing model in eco tect, it will be much more easy and effective.

Software could become more intelligent on how it handles adjoining zones. e.g. Floor and ceiling becoming one element

ecotect basic layout could be set out to be more user friendly as i found it quite difficult to get started having never used the software before

There were issues regarding surfaces between zones where differing materials conflicted eg. a plaster suspended ceiling ground floor clashed with concrete slab construction first floor, although I could sort this out manually it was time consuming and I felt the 3d modelling side of the software should recognise the juntions between these zones, and recognise the difference between and ground floor and intermediary floor construction.

ability to create non linear shaped zones
the ability for ecotect to sense when zones are created next to each other and to delete the common wall/ ammend the materials to make appropriate for inner walls.

when drawing the zones out, the default extrusion or z value seemed to always be 2400mm. i think it would make things easier it the zone was drew like a flat plane similar to sketchup then an extrusion can be done by selecting the surface, rather than currently trying to select the floor and change the z value.

the fact the two zones are touching each other should be understood by the software as the same , same material without the need of deleting every double zone.

accurate modelling, ie realistic thickness of wall and floor slab and ceiling

Optional - Any other comments on how software might be improved to assist in establishing performance criteria?

When constructing a roof in Ecotect, it may be the case that a pitched roof should not be assmebled as a group, rather a series of elements which would make it much easier to calculate the total incident solar radiation falling onto a surface.

the main thing was figures, maybe calculations should be kwh instead of various, or like sketch up ask at the start what metric you wish to work with, similar could be applyed. Maybe the software cold tell you when you have reached comfort levels etc. Also their is far too many tabs and setting boxes each tab should just have the related contex under it for apply changes in that area, the exploration factor makes it really slow and long winded in getting results.

Some optionbuttons are not clearly.

It will be better to improve the setting for different functional rooms

in the analysis some of the graphs are ahrd to read, the keys are too small etc.... a more interactive interface with the data would be good

Thermal comfort is fine, no problems.Just having boxes to type in the units for the calculation, then the software does it for you, would make the calculation a lot easier. Coming from not a particular physics or mathematical background i found myself slightly confused with some of the calculations i did for myself. I got confused with units. If you were able to type in the numbers, ecotect explained how to generate the numbers and then did the calculation for you, it might perhaps be easier.

create graphs with fixed scales, prevention of overlapping materialscreate easier ways of viewing and creating data

Could list potential appliances and give some basic information such as wattage/ temperature/ litres of water used, making it quicker to do personal calcuations.

The basic calculations and reasoning behind establishing performance criteria was not very complex, perhaps with Ecotect already having the ability to set schedules, this could be adapted to include appliances and water heating to make these calculations automatically.

there is no software that exists that i know of, where you can input type of building, floor area, number of occupants etc to help you calculate performance criteria...

more options regrading natural ventilation.

Optional - Any comments as to how the software could have assisted more in determining potential for renewable energy provision?

The calculations on Ecotect are only in watt-hours, when in reality, most calculations are completed in kWhs.
If you could visualise solar panels in Ecotect, you should be able to input the efficiency of them. It is likely that their efficiencies will improve over time as the technology does and so by manipulating this, it will be possible to get a more realistic calculation of the solar energy potential.

maybe if it has physical solar collectors and wind turbines maybe even as far as ground source heat pump systems, so you could determine which one to use for a poticular climate.

At times quantities of incident radiation seemed large, this was most likely correct however with limited knowledge on how much solar radiation is expected, it was hard to gauge whether the answer was suitable or not

the software only simply looks at renewable energy. it would be good if you could input objects like pv arrays and have the program work out output.
also the wind speed could be used as well as rainwater collection.

the idea of energy traget could be helpful but i would be unsure as to its releavance considering standards are different in every country. i need to be sure the figures on screen were trueful

n/a for what i used it for it was really good, a bit hard to learn at first but once your used to what your doing its fine.

Maybe a walk-though guide to applying renewable energy equipment.

