Exploiting BIM in Energy Efficient Domestic Retrofit: Evaluation of Benefits and Barriers

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Declaration

I hereby certify that this thesis constitutes my own work and investigation. Where other sources of information have been used, they have been acknowledged, as it should be.

I declare that this thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Signed: Elaheh Gholami

November 2017

Abstract

Energy efficient retrofitting of the existing building stock is important because of the need to reduce CO_2 emissions and improve building energy performance. The significance of refurbishing existing UK housing to help the government achieve its climate change targets has been widely recognised. However, the current practices for UK retrofitting, with one of the oldest domestic stocks in Europe, are still confronted by technical and social challenges such as late adoption of BPS tools, difficulties in effectively measuring energy consumption and disruption to users. Therefore, it is essential to improve the existing practices of the domestic retrofit process. Building Information Modelling (BIM) offers, potentially, a comprehensive and integrated platform for improving the retrofit process. Although BIM has been applied in many large-scale projects, it has not been used extensively for small-scale retrofit schemes in the UK. This study sort to test two common misconceptions – (i) BIM is only for complex large-scale projects; (ii) BIM is only for new projects - by investigating the potential implementation of BIM in energy efficient domestic retrofit in practice in the UK. This thesis has explored how the efficiency of the retrofit process could be improved through BIM implementation. A critical review of the literature was followed by a series of semi-structured interviews with professionals. An experimental study demonstrated why the existing simulation methods, such as 'detailed modelling', are not effective and why it is necessary to enhance the existing practices. One of the main barriers to improving the efficiency of existing practices is using Building Performance Simulation (BPS) tools too late in the retrofit process. Based on the experimental study, the results of detailed modelling, using DesignBuilder, were very accurate; however, such results are frequently used in an evaluative rather than proactive way in the existing practices. Running energy simulation is a lengthy process and putting architectural information into the BPS tools not only requires more time than is usually available at the early stage but, also, defining the thermal view by energy experts is subjective. Furthermore, evaluating the accuracy of 'standards and procedures' approaches, Standard Assessment Procedure (SAP) and Passive House Planning Package (PHPP), illustrated that analysing energy performance based on the inaccurate or notional assumptions, regardless of the unique characteristics of the projects are often arbitrary, unreliable and inaccurate. Therefore, BIM simulation approaches were evaluated and tested through a real-world case study. The scope of this research is limited to energy performance modelling process; however, the basic methods and principles could be also applied to other types of performance analysis. The experimental project, evaluating two BIM simulation approaches, integrated and interoperable BIM, provided the opportunity to evaluate BIM's usefulness in energy performance simulation and assess the accuracy and reliability of the outputs compared with the results of two-years of monitoring a house. Integrated BIM simulation approach, Graphisoft EcoDesigner Star, provided effortless interoperability and improved the effectiveness of the process. However, the integrated BIM approach requires intelligent guidance and depends on the vendors to integrate performance simulation tools into their BIM environment. The interoperable BIM, through gbXML, can facilitate the integration of BPS tools in the early design stage. By improving interoperability at the early design stage and adopting BIM, identified challenges could be addressed, such as, uncertainty about the quality of retrofit measure, lack of interoperability between BPS tools and BIM, and time-consuming iterative modelling.

The main contribution of this research is in identifying the barriers and potentials of BIM in energy performance simulation to enhance the existing practices of the retrofit process through the experimental study. However, this research is a starting point, where an initial analysis of the problem and its solution has commenced.

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Contents

Abstract iii

Acknowledgements iv

List of Figures x

List of Tables xii

1 INTRODUCTION 2

1.1 Overview 2

1.2 Research Problem 3

1.3 Research aim and objectives 5

1.4 Research Questions 6

1.5 Research Methods 7

1.6 Research Results 8

1.7 Outline of Thesis 8

2 LITERATURE REVIEW: CHALLENGES IN THE ENERGY EFFICIENT RETROFIT PROCESS.... 13

2.1 Introduction 13

2.2 Energy-efficient retrofitting of existing housing 14

2.2.1 Importance of energy efficient retrofit of housing 16

2.3 Building retrofit measures 17

2.3.1 Key phases in the retrofit process 18

2.3.2 BPS-based energy efficient retrofit process 19

2.4 Describing Barriers in Retrofit Process 21

2.4.1 Behavioural barriers 22

2.4.1.1 Energy Efficiency Gap 23

2.4.1.2 Rebound Effect 24

2.4.2 Financial barriers 26

2.4.3 Political barriers 28

2.4.3.1 Building regulations 28

2.4.3.2 Standard Assessment Procedure (SAP) 29

2.4.3.3 Energy Performance Certificate (EPC) 31

2.4.4 Education and skill barriers 34

2.4.5 Disruption to users 36

2.4.6 Technical barriers 37

2.4.6.1 Difficulties in effectively measuring energy consumption 37

2.4.6.2 Measuring actual thermal properties of building elements 38

2.5 Conclusion 39

3 RESEARCH METHODOLOGY 43

3.1 Introduction 43
3.2 Qualitative Research Approach 44
3.3 Quantitative Research Approach 46
3.4 Mixed methods research 47
3.5 Methodology Adopted 47
3.5.1 Intuition 49
3.5.2 Point of Departure (Theoretical Limitations) 50
3.5.3 Research Methods 51
3.5.3.1 Literature review 52
3.5.3.2 A series of semi-structured interviews 53
3.5.3.3 A real world case study 54

4 LITERATURE REVIEW: BUILDING INFORMATION MANAGEMENT (BIM) IN THE RETROFIT PROCESS 57

4.1 Introduction 57
4.2 What is BIM? 58
4.2.1 BIM's Background 58
4.2.2 BIM Definitions 58
4.2.2.1 BIM is a Sociotechnical System 59
4.2.3 BIM Adoption 60
4.3 BIM Benefits 62
4.4 Adopting BIM through the Retrofit Process 64
4.5 Challenges to Exploit BIM in Small-scale Retrofit Process 65
4.5.1 Capturing initial Data and uncertainty of captured data 66
4.5.1.1 Laser scanning 68
4.5.1.2 Photogrammetry 70
4.5.2 Interoperability and Interdisciplinary in BIM 72
4.5.3 Open Interoperability Standards 75
4.5.3.1 The Green Building XML schema (gbXML) 77
4.5.3.2 Construction Operations Building Information Exchange (COBie) 78
4.5.3.3 Industry Foundation Class (IFC) 78
4.6 Interoperability between BIM and BPS tools 79
4.6.1.1 Integration and direct links in early design 82
4.7 Conclusion 83

5 PRIMARY DATA COLLECTION 88

5.1 Introduction 88
5.2 Interview Design 88
5.3 Snowball sampling 90
5.4 Data Analysis Software: NVivo 92

5.4.1 Coding 94
5.5 Interviews of professionals in retrofit process and/or BIM......95
5.5.1 Challenges for energy efficient retrofitting in residential sector 97
5.5.1.1 Financial issues......98
5.5.1.2 Technical issues......98
5.5.1.3 Social issues......100
5.5.2 Drivers to improve the energy efficiency 100
5.5.3 BIM potentials in energy efficient retrofit process 103
5.5.4 Surveying approach in retrofit process......105
5.5.5 Challenges to implement BIM in small-scale retrofit in residential sector 107
5.5.6 Suggestion to implement BIM in the energy efficient retrofit process......109
5.6 Discussion and conclusion 110

6 REQUIREMENTS FOR THE EXPERIMENT 114

6.1 Introduction 114
6.2 The Importance of the Quality of Shared Information in the Model 114
6.3 Automated rule checking......117
6.3.1 Rule-based Checking......118
6.3.1.1 Automated compliance checking......121
6.3.1.2 Model Checking for Data Quality 122
6.4 Commercial application for automatic rule-based checking......123
6.4.1 Solibri Model Checker......124
6.4.1.1 Checking 126
6.4.1.2 Analysis......126
6.4.2 FORNAX......127
6.5 Quality Model Checker Software......128
6.6 BIM’s Tools and Platforms 129
6.6.1 Autodesk Revit......130
6.6.2 ArchiCAD Graphisoft 131
6.7 Conclusion......132

7 DATA COLLECTION AND ANALYSIS FROM THE REAL WORLD CASE STUDY 136

7.1 Introduction 136
7.2 Case Study: 2 Broxton Street, Liverpool, United Kingdom......137
7.2.1 Retrofit Process of 2 Broxton Street House......138
7.2.1.1 Openings......139
7.2.1.2 Walls 139
7.2.1.3 Floors......140
7.2.1.4 Roof 141
7.2.1.5 Mechanical Ventilation with Heat Recovery (MVHR) 141
7.2.1.6 Heating System......142
7.2.1.7 Hot Water System 142

7.2.2 Results of long term monitoring 144
7.3 Existing Methods for Assessing and Simulating the Energy Performance of Buildings 146
7.3.1 Energy Performance Assessment using SAP and PHPP 146
7.3.2 Detailed modelling: A stand-alone Building Energy Simulation 149
7.3.3 Evaluation the Effectiveness of the Existing Methods for Assessing and Simulating the Energy Performance of Buildings 151
7.4 BIM Simulation Approach 152
7.4.1 Steps to model the house in ArchiCAD 154
7.4.2 Solibri Model Checker (SMC): Checking the quality of 2 Broxton House modelled in ArchiCAD 156
7.4.2.1 Setting the Ruleset Manager 157
7.4.2.2 Classification 157
7.4.2.3 Checking the model 158
7.4.2.4 Rulesets in Solibri Model Checker 159
7.4.2.4.1 BIM Validation Architectural 159
7.4.2.4.2 General Space Check 161
7.4.2.4.3 Intersections between Architectural Components 162
7.4.2.4.4 Pre-check for Energy Analysis 163
7.5 Integrated BIM Simulation Approach: ArchiCAD EcoDesigner STAR 165
7.5.1 Operation files 166
7.5.2 Environmental Settings 167
7.5.3 Building Systems 167
7.6 Interoperable BIM: Green Building XML (gbXML) 168
7.6.1 The native gbXML export in ArchiCAD 20 169
7.6.1.1 Geometry 169
7.6.1.2 Material properties 171
7.6.1.3 Building systems 172
7.6.1.4 Weather and climate data 172
7.6.1.5 Building operation information 172
7.6.2 The plug-in to export gbXML in ArchiCAD 19: Cadimage 173
7.7 Conclusion 175

8 DISCUSSION 181

8.1 Introduction 181
8.2 Sustainable retrofit of housing for the elderly in historic district in London with Building Information Modelling (BIM) and Computer Numerical Control (CNC) 181
8.3 Building Information Modelling [BIM] for energy efficiency in housing refurbishments 184
8.3.1 How has BIM been implemented in S-IMPLER Project to reduce the CO_2 by improving the retrofitting solid wall home? 184

8.4 Learning points from the projects 185

9 CONCLUSION 188

9.1 Research significance 188
9.2 Research main findings 188
9.3 The limitations of this research 199
9.4 Future research direction 200
References 201
Appendix A: Interview Questions 243
Appendix B: Report of SMC for 2 Broxton Street 247
Appendix C: SAP Worksheet: Design - Draft 263