Explaining the different result columns for solar exposure to clarify what each column title describes.

have renewable energy systems available to edit like materials

To have clearer options e.g things that can be picked up and placed where wanted/needed and data to show how useful they are.

Could have been more clear about exact solar radiation on specific surfaces.being able to place good replicas of photovoltaic cells and solar panels on the model would help a lot to avoid mis-calculation of solar potential.

Regarding question 25 I think it would be good to be able to set this target value yourself, or choose from a list based on certain building uses, building regulations etc.

might be helpful if ecotect gave options for placing pv cells etc, and gave values of efficiency, to help calculate if the energy provided by the sun will satisfy the building requiremements

the option to use photo voltaic panels would be helpful as it could give standard dimensions rather than just stating an area. the placing of panels could include price and pay back time for the system. small notes to be made on the joining of heating panels efficiency levels fall when more than a certain number are linked together.

Optional - Comment on how the visualisation of data might be improved to assist your design process?

It may be useful to display a previous test's results next to the current ones, and also display the difference in these values in terms of + and -.That way it will be easier to identify the largest and smallest changes.
One misleading element which I encountered was that when the heating and cooling energy requirement decreased, the monthly load graphs did not really show this as the scale was reduced. If the graphs were all identical, it would be much easier to understand and comment on and be far less misleading

make the colours more releventred for hot blue for cold etc. and given examples of what is good to compare back.

Graphs, expecially monthly loads rarely seemed to change or if they did, the data along the y axis updated and the graphs visually looked the same. The data in text form was much more useful

add a dialog box which user types items which he/she wants, then the software genenrate a table lists all.

To ensure that the values used to label graphs do not change, allowing a more valid visual comparison to be made.

having a tracking system would be very useful also to load the graphs as there own windows to help. i would also be good to be able to specify the min and max values for graphs. currently you can only lock scales which is reset when you change graph type

like i mentioned above, the graph keys ang different coloured line are either hard to see or hard to differentiate especially at the size they are displayed so being able to zoom in etc... Also, the changing of scale of the graphs make them useless interms of direct viual comparison so the idea of having the data atomatically track whilst changes are made would be very usefully is this data could be comparred directly in the form of a graph

if it were to be updated in real time

It would be useful to flick between current and past graphs to directly see their change.

Some sort of logging system where the date is recored and out put as a seperate file, i found i was using screen capture and manually writing down stuff that was already on the screen.

The dashboard is a very good idea, which would show you parameters so you can be sure that it is a fair experiment by by keeping these values constant. I found i would get different results by accidentally changing a parameter. i can be easy to forget the parameters in your head, and its really frustrating when you cant find out why the results have changed from something you did two seconds ago. The dashboard feature would eliminate this, allowing you to easily keep an eye on the parameters.

Being able to see multiple graphs at a time would help in being able to analsye results. The graphs should come with a list of critera and settings that were used to create them. This is because it becomes very easy to forget which settings you used with each graph and the process becomes confusing.

the idea of a dashboard will facilitate the visualisation of data input and the data after the analysis so that we can go back at it and touch every point in the analysis and try to incorporate it in the design process.

ability to fix scales and units easily   ability to view changes and results quickly and combined create screen where everything is on the same page rather than flicking between editor and anaylsis pages

Having the software be able to indicate where the design is at fault would vastly improve the users analysis and understanding to make the design as passive as possible.

Graphs could be easier to understand. Had to rely mainly on numeric data below.

More obvious differences between zones - colours and thickness of wire frame on visual model aren't very distinct.

I think it would be useful to be able to pick and choose multiple graphs to view at once, but not just from the building as it stands in that current time, the feature to record changes and view data in a 'before and after' type way would be very useful for direct comparison. I think that the ability to view multiple graphs on the hourly temperature profile would also be useful eg. the ability to simultaneously view the hottest and coldest days. I have no problems with the user interface after extended use of this program, although it is not the most intuitive user interface I have used, after some tuition and reading of the help files it makes sense and is simple to use, I have used so called 'dashboard' interfaces before and think they are either too simple, with too few features, or too confusing with too many features, or graphics that distract from the actual purpose of the program. Simple menus and toolbars are much better.

Currently the axis values change each time a graph is re calculated. If there was a feature to fix the axis values any graphs could be instantly comparable.

to have a little dashboard that will be alterate with every change made to the model

Optional - Any suggestions as to how the software could give you more support to enable you to formulate a strategy for energy reduction?

was far to much exploration involves you shud b able to select all walls easyier and change, thought the dialong box was good though but agin further simplification could be possible and an automatic copy constructional detail should be made so thta it doesnt copy over the default.

U values where very often misleading. Some materials displayed low U Values yet sometimes gave much worse performances than materials with a higher U Value, especially in regards to testing Ecotect default materials. Using U values would have been a good way to gauge whether the material was being improved or not, it had very little impact and therefore for about 90% of testing was never referred to

Enable users can modeling nondistinctive 3D model, than assign property through right click menu.

Software is very bad at lettting you group or select faces making it hard to quickly change your building design.
the passive gain is very useful feature. And extension to this could be to show on your model where the gains and loss are.

i not sure if its the program's part to help you form a srategy, shouldn't that be developed on your own through the use of research?

Perhaps a walkthrough guide again, maybe explaining the theory behind any modifications to be made. Learning can be done there and then by the student. Becomes more of an educational tool then, which may not be what the software is about, i don't know.

It should help us to know about the materials and the insulation material used is correct for the particular construction detail

Passive gains breakdown is a very useful graph and it could maybe go into more detail. E.g. whick materials are causing greatest loss through conduction.

there should be provision wherein the software prompts us everytime we use a wrong material or a construction detail as it already knows the climatic conditions of the region where the building is made by the weather file which is loaded before the analysis.

needs a simpler way of edit/view data
needs to be able to see the changes that have been made and there results

Having the dashboard display would be extremely useful
Recording all changes made maybe in an accessible collapsible window so we can see where we're getting our results from
Identifying specific key elements to change which will reduce energy levels ie. walls in zone 3 etc. maybe in a separate zone graph?

It should prompt you when the wrong material or technique is being used. Or if the combination of systems could be wrong.

Does not give you any suggestions (if it can I didn't know it was able to do so) would be helpful to have a rough what could help option.

The software is neither supportive nor a hindrance to formulating a strategy. Although the software offers no assistance in offering a clear iterative process of changes, it also has no features which prevent you from doing so. I think this is alright as the software gives you the freedom to choose your own process and find your own way, however as already mentioned I think a 'history' tool would be useful in order to instantly jump back and forth between previous changes to effectively compare old and new data.

software gives no support- no indication of how using thermal mass, high density materials, low u-value materials etc would help to reduce loads. it is all relying on own knowledge. some help would useful, giving suggestions for strategies according to climate selection.

The option to create a checklist feature. The user could create there own or the software formulate a quick step way of reducing the energy of the building. For example
Location and Weather file
Occupany Schedule
Materials
Orientation
Solar
Wind
From the checklist if a user was stuck a link to help page or tutorial or even straight to the option to change the settings.

Optional - How do you think energy simulation software could be improved to enable design decisions to be made in which aesthetics could be considered?

I do not think that Ecotect can really be improved in this category. The software provides the facilities to modify the appearance of the building- which also can be visualised in a basic manner.

I use archicad and their is a plug in for enviromental construction, but i have not used this as their is a cost attached, however it would be amazing to use plug ins which give the calculations and substainable object attachments like solar and wind collectors.

better 3d visualisation, larger database of contemporary materials and building methods

In Ecotect the 'Visualise' tab displays a very neutral building. Change of material will affect the aethetics, yet this does not update within the 'Visualise' part. Could be useful.