List of Figures

Figure 1.1:1: Building emissions in the context of UK GHG emissions (1990-2030 and 2015) (NAEI, 2012) 2
Figure 1.1:2: Global buildings energy use by subsector, 2002-12 (IEA, 2015) 3
Figure 1.5:1: CIFE horseshoe research framework (adopted from: Fischer, 2006) 8
Figure 1.7:1: Thesis outline 9
Figure 2.1:1: Final energy consumption by sector 1970 to 2014, UK (DECC, 2015a) 13
Figure 2.2:1: Housing stock distribution by age to 2007 (millions) (Palmer & Cooper, 2012) 15
Figure 2.2:2: Housing stock distribution by age 2008-2011 (millions) (Palmer & Cooper, 2012) 15
Figure 2.3:1: Breakdown of heat loss (Carbon Trust, 2012) 17
Figure 2.3:2: BPS-based retrofit design process (Mondrup, 2014) 20
Figure 2.3:3: The iterative decision support process. (Adapted from Tanimoto, et al., 2001; Alanne, 2004). 21
Figure 2.4:1: Integrated model of proenvironmental behaviour (Wilson & Dowlatabadi, 2007) 25
Figure 2.4:2: Diagram: Green Deal Plan (DECC, 2010) 27
Figure 2.4:3: SAP and Environmental Impact rating for energy performance certificates (EPC) in England and Wales (Energy Efficiency Partnership for Homes, 2008) 32
Figure 3.5:2: The steps of the research process based on CIFE horseshoe research framework 50
Figure 4.2:1: Sociotechnical system with a technological base and layers of social components (Kennerley, 2013) 60
Figure 4.2:2: BIM Maturity Diagram (Bew & Richards, 2008) 61
Figure 4.2:3: BIM awareness and usage, adopted from (NBS, 2017) 61
Figure 4.5:1: Model creation process in new and existing building, adopted from (Volk, et al., 2014) 67
Figure 4.5:2: Systematic overview of data capturing and surveying techniques to gather existing building's information (Volk, et al., 2014) 68
Figure 4.5:3: Interoperability: direct translators vs. an open interoperability standard) 75
Figure 4.5:4: Communication Platforms 76
Figure 5.4:1: Result of word frequency queries in NVivo 93
Figure 5.4:2: Coding in NVivo 95
Figure 5.5:1: Classifying participants based on their professional backgrounds to address the challenges 96
Figure 6.1:1: Sharing information/data between domains and common (mis)conception of integrated (Kiviniemi, 2005) 114
Figure 6.2:1 Sharing information/data between domains and common (mis)conception of integrated (Kiviniemi, 2005) 115
Figure 6.3:1: The four classes of functionality a rule checking system should support. 119

Figure 6.3:2: Diagram for typical application implementing in four classes of rules. Adopted from: (Solihin & Eastman, 2015) 120
Figure 6.4:1: Overview of SMC QA/QC Process (Solibri, 2014) 124
Figure 6.4:2: FORNAX system architecture 127
Figure 6.4:3: FORNAX system architecture 128
Figure 7.2:1: 2 Broxton Street House before retrofit 137
Figure 7.2:2: Detail of Windows before and after fitting lining to timber frame (Larrosa Marshall and Associates, 2010) 139
Figure 7.2:3: SupaWall System (Larrosa Marshall and Associates, 2010) 140
Figure 7.2:4: SupaFloor: Plan section at panel Junction before and after location (Larrosa Marshall and Associates, 2010) 141
Figure 7.2:5: Mechanical system in 2 Broxton Street, Liverpool 143
Figure 7.3:1: PHPP results 147
Figure 7.3:2: Model 2 Broxton house in DesignBuilder 150
Figure 7.3:3: Comparison of estimated primary energy consumption by DesignBuilder 151
Figure 7.4:1: Comparison of existing approaches and BIM approaches 153
Figure 7.4:2: Proposed phases to model in ArchiCAD for energy evaluation 154
Figure 7.4:3: ArchiCAD model of 2 Broxton Street 156
Figure 7.4:4: Checking the components classification in SMC 158
Figure 7.4:5: Modifying the components classification in SMC 158
Figure 7.4:6: Used rulesets to check the model in SMC 159
Figure 7.4:7: Detecting Clashes in BIM Validation- Architectural 160
Figure 7.4:8: BIM Validation Architectural: Example of Deficiency Detection Check 161
Figure 7.4:9: Detecting Clashes in General Space Check 161
Figure 7.4:10: Example of clash detection in Space Validation 162
Figure 7.4:11: Detecting Clashes in Intersection between Architectural Components 163
Figure 7.4:12: Intersection between slabs and walls 163
Figure 7.4:13: Detecting Clashes in Pre-check Energy Analysis 164
Figure 7.4:14: Detecting Clashes in Pre-check Energy Analysis: Space validation 164
Figure 7.6:1: Exported gbXML file into DesignBuilder through native option of gbXML in ArchiCAD 20 170
Figure 7.6:2: Comparing the U-Value of exported file in DesignBuilder (top) with EcoDesigner STAR (below) 171
Figure 7.6:3: Exported gbXML file into DesignBuilder through Cadimage from ArchiCAD 19: displacements and absence of original elements 174
Figure 9.2:1: The comparison of existing energy performance assessment and stand-alone simulation approache with actual performance 192
Figure 9.2:2: BIM simulation approaches 197

List of Tables

Table 2.4:1: Comparison of the standard maximum permitted U-Value of construction elements in the UK Building Regulations from 1965 to 2010 (Planing Portal, 2011; Chow & Levermore, 2010). 29
Table 2.4:2: Typical costs and CO_2 savings for UK dwellings (Shorrock, et al., 2005) 31
Table 3.2:1 Strengths and weaknesses of qualitative research (Groat, 2002, p. 199) 45
Table 3.5:1: Interview Participants 53
Table 4.3:1: BIM's Potentials 63
Table 4.5:1: Comparison of 3D laser scanning and photogrammetry for remote sensing (Klein, et al., 2012) 71
Table 4.6:1: Characteristics, advantages and disadvantages of four different simulation methods, Adapted from (Citherlet, 2001; Petersen, 2011; Østergård, et al., 2016) 81
Table 5.5:1: Interview Participants 97
Table 6.5:1: Implementing different classes of rules in Solibri Model Checker and FORNAX (adopted from Solihin and Eastman (2015)) 128
Table 7.2:1: Input data before and after retrofit 144
Table 7.2:2: Primary energy use in 2011 and 2012 for the Broxton Street house 145
Table 7.2:3: Total CO2 emissions in 2011 and 2012 for the Broxton Street house 146
Table 7.3:1: Comparison of monitored results with PHPP and SAP 147
Table 7.5:1: Key Values results evaluated by EcoDesigner STAR 167
Table 7.5:2: Comparison of all simulations and assessments with monitored results 168
Table 7.6:1: gbXML vendor certification validator 174
Table 9.2:1: Barriers to improving the energy-efficient retrofit process 189
Table 9.2:2: BIM's potentials to improve the efficiency of retrofit process 193
Table 9.2:3: Challenges to implementing BIM to improve the efficiency of retrofit process 194

Chapter One

Introduction

1 Introduction

Overview

Energy efficiency is not only deemed as an essential and the most cost-effective option to mitigate climate change (Morita, et al., 2001); it also offers multiple benefits, such as reducing environmental pollution, ameliorating poverty, improving energy security and creating new jobs (GEA, 2012). In the UK around half of primary energy consumption and CO_2 emission is related to the built environment (Stafford, et al., 2012). The creation of new, energy efficient building stock is a very slow process, and so reducing the energy use of existing buildings through energy efficient retrofitting provides considerably more opportunities to lessen CO_2. (GEA, 2012). The UK government's target is to reduce greenhouse gas emissions by 80% (compared to 1990 levels) by 2050, as shown in Figure 0:1 (DECC, 2012a).

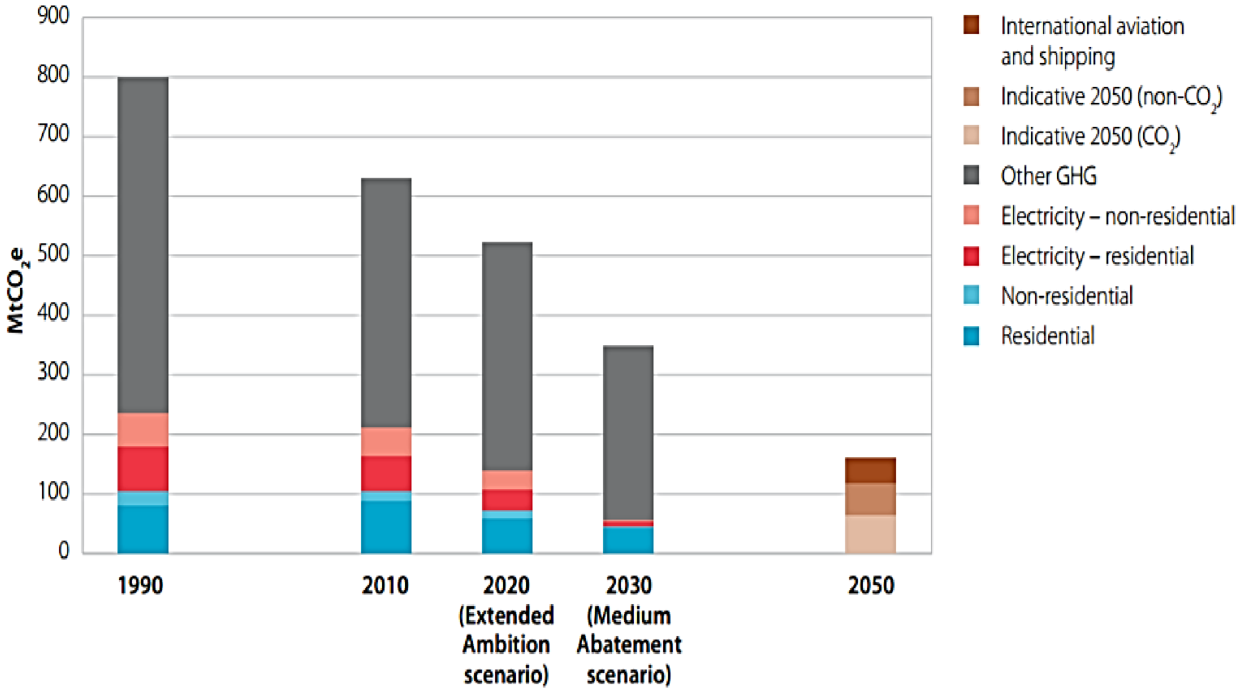


Figure 0:1: Building emissions in the context of UK GHG emissions (1990-2030 and 2015) (NAEI, 2012)

According to an IEA (2015), residential buildings account for 74% of total energy consumption within the building sector, with non-residential buildings accounting for the remaining 26% (Figure 0:2). Existing homes account for 99.7% of CO_2 emissions, with only 0.3% of CO_2 emissions being associated with the new housings built each year (Rickaby & Willoughby, 2014). A statistical study (T.R.C.C., 2008) indicated that 75% of existing residential buildings will still exist in 2050 in the UK. Therefore, enhancing the residential eco retrofit process is critical to achieving emission target in the UK (Legislation.gov.uk., 2008). Policy makers believe that the most cost-effective approach to reducing CO_2 by 2050 is by the energy-efficient retrofit of domestic stock (Lewis, 2014; Legislation.gov.uk., 2008).

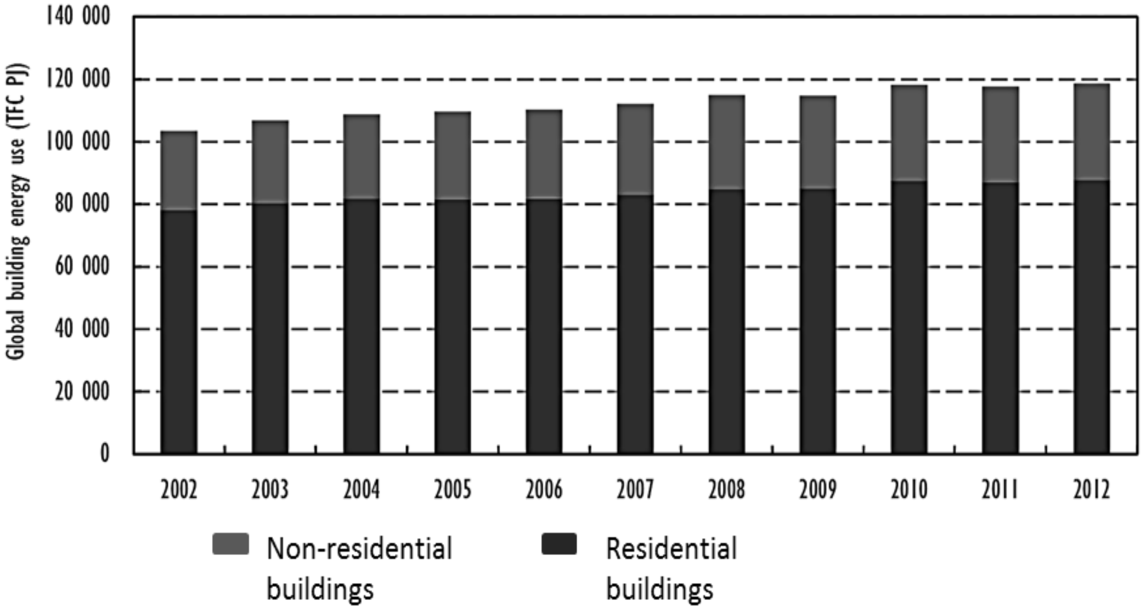


Figure 0:2: Global buildings energy use by subsector, 2002-12 (IEA, 2015)

Research Problem

Although a great number of strategies and technologies have been instigated to improve the efficiency of the energy efficiency of existing UK housing in recent years, the existing practices for retrofitting, with one of the oldest domestic stocks in Europe, is still faced with challenges to reduce CO_2 emissions (Ma, et al., 2012).