Develop energy simulation software as a package for standard software, and as what I mentioned above offer the model components which built by standard software the thermal properties. Of course, as to reduce the calculation load for computer system, users would be offer the selection to turn off these properties.

you can currently import obj files into ecotect making it integrate with all cad software the problem with it is defining zones and surfaces. i used ecotect to calculate the lighting and thermal properties of my first semester design project which was a complex same created in 3dmax. the other problem with ecotect is that it has a simple hardware support and uses only a single thread to do calculation meaning it takes along time to work out values for complex shapes. especially with new cup architecture like the i7 chips that run on 12 core.

The comfort degree will be shown on the graph, you can change the design while the consequence is not satisfied.

if we are talking ecotect as an example its 'visualise' part is horrible, mainly it wasnt design with aesthetics in mind so the buidling is very difficult to edit. When compared with traditional 3d modeling software it doesnt provide the oppertunities or user interface which allows people to easliy edit the design. in my mind design software and environment software are seperate so is it neccessary for on program to do both? what is important is making different modeling softwares compatible with environmental software so that design can be tested but built in programs that are very good at what they do and every one knows how to use.

The better the physical form of a building can be expressed the better the thermal analysis of it will be. It would be good to use the visual aspects of ecotect more in order to create a building more like your design.

I think energy sofware is important but the design of a building should not totally depend on it,

By allowing you to create more complex forms in an easier manner.

it could give examples of construction types to justify decisions or materials increase the number of default eco tect materials and give better specifications of materials e.g. drawings and designs

I find materials contribute quite a lot to building design. Introducing materials to the model façades would help visualize the overall aesthetic

models from design software to be compatible and be imported into energy simulation software upon which they can be simulated

instead of just using colour on the visualisation, could help to show realistic materials similar to Sketchup.

Better visual 3D modelling

I think a programme with all the design features of CAD and the energy simulation of Ecotect would be a huge leap in terms of low energy design, the seperation of these two pieces of software may represent typical attitudes towards low energy and design as two seperate fields, ideally they should be one and the same and a piece of software that could bridge that gap would be very useful in designing aesthetically pleasing and low energy buildings, without one factor becoming an afterthought.

similar to a sketchup model where a paint option is available, a wide range of materials are available. When changing the material construction if each material had its own image assigned. when visualising the model more detail could be seen. The image may help create more realistic design details if imagery was used.
Further assistance could be at hand, if the user was unsure about what a certain material was a link to maybe a supplier or just a information sheet which included a precedent, green credentials, location of material, embodied energy.

i do not have any ideas for this, some render options to make better presentation of the outcome

Optional - What were the questions you could not find an answer to?

What am i looking to achive?
Does this graph look correct or not?
Where and how do i perform calculations?
what tab to i use again?, confussion

Those about using the data from Thermal Analysis efficiently.

The consumption of water and electricity

When I was making a new material for the wall, I was not quiet sure which attribute would affect the U-Value of wall. It will be much better if it is showed in the software as a help.

kind of materials and insulation materials used for construction details

what determines degree hours and environmental temperatures
why is it that if you change one little aspect of the building the whole analysis changes to something that doesn't make sense!!

why, when the u-value for a wall/roof/floor is lowered considerably, with much insulation added, does the load increase? this makes no sense!
why, when i change the materials for varies parts of the construction individually, and they reduce the load by x amount, does this value not correspond to when i do the changes one after the other. surely if a change is made that is a good change, it should reduce the load by the same amount, regardless of the order in which you do it?
why, when i make a change to the building, do the analysis calculation, realise that the load has increased, press undo to undo the change, redo the analysis calculation, has the load amount completely changed to a number that it never was?
what is internal gains; and how do u reduce them?

When certain error messages appeared within the analysis the option to isolate the problem still did not give any clarity on what was wrong with the model.
Another question was the importance of whether a zone that appeared to have zero volume was actually being counted in analysis.
Another question was when the roof and floor of vertical zones overlap what was the correct way to alter the materials involved. Do you group both together to make one construction detail or create a ceiling and a floor.

i never got the right way to modify and calculate the water suply and at the end i could present that .

basically how to read the calculation graphs; why low u value of materials doesnt ensure a lower energy consumption of the building; how effective is the daylight exposure simulation, etc

Optional - Comment on any other aspects relating to how an Expert or Design Support System could assist your design process?

it could intergarte air flow, form, vetilation and solar gain all in one model. I feel more visual aspects using the actual model would be far more help than a graph.