The problem is 'lack of systematic approach to improve the efficiency of energy efficient domestic retrofit'. The challenges in the energy-efficient retrofit process, including behavioural barriers, financial barriers, political barriers, education and skill barriers, disruption to users and technical barriers will be discussed in Chapter 2.

Building Information Modelling (BIM) is envisaged as a methodology to change existing building practices and has benefitted the Architecture, Engineering and Construction (AEC) industry (Eastman, et al., 2011) in large complex projects for new buildings.

by adopting BIM, the construction industry has benefitted considerably, including improved sustainability (Eastman, et al., 2011, p. 156), reduced time-to-market (Eastman, et al., 2011, p. 165), improved energy efficiencies (Eastman, et al., 2011, p. 23), reduce construction costs (Eastman, et al., 2011, p. 156) and improve decision making process at the early stages (Eastman, et al., 2011, p. 381). However, there is a common misconception that BIM is only suitable for complex mega projects or government projects (NBS, 2016). However, the contention to be tested in this thesis is that small-scale projects, such as domestic scale, can also benefit from adopting BIM. One of the construction professionals interviewed for this research between April 2013 and July 2014, interviewee D (2014), highlighted the importance of the BIM in the small-scale project and stated *"in many cases, it might be more useful to start with small simple residential projects and after learning BIM potentials, implement it in huge complex projects. We have been implementing BIM for new residential construction in Finland, Norway and Sweden. We do not believe that BIM should be implemented in massive and complex projects only".* In Skanska, Finland, where BIM has been adopted for residential projects profit margins were reported up by 45%, waste reduced by 45%, accident reduced by 5% and client satisfaction increased by 5% in comparison with non-BIM projects (Jeffrey, 2012).

In addition to the misconception of using BIM only for complex mega projects, there is another misapprehension, which is observed and reviewed by the researcher, that BIM is only for new buildings. The reason for that claim is that there are just a few examples of research about BIM implementation in retrofit projects (Volk, et al., 2014; CIOB, 2014). However, the majority of interviewees believe that implementing BIM only for new complex projects is a misconception and that retrofit projects can also benefit from adopting BIM. Moreover, the cost associated with upfront investments is considered as the main barrier to using BIM (NBS, 2015). However, a survey of 2,228 respondents, including architects, engineers, contractors and other industry respondents, reported that 87% of them experienced a positive Return On Investment (ROI) from BIM (McGraw Hill, 2009). Furthermore, based on a NBS report, cost efficiency is improved by 59% and profitability increased by 48% (NBS, 2015). Although exploiting BIM has improved sustainability, energy efficiencies, cost reliabilities, decision-making process and reduced time-to-market at the early stages in new buildings (Tanga, et al., 2010; Eastman, et al., 2011), the knowledge of BIM implementation in the small-scale retrofit project is practically non-existent (Ilter & Ergen, 2015). The researcher’s intuition was that if adopting BIM has improved the existing practices in complex new projects, then it might have the potential to improve the efficiency of small-scale retrofit processes.

Research aim and objectives

The main focus of this study is to investigate the potential benefits, in terms of energy efficiency, of BIM implementation in the energy efficient domestic retrofit process. This study aims to develop a systematic approach to support decision making process at the early stage of retrofitting by exploiting BIM. Therefore, to achieve the aim, the study targeted a number of objectives as follows:

- To explore barriers and enablers in the residential sector with respect to energy efficiency.
- To identify the potential benefits and barriers of BIM implementation to achieve an efficient approach in energy efficient domestic retrofit through literature review, primary data collection, analysis of real world case study and simulations.
- To develop a framework to improve the efficiency of the energy efficient domestic retrofit by the opportunities provided with BIM implementation.

Research Questions

The main criterion for good research questions is whether the research questions can be tested, generalised to address the problem statement or not: "*It is vitally important that a specific scope of work is identified in the question(s) for a particular research project. Finally, a research question needs to be formulated in way that makes any finding to the question an interesting answer*" (Fischer, 2006, p. 197). To achieve the aim and objectives, this research targets to answer the following main research question:

How could exploiting BIM in the energy efficient domestic retrofit improve the efficiency of the process in the UK?

The following sub-questions are designed to address different aspects related to the main research question:

- What are the barriers in the residential sector with respect to the energy efficiency?
- How are BIM applications comprehended and used in the construction industry to improve the efficiency of existing practices in new buildings?
- What are the deficiencies in the current practices to improve the efficiency of energy efficient retrofit process?

- What are the BIM’s potentials and challenges to improve the efficiency of energy performance simulation?
- How can interoperability improve the efficiency of the energy efficient retrofit process at the early stage?
- What is the importance of the quality of shared information in BIM to achieve reliable energy performance simulation analysis?
- In the current situation, to what extent does BIM provide an effective method to pave the way to improve the energy performance simulation in the energy efficient domestic retrofit process in practice?

This research does not aim to develop energy performance evaluation tools or technical solutions to improve the energy efficiency of existing buildings. Instead, it strives to develop a systematic framework to improve the process of retrofitting by exploiting BIM.

Research Methods

Mixed methods research synthesising and combing both qualitative (Literature review and interviews) and quantitative approaches (analysis of real world case study and simulations) were used to find solution for the observed problem. An extensive review of literature is conducted in two stages in this research. The first stage is to explore and identify the barriers to improve the efficiency of the retrofit process which will be discussed in Chapter 2. Built on the well-defined problem and clearly articulated intuition, the second stage of the literature review (Chapter 4), will explore how BIM implementation could benefit the retrofit process and what are the challenges to exploiting BIM in this process. A series of semi-structured interviews were conducted to obtain more up-to-date information from leading experts in this field and also to reinforce the findings from the literature review which will be discussed in Chapter 5. Finally, chapter 7 will analysis the data collected from a real world case study to investigate the actual energy consumption of the house over a two-year period. The results of the monitored house over a two-year period enabled the researcher to evaluate the accuracy of the experiment by comparing the results of the monitored house with simulated energy consumption predictions of the house through different types of interoperability between BIM and Building Performance Simulation (BPS) tools. The research process follows the adopted CIFE horseshoe research method which will be discussed in Chapter 3 (Figure 1.5:1).

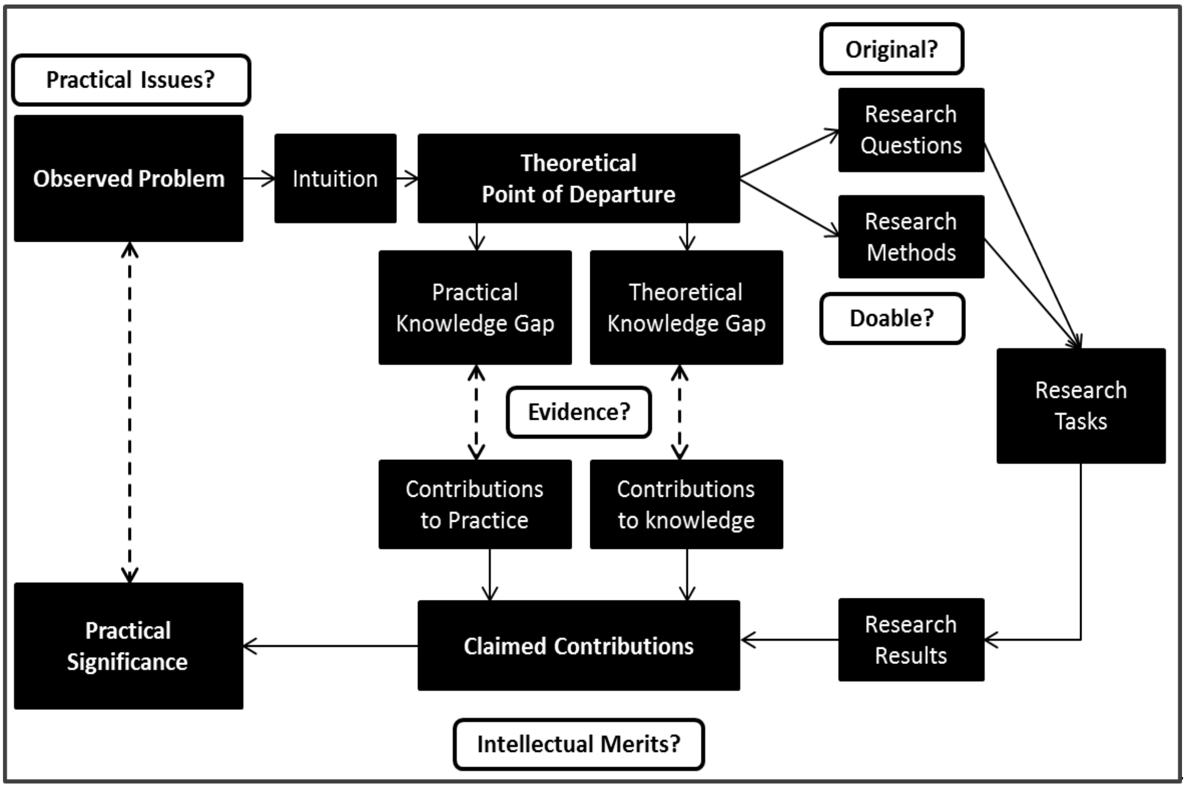


Figure 0:1: CIFE horseshoe research framework (adopted from: Fischer, 2006)

Research Results

The research results answer the research questions, including the evidence and results from simulation the case study, literature and interviews. The research results are discussed in Chapter 7. The contributions to knowledge and practical significance are discussed in Chapter 9.

Outline of Thesis

This thesis consists of 9 chapters. The content of each chapter is briefly outlined in Figure 1.7:1.