1. Construction details in a model in standard software can be display by click some buttons.
2. Users can see the changes both of the construction detail shapes and thermal parameters through using sliders.
3. Enhance the linkage between the data iterated by software and the expertised advices generated by the system.

i think a 3D modelling and thermal simulation software could have a places in a architetural work flow but i think it would be more toward the end of the design proses to look at surfaces and construction details.

i only answered no because personally i have never used any programs 'help' or 'support system' they are not where i naterually defer to if i have a problem. I much more likely to look it up online or ask someone i know

A graph showing your progress from your intial building performances to the latest- this would help you understand what aspects have improved the building the most.

Explaining what the graphs for thermal analysis do. Took me a while to work out what the readings meant.

It could explain why theoretically good changes to the building had no or bad influence on energy outcome.

If a certain location was specified in the model, maybe the option to view local materials, or the embodied energy of certain materials reaching the site.

it should show the development of the project, how it all begins and how it goes improving in every way, construction and environmental , materials, lighting, ventilation, all together

Appendix 4 – IFC and gbXML Tables

IfcObjectDefinition	captures tangible object occurrences and types such as a wall object
IfcRelationship	captures relationships among objects
IfcPropertyDefinition	captures dynamically extensible properties about objects.

Table A3. 1 The three subdivisions of IfcRoot

IfcActor	represents people or organizations.
IfcControl	represents rules controlling time, cost, or scope such as work orders.
IfcGroup	represents collections of objects for particular purpose such as electrical circuits.
IfcProduct	represents occurrences in space such as physical building elements and spatial locations.
IfcProcess	represents occurrences in time such as tasks, events, and procedures.
IfcResource	represents usage of something with limited availability such as materials, labor, and equipment.

Table A3. 2 The six groupings for IfcObjects

IfcRelAssigns	captures assignment relationships where one object consumes the services of another object, such as a labour resource assigned to a task
IfcRelAssociates	indicates an external reference for an object such an external classification, library file or document where an object is defined.
IfcRelConnects.	indicates a relationship that connects objects such as a floor slab connected to a beam
IfcRelDeclares	handles the assignment of objects (subtypes of *IfcObject*) or properties (subtypes of *IfcPropertyDefinition*) to a project or project libraries (represented by *IfcProject*, or *IfcProjectLibrary*).
IfcRelDecomposes	captures a whole-part relationship having exclusive containment. An example is the subdivision of a building into floors and rooms or a wall into studwork and plasterboard.
IfcRelDefines	indicates an instance-of relationship such as a window being of a particular type.

Table A3. 3 The six relationship types for IfcObjects

IfcMaterial	indicates a specific material, with optional properties (e.g. mechanical, thermal) and styles (e.g. colors, textures).
IfcMaterialLayerSet	captures a list of layers, each indicating a material of a specified thickness.
IfcMaterialProfileSet	captures a set of profiles, each indicating a material of a specified cross-section.
IfcMaterialConstituentSet	captures a set of constituents, each indicating a material used at a named shape aspect.

Table A3. 4 The four methods for defining materials for objects

	IfcMaterial	IfcMaterialLayerSet	IfcMaterialProfileSet	IfcMaterialConstituentSet
Attributes	Name Description Category HasRepresentation IsRelateWith RelatesTo	MaterialLayers LayerSetName Description TotalThickness	Name Description MaterialProfiles CompositeProfile	Name Description MaterialConstituents
Description	A homogeneous or inhomogeneous substance that can be used to form elements (physical products or their components).	A designation by which materials of an element constructed of a number of material layers is known and through which the relative positioning of individual layers can be expressed.	A designation by which individual material(s) of an prismatic element (e.g. beam or column -type elements) constructed of a single or multiple material profiles is known. If only a single material profile is used (the most typical case) then no CompositeProfile is asserted.	A designation by which the different materials of a construction shall be provided. An example is a window construction that can include the window lining and the window glazing.