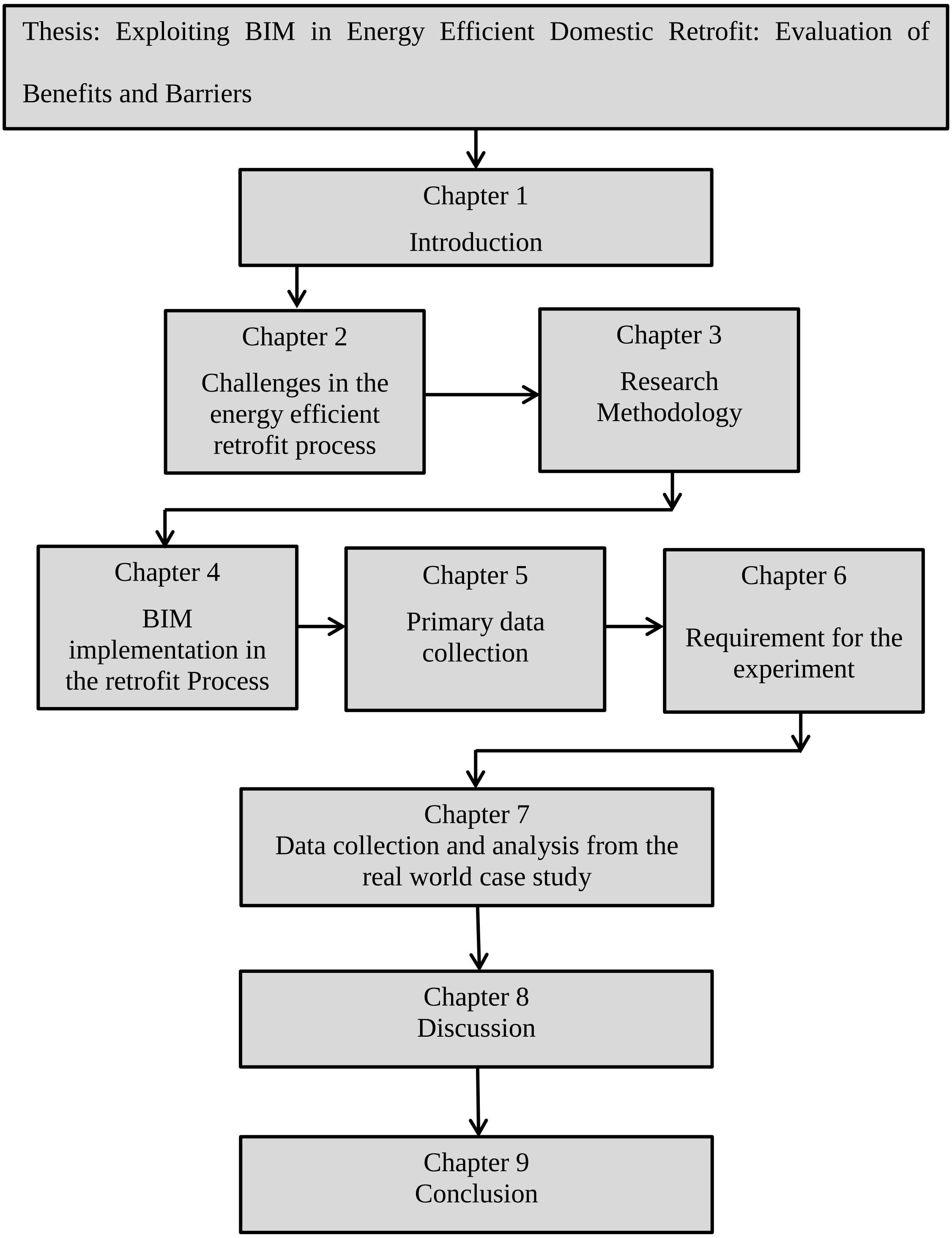


Figure 0:1: Thesis outline

Chapter 1 explains the importance of energy-efficient retrofit of domestic stocks to reduce the CO_2 emissions and common misconceptions to implement BIM to improve the existing practices. It follows by introducing research aim and objectives; research methodology research questions; and outline of thesis.

Chapter 2 will examine the challenges in the energy-efficient retrofit process by determining the importance of energy-efficient retrofit in the UK; reviewing key phases and measure in energy efficient retrofit process; and analysing barriers to achieve the energy efficient retrofit process including behavioural, financial, political, education and skill, social and technical barriers.

Chapter 3 will provide an overview of the research methodology used in the field of built environment. It will present and justify the research method adopted in this research. The chapter ends with a description of the methods used in this research include: literature review, interviews with industry and academic experts, a real world case study and simulations.

Chapter 4 will explore the enablers and barriers to improve the existing practices through exploiting BIM in small-scale retrofit process by examining the challenges to implementing BIM in existing building including data capturing techniques and lack of interoperability between BPS and BIM tools; and reviewing two main capturing techniques and four different types of interoperability methods.

Chapter 5 will explore professional perspectives towards challenges in the energy-efficient retrofit process, and BIM potentials and barriers in energy efficient retrofit process. Chapter 4 involves an introduction to the interview design; the adopted methodology; data analysis through NVivo; and interview results.

Chapter 6 will provide an overview about the required tools for BIM and automatic rule-based checking which are essential for the experiment. Two widespread BIM tools, namely Revit and ArchiCAD, regarding their file formats and their interoperability with energy simulation tools will be discussed. Then the automated rule-based checking; and two commercial applications, Fornax and Solibri Model Checker (SMC), will be discussed to select the right model checking software for this research.

Chapter 7 will introduce the adopted real world case study, discuss the results of existing building energy simulation practices and BIM simulation approaches and compare those with the results of a monitored house over a two-year period to evaluate their accuracy and efficiency. Chapter 7 also includes an introduction to implemented energy efficiency measures in the case study; evaluating the potential issues and efficiency of existing building energy simulation practices; determining the steps to model in a BIM tool (ArchiCAD); examining the quality of the model via SMC; evaluating and discussing the potential of BIM simulation approaches (integrated BIM and interoperable BIM), and their limitations to be used in the retrofit process.

Chapter 8 will study two other projects commenced implementing BIM in the domestic retrofit process to explore how these projects have benefitted from BIM implementation in small-scale retrofit projects and also if BIM implementation has faced challenges which are identified by the author in this research.

Chapter 9 will conclude the study by summarising the research significance, the main findings, the limitation of the research and future research direction.

Chapter Two

Challenges in the Energy Efficient Retrofit Process

2 Literature Review: Challenges in the Energy Efficient Retrofit Process

Introduction

In the UK around half of primary energy consumption and CO_2 emission is related to the built environment (Stafford, et al., 2012). Figure 0:1 presents the changing level of energy consumption by sector from 1970 to 2014 in the UK. In 1970, the domestic sector was responsible for 24 % of energy consumption and it had risen slightly to 27 % in 2014 (DECC, 2015a). More than 50% of emissions of energy use in buildings are related to the housing stocks and it accounts for 27% of total energy use in the UK (Rickaby & Willoughby, 2014).

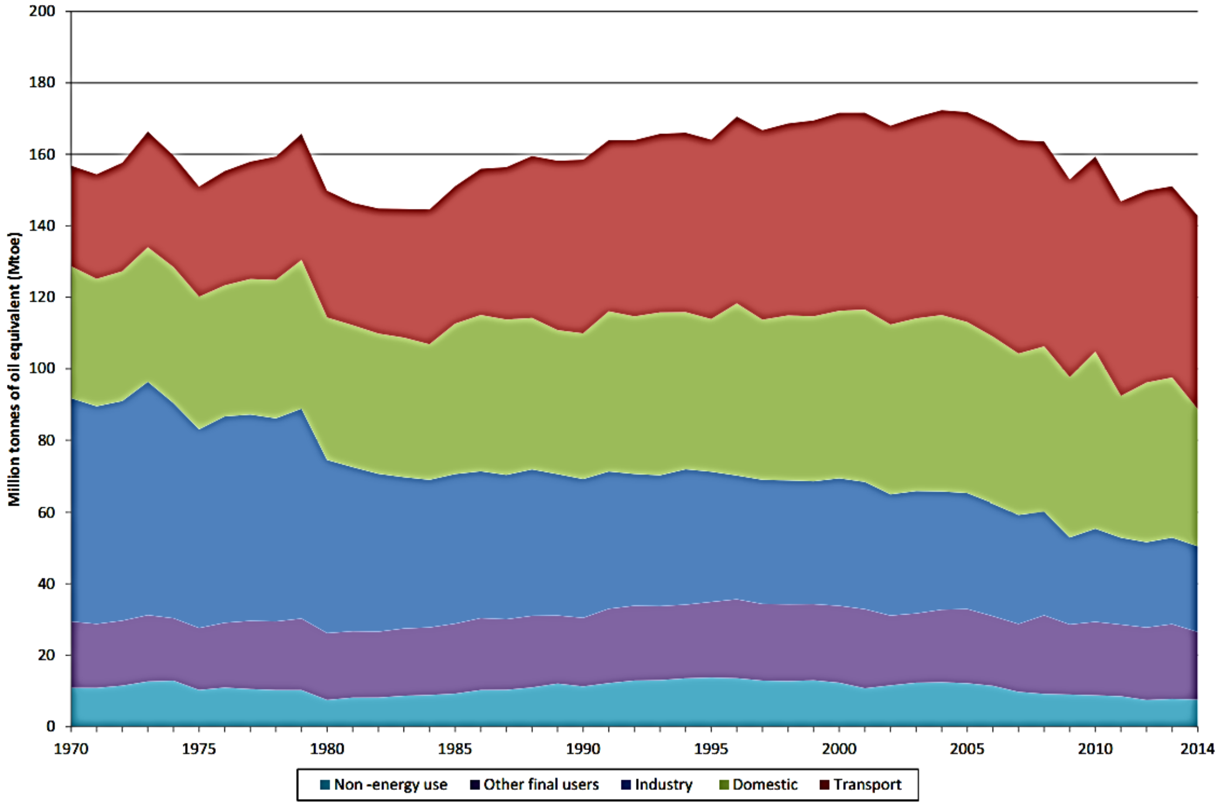


Figure 0:1: Final energy consumption by sector 1970 to 2014, UK (DECC, 2015a)

Policy makers believe that the most cost-effective approach to reduce CO_2 emissions by 80% compared to 1990 levels by 2050, and to meet the UK climate change target, is an energy-efficient retrofit of domestic stocks (Lewis, 2014; Legislation.gov.uk., 2008). Reducing the energy use of existing buildings through energy-efficient retrofitting provides considerable opportunities to lessen CO_2 emissions and alleviate environmental degradation (Ma, et al., 2012).

This chapter reviews the importance and challenges in the retrofit process and it is structured as follows: Section 0 provides a description of the segmentation of homes according to type and age of dwelling over time in the UK and importance of energy efficient retrofit in the UK. Section 0 reviews the building retrofit measures and five key phases in the retrofit process. The barriers to achieving energy efficiency in the retrofit process including behavioural, financial, political, social, education and technical barriers are critically reviewed based on the existing literature in section 0.

Energy-efficient retrofitting of existing housing

New homes will have to be more energy efficient in the future. However, since the replacement rate of new dwellings has been less than 1% per year during the last fifty years, then new build will not have a significant effect, in the short term, to achieve climate change target in the UK (Rickaby & Willoughby, 2014). The problematic area to reduce CO_2 emission is related to existing homes. The UK's existing housing stock is one the oldest in Europe and almost 13 million dwellings were built before 1960 (Baeli, 2013).

The domestic stock has grown by almost 50% in less than fifty years, from 18 million in 1976, and it is assumed to rise to 27 million by 2020 (Rickaby & Willoughby, 2014). It is estimated that over 70% of the housing stock will still exist in 2050, including 4.7 million of the least energy efficient homes that were built before 1919 (Baeli, 2013; DECC, 2012). In the domestic sector, only 0.3% of CO_2 emissions are associated with new housing and 99.7% of CO_2 emissions are related to existing homes in past years (Rickaby & Willoughby, 2014). Figure 0:1 and Figure 0:2 illustrate the segmentation of homes according to age and type of dwelling over time in the UK.

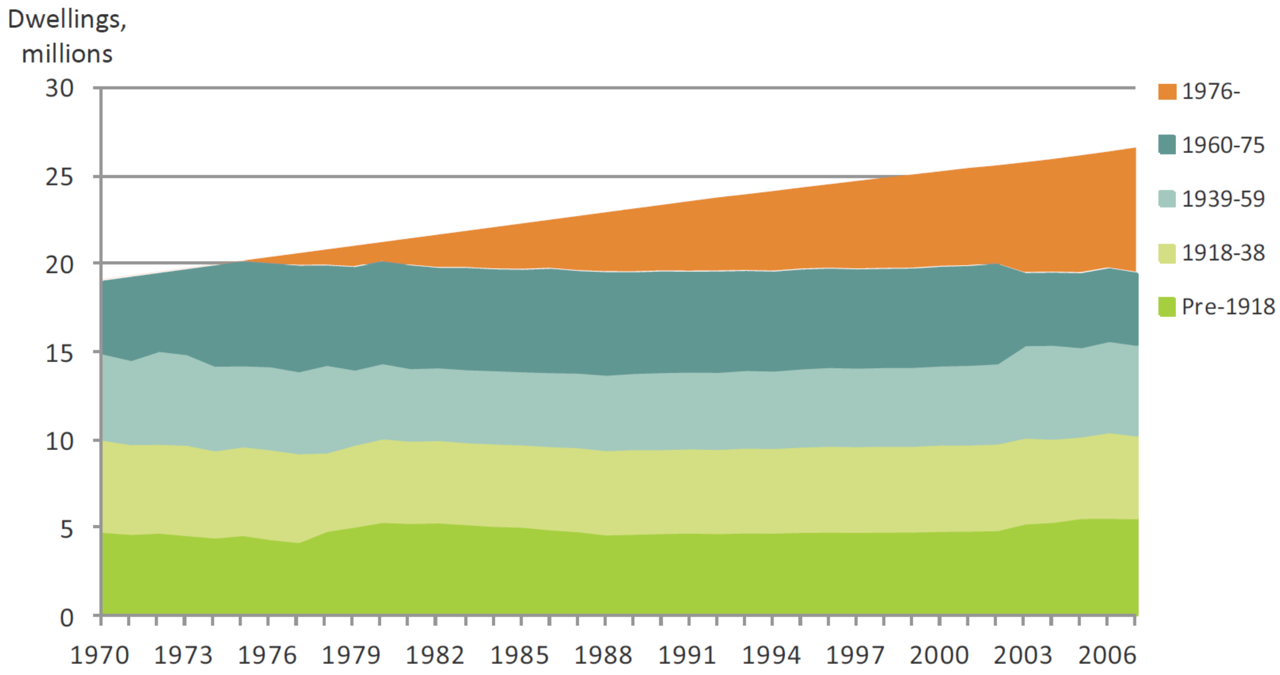


Figure 0:1: Housing stock distribution by age to 2007 (millions) (Palmer & Cooper, 2012)