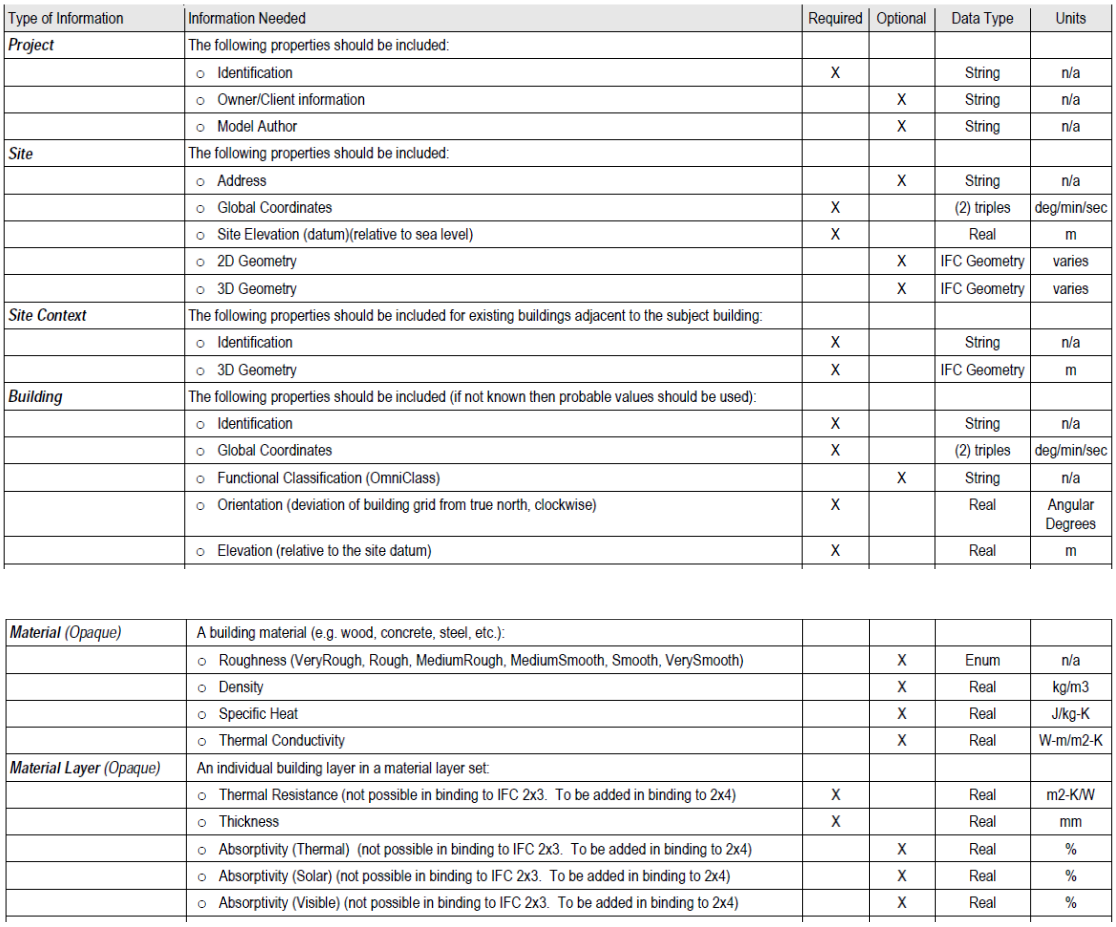
Table A3. 5 The four types of material object in IFC