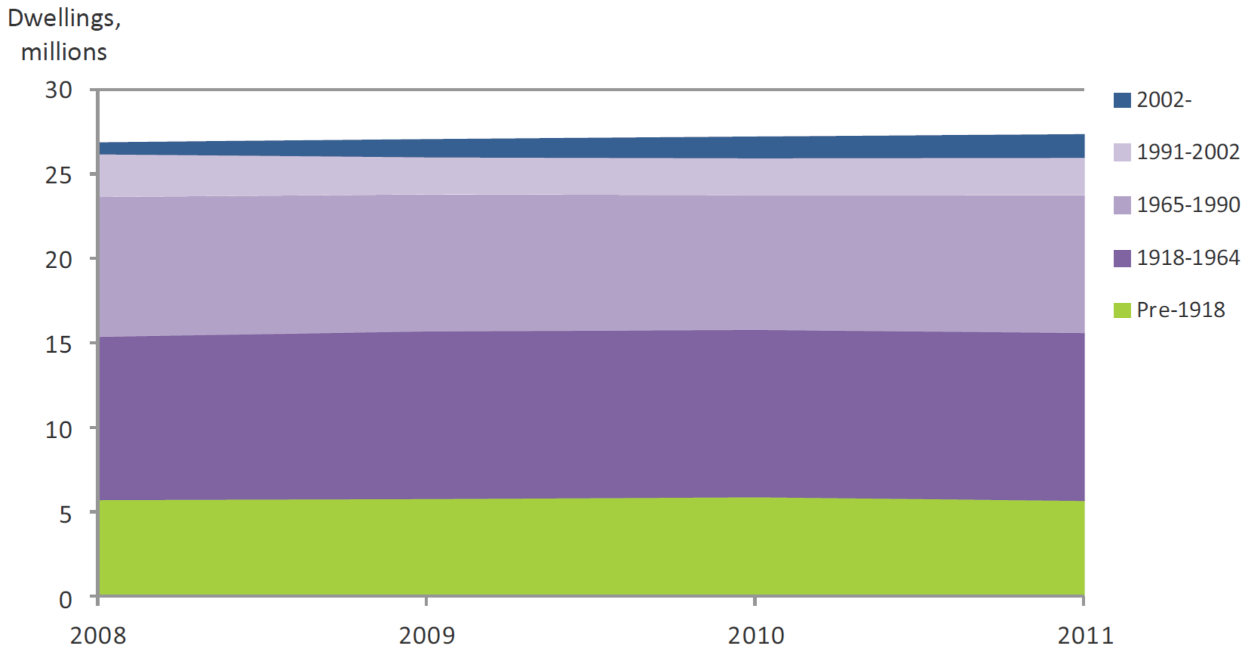


Figure 0:2: Housing stock distribution by age 2008-2011 (millions) (Palmer & Cooper, 2012)

During the last decade, the energy efficiency of existing buildings has been addressed by many international and governmental organisations. In the UK, the International Energy

Agency (IEA) has commenced a series of Annex projects to improve the retrofit process by providing technical support and policy guidelines such as Annex 46, 50, 55 and 56 (IEA, 2011). Also, in 2010, the UK Government set the target to reduce CO_2 emissions by 29% through upgrading the energy efficiency of seven million of existing homes by 2020 (DECC, 2012a). In general, owing to these schemes and a better understanding of building physics, approximately 50% of the energy consumption of domestic buildings, has reduced from 1991 onwards (Baeli, 2013). To achieve energy efficient homes, a wide range of considerations need to be addressed throughout various phase of retrofit and necessary steps and a multi-disciplinary approach have to be taken (Torgal, et al., 2014).

2.1.1 Importance of energy efficient retrofit of housing

Increasingly, retrofit is becoming an essential economic driver for the Architecture, Engineering and Construction (AEC) industry in the UK (Rahmat, 1997). Improving the energy efficiency of buildings through retrofit offers substantial benefits. In the UK, Mills & Rosenfeld (1996) identified several motivations to improve the energy efficient measures in the retrofit process. At the national level, it can improve energy security by lessening oil imports, enhance competitiveness, create jobs, alleviate environmental degradation and reduce pollution (Mills & Rosenfeld, 1996). However, consumers and decision-makers are usually motivated by non-energy benefits to adopting energy efficient measures. Non-energy benefits include enhanced indoor environmental quality, health, and safety; noise reduction; saving labour and time; improved process control; improved amenity; saving water; waste reduction; and economic benefits from elimination or reduction of equipment (Mills & Rosenfeld, 1996). However, implementing energy-efficient retrofit process is confronted with several challenges. These challenges are studied in section 0 in more detail.

Building retrofit measures

To improve the energy efficiency of existing buildings, retrofit measures can be classified into three main categories - measures associated with demand-side management, energy consumption patterns, and supply side management (Ma, et al., 2012). This research focuses more on the measures associated with demand-side management to decrease energy demand and, to a lesser extent, on the energy consumption patterns, by considering influencing human factors which can be improved by BIM implementation in the retrofit process. Demand side management is affected by multifaceted factors. These factors include building fabric insulation, opening retrofit, air tightness, ventilation, lighting upgrade, energy efficient appliances, thermal storage, heat recovery, control system and so forth (Ma, et al., 2012). For example, Figure 0:1 represents the heat loss associated with diverse elements in the uninsulated building. It represents the energy lost is due to poor condition of building fabrics (Carbon Trust, 2012).

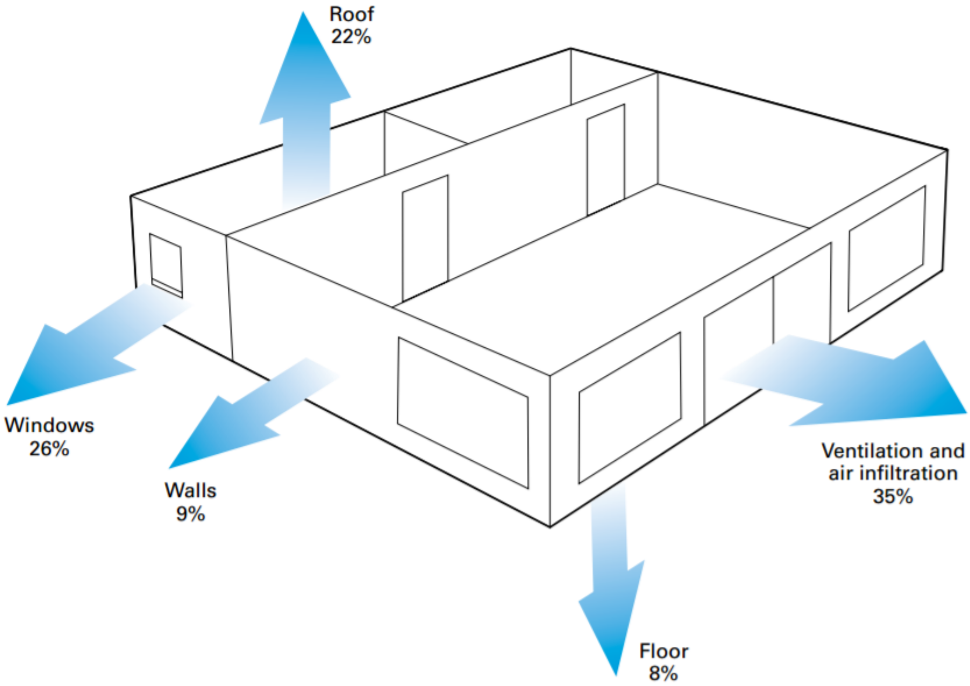


Figure 0:1: Breakdown of heat loss (Carbon Trust, 2012)

2.1.2 Key phases in the retrofit process

An energy efficient building retrofit process can be broken down into five main stages. The first stage comprises pre-retrofit survey and the set-up of the project. The scope and targets of the project need to be defined by stakeholders or their representatives. To obtain a better understanding of operational problems and residents' concerns, a pre-retrofit survey is required, then the available sources and budget can be established (Ma, et al., 2012).

The second stage is an energy audit to understand how the building uses energy, evaluate building energy data, and recognise areas with energy waste (Alajmi, 2012). Furthermore, inefficient equipment, services systems, facilities and inappropriate control schemes need to be identified (Ma, et al., 2012; Jaggs & Palmer, 2000). Energy audits play a key role to achieve an efficient process for energy-efficient retrofit. Energy audits are varied in depth and ranges and they should be selected based on the required levels of accuracy, the scope of the project, project goals, and budget. Energy audits can be divided into three levels including - walk through evaluation, energy survey and detailed energy analysis (Standards Australia, 2000; ASHRAE, 2011). This stage is essential, since the parameters and information in the model need to be calibrated through the data of energy audit to identify the optimal solution among various possible options via energy simulation model (Ascione, et al., 2011).

The third stage is the identification of retrofit alternatives and the optimisation of retrofit options based on the intended purpose of the retrofit process. A range of retrofit options can be classified and optimised based on the related factors to the energy and non-energy related factors, such as energy, technical, environmental and regulations (Haapio & Viitaniemi, 2008; Reed, et al., 2009). To assess retrofit alternatives quantitatively, the energy simulation, cost estimation and risk management can be implemented (Kreith & Goswami, 2008). The cost effective and energy efficient retrofit measures can be identified in the second phase through the energy audits.

The fourth stage is the on-site implementation of a range of selected retrofit measures and then commissioning process to assure all components and systems operate as they are designed and installed for (Ma, et al., 2012; Tobias & Vavaroutsos, 2009).

The fifth stage is post-occupancy measurement, verification and evaluation (AEPCA, 2004). Energy saving measures need to be validated and verified. Post occupancy evaluation includes systematic evaluation of occupants' opinions about the building and its performance. It assists in understanding whether the performance of the building meets the requirements of end users and owners. It involves the identification of ways to improve the performance of the building to make sure measures are well tuned and occupants are satisfied (AEPCA, 2004).

To achieve an efficient process for energy efficient retrofit, it is essential to follow these five stages. However, there are many factors affecting the success of retrofit projects comprising building regulations and policies, unique characteristics of each building, human factors, retrofit technologies and facilities, occupants' expectations, human factors, available resources and uncertainty factors (Ma, et al., 2012).

2.1.3 BPS-based energy efficient retrofit process

Selecting an appropriate retrofit strategy is a complex endeavour and a wide range of consideration needs to be addressed (Koehn & Towers, 1982; Boyd & Weaver, 1994; Kolokotsa, et al., 2009). Building Performance Simulation (BPS) tools play a key role in simulating the alternative options and evaluating the performance before implementation (Peltomäki, 2009; Doukas, et al., 2009; Beaven, 2011).

To implement optimal retrofit strategies, it is essential to analyse existing conditions, the requirements of stakeholders and end-users, and limitations of the project, as shown in Figure 0:2 (Mondrup, 2014).

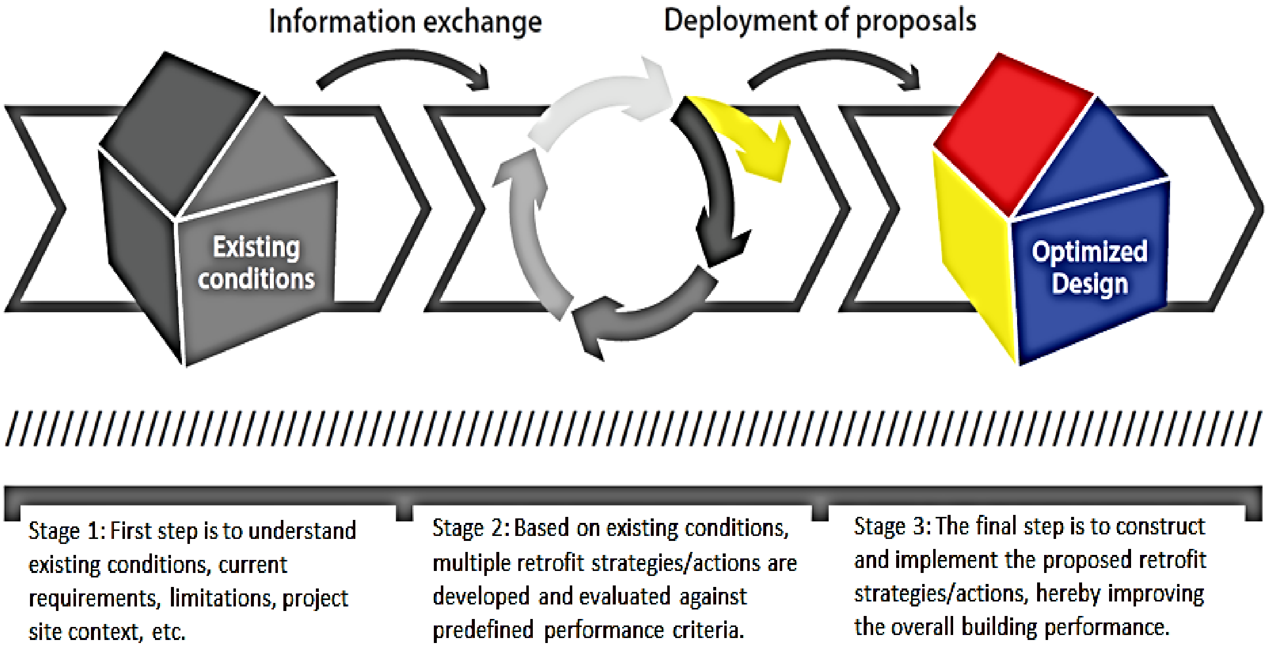


Figure 0:2: BPS-based retrofit design process (Mondrup, 2014)

Then, based on existing conditions and predefined energy performance criteria, possible solutions are developed and simulated to choose optimal retrofit strategies, leading to informed decision-making at the early design stage (Mondrup, 2014; Shaviv, et al., 1996). If the simulation results are not satisfactory to meet predefined energy performance criteria, the retrofit strategies are changed or modified to meet the energy performance criteria (Attia, 2012). This iterative procedure is illustrated in Figure 0:3.

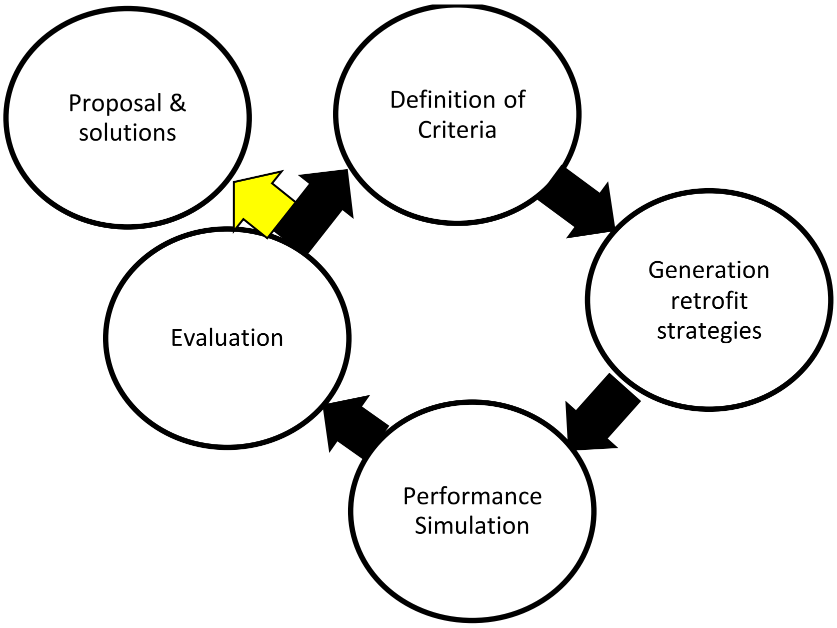


Figure 0:3: The iterative decision support process. (Adapted from Tanimoto, et al., 2001; Alanne, 2004).

Describing Barriers in Retrofit Process

An efficient process for energy efficient retrofit provides considerable benefits to the AEC industry. However, it has been faced with several challenges. Generally, the retrofit process is considered more complex than new build (Koehn & Towers, 1982; Boyd & Weaver, 1994). In this section, challenges to achieving an efficient process for energy efficient retrofit are discussed, including social barriers, financial barriers, political barriers, education barriers, disruption to users, and technical barriers. Critically reviewing the challenges and, on the other hand, identifying the potential of BIM for small scale retrofit projects (explained in chapter 4), assisted the researcher to link and propose solutions to address the issues in the current situation.

2.1.4 Behavioural barriers

One of the challenges to carrying out energy efficient retrofits is social and behavioural barriers. Home occupants play a critical role in energy efficiency measures alongside the technical and financial incentives (JANDA, 2011). The lack of occupants' knowledge and unwillingness to adopt energy efficient measures are considered as complex issues to boost the uptake of energy-efficient retrofit (Crosbie & Baker, 2010). According to Crosbie and Baker's survey (2010), the improvements in technological issues and state of the art approaches cannot be effective without the cooperation of building occupants. If occupants are not willing to engage with the installation and utilisation of energy efficient heating or lighting effectively, then the expected efficiencies cannot be achieved, regardless of how much these energy efficient measures hypothetically could be saving energy (Crosbie & Baker, 2010). Therefore, to boost the uptake of energy efficient retrofit, it is critical to enhance end-users' knowledge about the benefits achieved by energy efficient retrofit measures. It is necessary to understand why and how inhabitants react to these measures.

In addition, there is a lack of appropriate communication and collaboration approaches amongst occupants, designers and contractors, which result in some misconceptions in the retrofit process (Crosbie & Baker, 2010). Misunderstandings by homeowners due to insufficient levels of knowledge about the building, and the lack of a comprehensive method at the early stages of retrofit, are considered as social obstacles accompanied by technical challenges in the retrofit process (Crosbie & Baker, 2010). In order to avoid misunderstandings, designers and contractors should be able to clarify the options in a way that helps occupants to understand the impacts of their decisions (Crosbie & Baker, 2010; Ma, et al., 2012). However, due to the lack of a comprehensive method at the early stages of retrofit occupants are not able to understand the benefits and limitations of different options and challenges arise for users to make decisions (Crosbie & Baker, 2010). Hence, to implement new technologies, the communication methods between contractors and clients should be reconsidered; residents should have a comprehensive understanding of what is happening in the retrofit process (Crosbie & Baker, 2010). Moreover, post-occupancy evaluation (POE) and maintenance should be considered to ensure inhabitants do not encounter technical problems causing occupants' dissatisfaction (Crosbie & Baker, 2010). There is an urgent need to contemplate a systematic approach to make stakeholders informed about the potential benefits of retrofit and protect them against post-occupancy difficulties (Crosbie & Baker, 2010).

Pelenur and Cruickshank (2011) studied social barriers to adopting energy-efficient measures through interviews with 198 participants gathered by random sampling street interviews in Manchester and Cardiff. Their results revealed a range of social barriers to achieve energy efficient retrofit including general unwillingness to change lifestyle, mistrust of energy companies or contractors and their services, and socioeconomic issues. To reduce the energy consumption, it is critical to understand the crucial importance of social barriers alongside the technical, financial and informational aspects of the retrofit process to minimise rebound effects (section 2.1.4.2) and energy efficiency gap (section 2.1.4.1) (Pelenur & Cruickshank, 2011).

2.1.4.1 Energy Efficiency Gap

From psychological and sociological perspectives, overlooking the importance of social and behavioural factors on energy decision has posed obstacles to achieving energy efficiency during the retrofit process (Lutzenhiser, 1992; Abrahames & Steg, 2009). This has caused shortfalls between expected results and the full potential of energy efficiency measures, which is known as the "Energy Efficiency Gap" (Jaffe & Stavins, 1994). Occupants' interaction with energy is subjective and treating occupants as rational actors give rise to the Energy Efficiency Gap due to the conflicting market signals and hidden costs or benefits (Lutzenhiser, 1992; Stern, 2006). From socio-economic viewpoints, Jaffe and Stavins (1994) claimed that market and non-market failures, such as lack of comprehensive information about the potential of energy efficiency measures and transaction costs of implementing energy-efficient retrofit measures, result in Energy Efficiency Gap. Various empirical and exploratory studies have argued that adopting energy efficiency measures has not necessarily changed occupant's energy consumption (Shipworth, et al., 2010; Pelenur & Cruickshank, 2013). To reduce the energy consumption and achieve energy-efficient retrofit, policy makers should contemplate social and behavioural factors such as individual's cognitive abilities, attitudes, values and social networks (Faiers, et al., 2007).

2.1.4.2 Rebound Effect

In addition to the Energy Efficiency Gap, the 'Rebound Effect' poses another social barrier for energy-efficient retrofit. William Jevons (1906) called this phenomenon "Khazzoom-Brookes postulate" for the first time in late 19th century (Madlener & Alcott, 2009). Three types of Rebound Effects from energy efficient measure are categorised in the literature; direct, indirect and economy-wide rebound effects. This research strives to reduce energy consumption by minimising the direct and indirect rebound effects. Barker, et al. (2007, p. 4935–4936) explain direct and indirect rebound effects as follows:

"Direct rebound effects: Improved energy efficiency for a particular energy service will decrease the effective price of that service and should therefore lead to an increase in consumption of that service. This will tend to offset the expected reduction in energy consumption provided by the efficiency improvement.

Indirect rebound effects: For consumers, the lower effective price of the energy service will lead to changes in the demand for other goods and services. To the extent that these require energy for their provision, there will be indirect effects on aggregate energy consumption."

Therefore, to reduce the energy consumption, it is essential to obtain a better understanding of how occupants interact and consume energy. Wilson and Dowlatabadi (2007) established an integrated model of proenvironmental behaviour (Figure 0:1) to visualise household decision making in the context of domestic energy use (Wilson & Dowlatabadi, 2007). The model is not presenting specific behaviour; however, individual and contextual domains are distinguished (Wilson & Dowlatabadi, 2007).

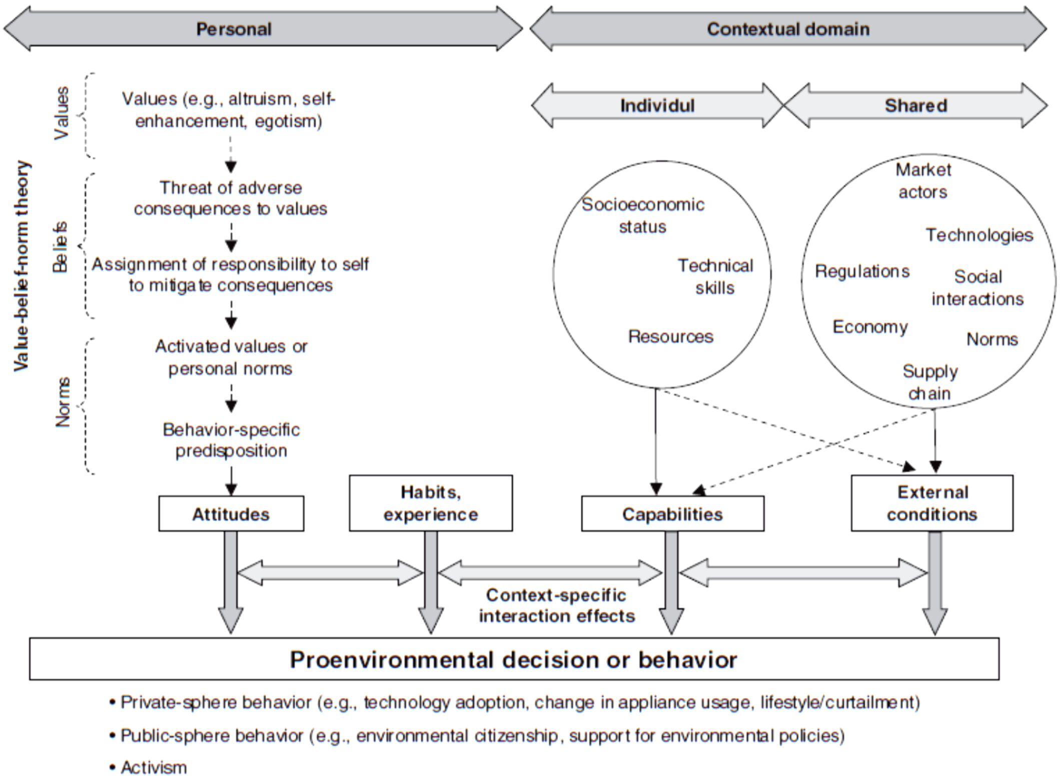


Figure 0:1: Integrated model of proenvironmental behaviour (Wilson & Dowlatabadi, 2007)

This section presented the importance of social and cultural factors alongside technical factors in energy efficient retrofit. These factors are overlooked in the current situation and lead to energy efficiency gap and rebound effects (Pelenur & Cruickshank, 2011). Adopting interdisciplinary research between engineering and socio-technical research can help overcome this challenge (Lutzenhiser, 1992; Abrahames & Steg, 2009).