IfcExtendedMaterialProperties	
Properties (It has Properties instead of Attributes)	Extended Properties
General Material Properties General Mechanical Properties ▪ Steel Mechanical Properties ▪ Concrete Mechanical Properties ▪ Timber and Wood-based Mechanical Properties	IfcMassDensityMeasure See buildingSMART for further details[80]
General Thermal Properties **Name:** ThermalProperties	SpecificHeatCapacity BoilingPoint FreezingPoint ThermalConductivity
General Hygroscopic Properties **Name:** HygroscopicProperties	LowerVaporResistanceFactor IsothermalMoistureCapacity VaporPermeability MoistureDiffusivity
General Optical Properties **Name:** OpticalProperties	VisibleTransmittance SolarTransmittance ThermalIrTransmittance ThermalIrEmissivityBack ThermalIrEmissivityFront VisibleReflectanceBack VisibleReflectanceFront SolarReflectanceBack SolarReflectanceFront
General Water Properties General Fuel Properties General Products of Combustion Properties	See buildingSMART for further details
General Energy Calculation Properties **Name:** EnergyCalculationProperties	ViscosityTemperatureDerivative MoistureCapacityThermalGradient ThermalConductivityTemperatureDerivative SpecificHeatTemperatureDerivative VisibleRefractionIndex SolarRefractionIndex GasPressure

Table A3. 6 The material properties included in IFC relevant to thermal simulation calculation

---

[80] Industry Foundation Classes Release 2x4 (IFC2x4) Release Candidate 2, BuildingSMART http://buildingsmart-tech.org/ifc/IFC2x4/rc2/html/index.htm



Type of Information	Information Needed	Required	Optional	Data Type	Units
Project	The following properties should be included:				
	○ Identification	X		String	n/a
	○ Owner/Client information		X	String	n/a
	○ Model Author		X	String	n/a
Site	The following properties should be included:				
	○ Address		X	String	n/a
	○ Global Coordinates	X		(2) triples	deg/min/sec
	○ Site Elevation (datum)(relative to sea level)	X		Real	m
	○ 2D Geometry		X	IFC Geometry	varies
	○ 3D Geometry		X	IFC Geometry	varies
Site Context	The following properties should be included for existing buildings adjacent to the subject building:				
	○ Identification	X		String	n/a
	○ 3D Geometry	X		IFC Geometry	m
Building	The following properties should be included (if not known then probable values should be used):				
	○ Identification	X		String	n/a
	○ Global Coordinates	X		(2) triples	deg/min/sec
	○ Functional Classification (OmniClass)		X	String	n/a
	○ Orientation (deviation of building grid from true north, clockwise)	X		Real	Angular Degrees
	○ Elevation (relative to the site datum)	X		Real	m

Material (Opaque)	A building material (e.g. wood, concrete, steel, etc.):				
	○ Roughness (VeryRough, Rough, MediumRough, MediumSmooth, Smooth, VerySmooth)		X	Enum	n/a
	○ Density		X	Real	kg/m3
	○ Specific Heat		X	Real	J/kg-K
	○ Thermal Conductivity		X	Real	W-m/m2-K
Material Layer (Opaque)	An individual building layer in a material layer set:				
	○ Thermal Resistance (not possible in binding to IFC 2x3. To be added in binding to 2x4)	X		Real	m2-K/W
	○ Thickness	X		Real	mm
	○ Absorptivity (Thermal) (not possible in binding to IFC 2x3. To be added in binding to 2x4)		X	Real	%
	○ Absorptivity (Solar) (not possible in binding to IFC 2x3. To be added in binding to 2x4)		X	Real	%
	○ Absorptivity (Visible) (not possible in binding to IFC 2x3. To be added in binding to 2x4)		X	Real	%

Figure A3. 1 Snippets of the MVD, taken from the IFC Solutions Factory website (2011)

	Material	Layer	Construction
Attributes	Id DOELibIdRef	Id DOELibIdRef	Id DOELibIdRef
Children	Name Description ImageTexture R-value Thickness Conductivity Density SpecificHeat Permeance Porosity RecycledContent Fire Cost IndoorAirQuality CADMaterialId Reference	Name Description Cost InsideAirFilmResistance MaterialId	Name Description U-value Absorptance Roughness Albedo Reflectance Transmittance Emittance Cost PercentExisting FireFace LayerId LoadCalcInputParameters

Table A3. 7 the attributes and children of the three types of Material in the gbXML standard