2.1.5 Financial barriers

According to the Pelenur and Cruickshank's study (2011) through 198 interviewees, the cost of energy efficiency measures is identified as one of the main barriers with approximately 25% of respondents.

The economic barriers are mostly associated with the perceived costs by the general public and uncertainty over the payback period of energy efficient measures (Pelenur & Cruickshank, 2011). Also, the upfront cost of energy efficiency measure is one of the main challenges to achieving energy-efficient retrofit (Webber, et al., 2015). The UK government has addressed this challenge to some extent through introducing several schemes and initiatives, such as the Carbon Emissions Reduction Target (CERT) and Community Energy Saving Programme (CESP). However, these initiatives are not addressing all the requirements of diverse types of owners with limited funds or solid walled house, or are only available for those on low-income levels (Mallaband, et al., 2011). To assist occupants to achieve more efficient home, the initiative the Green Deal was established in December 2010 (DECC, 2011a). Green Deal introduced a "*framework to enable private firms to offer consumers energy efficiency improvements to their homes, community spaces and businesses at no upfront cost, and recoup payments through a charge in instalments on the energy bill*" (DECC, 2011a). The Green Deal has not delivered the levels of success that was expected and had thus far failed to persuade large numbers of occupants to undertake Green Deal plan (Marchand, et al., 2015; Harvey, 2013). The Green Deal does not cover all the cost, and the interest rate is too high (Lewis & Smith, 2014). The failure is due to a distinct lack of awareness and understanding of residents of the Green Deal, high assessment costs, high-interest rate for a Green Deal loan, and uncertainty about the actual savings that it claims (Marchand, et al., 2015; Harvey, 2013; Collinson, 2014). Figure 0:2 demonstrates the assessment and installation and how it becomes a Green Deal plan (DECC, 2010).

There is a lack of transparent information related to the benefits of adopting energy efficiency measures (Marchand, et al., 2015). If perceived benefits of retrofit measures and payback period can be identified, the challenges associated with financial barriers will be minimised (Pelenur & Cruickshank, 2011).

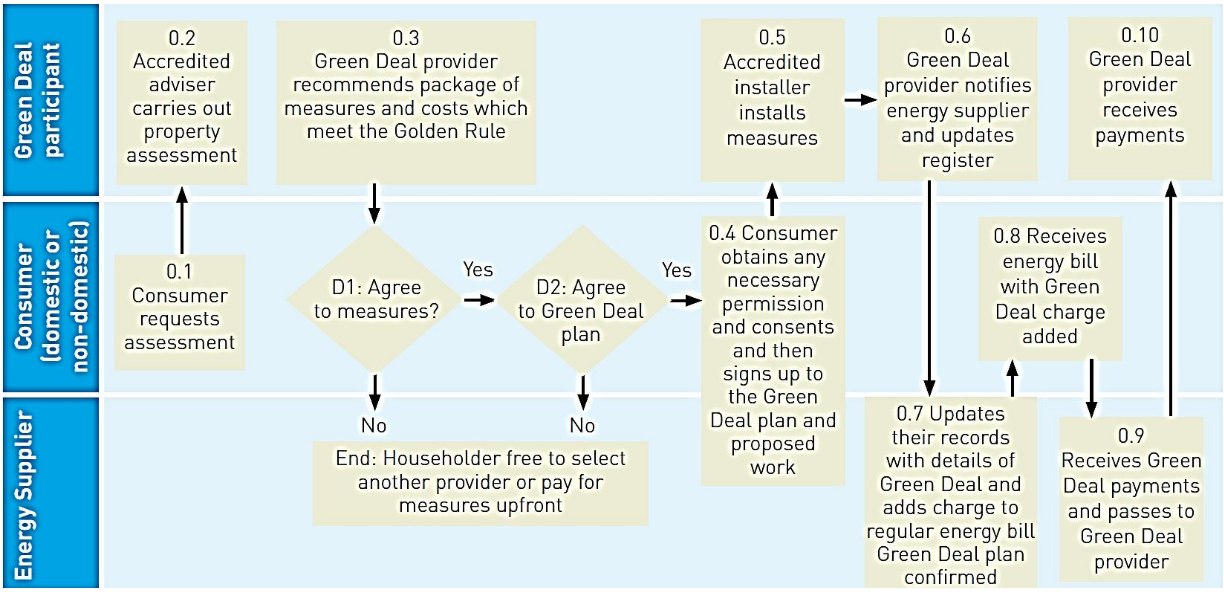


Figure 0:2: Diagram: Green Deal Plan (DECC, 2010)

However, if the benefits of energy efficiency measures are not correctly valued by homeowners/tenants, then decreasing the cost of energy efficiency measures may not necessarily develop its up-take (Pelenur, 2013). Also, information solely is insufficient to alter behaviours (Crompton, 2010). It is essential to motivate householders by factors such as increasing comfort level, saving money and transparent information on required efforts and actual benefits (Steg, 2008). Financial barriers are considered as the main challenge to implementing energy efficiency measure in the residential sector.

2.1.6 Political barriers

Political barriers consist of lack of transparency of roadmap from government, low standards and lack of legislation to go beyond building regulations (Lewis & Smith, 2014).

2.1.6.1 Building regulations

Prior to 1966, implementation of building regulations was more adoptive rather than compulsory. Towns and counties commenced introducing their own local acts and, building regulations were widely varied throughout the country (Ceredigion County Council, 2010). The mandatory national building regulations and building standards were established in 1965 (Ceredigion County Council, 2010). Thereafter, Building Act 1984 officially introduced the concept of using Approved Documents to execute varied aspects of the building (Building Act, 1984). Minimum targets for domestic energy efficiency requirements for existing dwellings set out in 'Approved Documents L1B: Conservation of fuel and power in existing dwellings' (Planing Portal, 2011). Building regulations play a key role to reduce the CO_2 emission and conserve fuel and the regulated U-Value has upgraded on average by 70% from 1966 to 2010 as it shows in Table 0:1 (Planing Portal, 2011).

These improvements illustrate the importance of building regulation from 1966 with no national building regulation to 2010 (Chow & Levermore, 2010). In the UK the energy performance of the dwellings can be estimated by Standard Assessment Procedure (SAP) (GOV.UK, 2014). In section 2.1.6.2 Standard Assessment Procedure, its advantages and associated issues are studied.

Table 0:1: Comparison of the standard maximum permitted U-Value of construction elements in the UK Building Regulations from 1965 to 2010 (Planing Portal, 2011; Chow & Levermore, 2010).

Year of Buildings Regulation	U-Value (W/m^{2}K)				
	Wall	Window	Floor	Roof	Door
1965	1.70	5.60	1.42	1.42	3.00
1976	1.00	5.60	1.00	0.60	3.00
1984	0.45	3.30	0.45	0.25	3.00
1995	0.45	3.00	0.35	0.20	3.00
2002	0.35	2.20	0.25	0.20	2.20
2010	0.30	2.00	0.25	0.20	2.00

2.1.6.2 Standard Assessment Procedure (SAP)

The Building Research Establishment (BRE) developed SAP as a tool to assist delivery of energy efficiency policies in the Department of the Environment in 1992 for new buildings (GOV.UK, 2014). *"SAP is the methodology used by the government to assess and compare the energy and environmental performance of dwellings."* (GOV.UK, 2014). In 1994 to assess dwelling performance, SAP was used in Part L of the Building Regulations. Reduced Data SAP (RDSAP) was introduced as a methodology with lower cost to assess the energy performance of existing properties in 2005 (GOV.UK, 2014). In RDSAP, to cover incomplete or missing information, additional default standard values are added to the energy model. Although this reduces the time to carry out building performance assessment by reducing the data requirements, the accuracy of building performance simulation is reduced with the default standard values (Kellya, et al., 2012).

SAP, RDSAP and such schemes provide a common standard in which all buildings can be compared and estimated. These certification schemes and national building performance standards clear up the confusion related to the energy performance of the buildings. Therefore, by increasing the disclosure of information, market competition has improved (Kellya, et al., 2012). In the current situation, SAP as an independent calculation methodology forms the backbone of government policy to estimate building performance in the UK. SAP has been fully incorporated to deliver the EU Energy Performance of the Building Directive (EPBD), the creation of Energy Performance Certification (EPC), measuring the energy performance in part L1A and L1B Building Regulations, Code for Sustainable Home (CSH) and many other policy instruments and schemes (Kellya, et al., 2012).

SAP ratings have measured energy performance through notional assumptions and an index calculated from a collection of different building components, frequently leading to suboptimal solutions. It has provided developers with an option to meet the minimum SAP requirement by a mix and match of different building elements, resulting in suboptimal outcomes (Kellya, et al., 2012). For example, installing condensing gas boiler instead of insulating building fabric is more cost effective to meet SAP requirements. This results in suboptimal solution since lifecycle cost is not taken into consideration in SAP calculations. The most cost effective CO_2 emission reduction over the whole lifecycle of building is upgrading building fabrics rather than replacing boilers as it shows in Table 0:2 (Kellya, et al., 2012).

Nevertheless, developers wishing to meet minimum SAP requirements and regulatory compliance prefer to choose the option with the least capital at the time of installation (Kellya, et al., 2012). To compare the most cost-effective CO_2 saving measures, the net annual cost (NAC) approach should be used since expected life of energy efficient measures are left out of the SAP rating. For example, expected life of cavity wall insulation is more than 40 years while a condensing gas boiler's lifetime is 15 years (Kellya, et al., 2012).

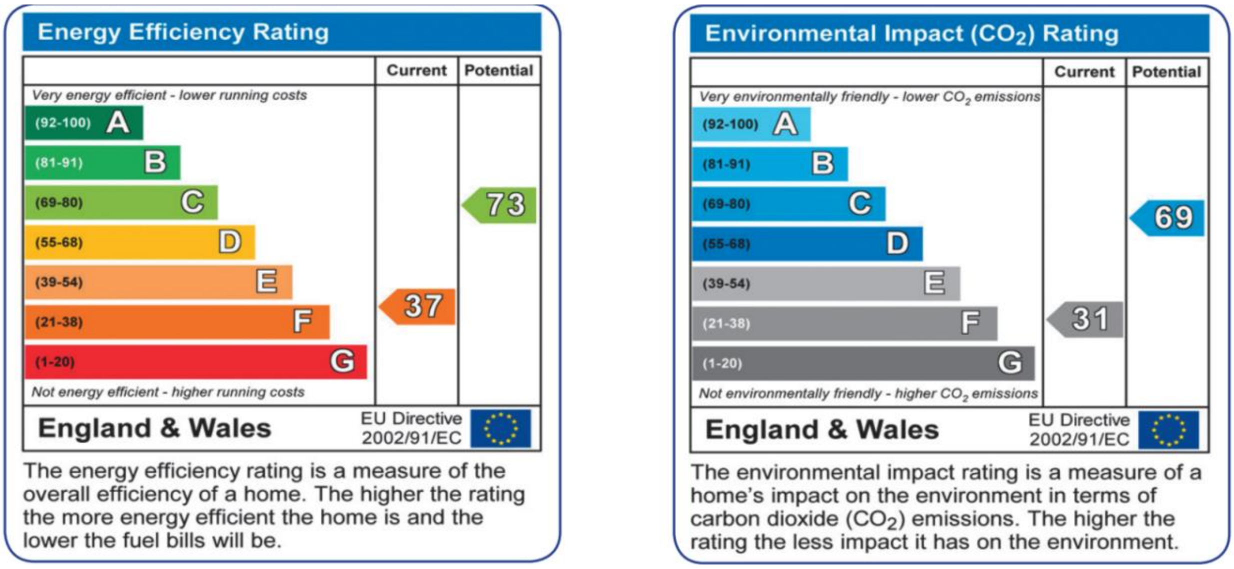
Since different building efficiency measures have different estimated life span, SAP ratings need to include this factor to achieve the most cost-effective measures over the whole lifecycle of buildings that at present these factors are left out of SAP calculation (Kellya, et al., 2012).

Table 0:2: Typical costs and CO_2 savings for UK dwellings (Shorrock, et al., 2005)

	Energy Consumption	**Difference in cost of installation**	**Annual energy savings**	**Lifetime**	**End of life carbon savings**	**Net annual cost**
	KW h/year	£	£/year	Years	$KgCO_2$/year	£/year
A/B rated boiler	14,623	£50	57	15	5,610	-£53
With roof insulation	11,687	£339	87	40	27,840	-£71
With cavity insulation	10,783	£406	133	40	35,480	-£144
Glazing E to C rated	14,542	£253	14	20	1,760	-£4
Hot water cylinder insulation	14,059	£20	29	10	1,945	-£27

2.1.6.3 Energy Performance Certificate (EPC)

To meet the requirements of the Energy Performance of Buildings Directive 2002/91/EC, the UK government introduced Energy Performance Certificates (EPC) in 2007 (Planing Portal, 2007). It is an important strategy to tackle climate change by making the energy use in dwellings transparent through the issuing of a certificate. To meet the EU's Energy Performance of Building Directive, the updated EPC must be provided whenever a property is sold, rented or built (Department for Communities and Local Government, 2011). The EPC is based on the SAP calculations for new buildings and RDSAP for existing buildings and it shows the energy efficiency on an A-G rating scale like those used for electrical appliances (Figure 0:3) (Department for Communities and Local Government, 2011). The EPC is not only a simple tool to compare buildings as a policy instrument for decreasing CO_2 emissions, but it also successfully stimulates the transition to more energy efficient buildings (EPBD, 2011). The energy performance of buildings provides occupants with the opportunity to make a well-informed decision. This certificate, by informing occupants about the energy performance of the building, motivates them to implement energy efficient retrofit that drives value in the property market (Kellya, et al., 2012). The EPC facilitates the exchange of information between the sellers and buyers. According to the research from Energy Saving Trust (2006), approximately 70% of buyers are prepared to pay more for an energy efficient home. The EPC may motivate the sellers to improve the building performance of homes to improve their market competition (Kellya, et al., 2012).



The energy efficiency rating is a measure of the overall efficiency of a home. The higher the rating the more energy efficient the home is and the lower the fuel bills will be.

The environmental impact rating is a measure of a home's impact on the environment in terms of carbon dioxide (CO_2) emissions. The higher the rating the less impact it has on the environment.

Figure 0:3: SAP and Environmental Impact rating for energy performance certificates (EPC) in England and Wales (Energy Efficiency Partnership for Homes, 2008)

In the UK, although the EPC includes scale ratings, Environmental Impact rating and related information on the estimated running cost of service types of buildings, the information has limited usefulness (Kellya, et al., 2012). Kellya (2012) suggested that if the average building performance was given by the same category of building in terms of construction materials, ages, size and building type, then owners could be provided with more comprehensive information, in particular building category and make it transparent why their building under-performing.

Furthermore, another drawback of EPC is associated to cost estimation using a simple payback calculation. Although one of the valuable information on the EPC is about its recommendations for cost-effective energy efficient measures, it is not accurate and reliable (Kellya, et al., 2012). This approach has several drawbacks owing to the sensitivity of this approach to cost changes and it does not consider the anticipated future prices of energy. Using Net Present Value (NPV) or Internal Rate of Return (IRR) would be a more accurate cost estimation for improving the performance of the building (Kellya, et al., 2012). Since the UK government established an annual anticipated future price of energy, using it could be helpful to improve the accuracy of cost estimation and has a profound effect to realistically evaluate the cost-effectiveness of different energy efficient measures. EPC includes recommendations for cost-effective measures categorised into 'lower cost measures', 'higher cost measures' and 'other solutions' (Kellya, et al., 2012). The EPC certificate in the 'potential column' contains only improvements with lower cost and it has posed a real challenge to residents with little or no knowledge, since it is estimated using simple payback calculation without considering the future cost of energy (Oxera, 2006; Kellya, et al., 2012). The 'other solution' category provides recommendations with longer payback period. It misleads residents to evaluate which approach has a lower cost with actual energy consumption over the lifespan of energy efficient measures (Kellya, et al., 2012).

One of the challenges to applying EPC is related to the cost of carrying out the assessment. Carrying out an EPC is taxed at the full rate of 20%, while the VAT rate on energy consumption for heating like natural gas is set at 5% (Banks, 2008). Banks (2008) recommends this government policy with the wrong message to occupants and owners needs to be changed to reduce such apprehension. The calculated energy consumption is very different with actual energy consumption and sometimes varies by as much as three times that indicated on the EPC (Kellya, et al., 2012). While sociodemographic variables explain much of the variance, it may have a harmful effect on the reliability of EPC. Improving EPC through accurate information over the actual energy consumption of dwellings and enhancing estimated cost on energy efficient measures, improves the credibility of EPC certificate for occupants. Providing occupants with more accurate recommendation over the most cost effective energy saving measures, can assist the UK government to achieve the climate change target and reduce the CO_2 emission (Kellya, et al., 2012).

2.1.7 Education and skill barriers

One of the challenging issues within the construction industry is the chronic shortage of a skilled labour force (Clarke, et al., 2008). In 1994, Latham (1994) reported that there was a lack of education and training within the construction industry. To improve the quality and efficiency of buildings, the upskilling of workers is still a challenging issue in the construction industry (Clarke, et al., 2008). The historical trend towards education, skills and training systems in the construction industry needs to be reappraised in line with rapid technological changes. It is essential that involved bodies in a project have sufficient level of knowledge and skills associated with the state-of-the-art approaches to achieve energy efficient housing (Lowe & Oreszczyn, 2008).

One of the barriers to delivering an energy efficient retrofit process is associated with the knowledge and skill gaps among suppliers, surveyors, designers and installers; they cannot always distinguish and introduce optimal retrofit measures (Mashford, et al., 2015). Furthermore, a lack of coordination and mutual understanding in communication and the fragmented supply chain among different trades has averted supply aside from the full potential of market opportunities and made the consumer journey more complicated (Mashford, et al., 2015). To advise accurate recommendations for energy saving measures, the skills of energy surveyors and assessors are as crucial as the accuracy of software and methodologies used (Smith, 2011). According to Smith (2011), a member of Institute for Sustainability group, energy surveyors should have several essential skills as follows:

Clear Communication skills: They should be able to communicate with homeowners clearly and explain the entire process to assist them in appreciating their roles and possible solutions. The effective communication between energy surveyors and householders lead to identifying an optimal solution.

Good understanding of how energy is used in buildings: As each building is unique and have its own specific requirements and quirks, and different occupants’ attitudes, they should be able to understand and appropriately take them into consideration.

Professional manner and well organised.

Mostly energy surveyor will conduct the energy assessment as well. Energy assessor should have several skills as follows:

Use software proficiently: They should have the ability to enter data and interpret results effectively to present to clients. Also, when errors happen, they should be able to recognise them soon to correct them.

A sufficient level of knowledge is needed of the improvement measures, their cost, limitations and also how the possible sequence of work on the site.

Presenting reports and manage file clearly: the report should be written in a way that can be appreciated by occupants and specialists with different level of knowledge (Smith, 2011). Improving the level of knowledge of involved bodies in a project and expanding their knowledge of the modern technology can improve the energy efficiency of the retrofit process (Lowe & Oreszczyn, 2008).

2.1.8 Disruption to users

One of the main barriers in domestic retrofits is occupants' disruption especially where buildings are occupied (Ciria, 2004; Sunikka-Blank, et al., 2012; Jones, 2013; Chaves, et al., 2016). Whiteman and Irwig (1988) underlined the importance of minimising users' disruption to improve the productivity and efficiency of the retrofit process. In other words, to improve the management of retrofit projects, it is necessary to consider solutions minimising the end-users' disruption (Whiteman & Irwig, 1988; Chaves, et al., 2016). According to Vainio (2011), informing end-users about the issues clearly in advance, may make disruptions better accepted. Haines and Mitchell (2014) highlighted that disruptions may be better accepted if the improvements and results of retrofit measures perceived more significant than scale of disruptions.

Therefore, it is necessary to develop detailed plans for the execution of retrofit and inform the users about the benefits of alternative solutions through transparent communication of costs, time and technical solutions (Sunikka-Blank, et al., 2012; Chaves, et al., 2016).

Chaves, et al., (2016) suggested use of 4D building information models in the retrofit process to cut disruption in housing retrofit while delivering cost-effective and energy efficient solutions. The proposed 4D BIM protocol was verified and validated through evaluating in different project contexts (Chaves, et al., 2016).

2.1.9 Technical barriers

2.1.9.1 Difficulties in effectively measuring energy consumption

In current approaches, architects mostly design buildings and energy specialists then evaluate the energy performance of the buildings by recreating an energy model manually (Bazjanac & Kiviniemi, 2007). It is not only a repetitive and redundant process to recreate a model, but also some of the missing materials data, such as U-values, must be added to an energy model (Bazjanac & Kiviniemi, 2007). Providing the required information to create the thermal view of the building typically occurs after sufficient progress in the architectural and HVAC design. The lengthy process of capturing required information results based on questionable assumptions and documentations can generate unreliable simulation results at the early stage of the process (Bazjanac, 2008a). Furthermore, due to the time and resource limitations, the geometry of the building must be simplified. Therefore, an energy specialist or whoever analyses the energy performance, takes the 2D drawing information and defines their thermal view of the building. This is very subjective and depends on the person’s knowledge, experiences, skills, understanding and the complexity of the building (Bazjanac, 2008a). Different people defining thermal views and geometries of the same building will generate definitions and geometries that differ from each other. Hence, additional subjective decisions have been made to define the thermal view geometry regarding the details and accuracy of the geometry (Bazjanac, 2008a).

These are the reasons why some professional are not taking simulation approach into consideration; it is not just because the process is labour intensive and too costly, but also because the process takes a long time, and the results are irrelevant by the time they are delivered (Bazjanac, 2008a; Osello, et al., 2011). This approach should be replaced with the more effective approach by executing BPS tools through interoperability with BIM (Bazjanac, 2008a).

2.1.9.2 Measuring actual thermal properties of building elements

One of the most important factors to estimate the energy consumption is the accuracy of thermal properties such as thermal transmittance (U-value) of building elements (Lagüela, et al., 2014). In current practice, there is Lack of transparent approach to estimate actual thermal properties and these data are usually gained from generic properties of building elements in energy simulation (Ham & Golparvar-Fard, 2015). To quantify the actual thermal properties, there are two measurement approaches; destructive methods and Non-destructive methods (Ham & Golparvar-Fard, 2015).

Destructive methods: Often disassembling of building elements are impossible and challenging especially when occupants live in houses within the retrofit process (Ham & Golparvar-Fard, 2015).

Non-destructive methods: To measure the actual thermal properties, several studies have presented thermography-based methods (Dall'O', et al., 2013; Fokaides & Kalogirou, 2011; Albatici & Tonelli, 2010; Madding, 2008). To evaluate the accuracy of these methods, these measurement using thermal images were compared with as-is building condition (Ham & Golparvar-Fard, 2015). In all cases the difference between thermography-based methods and as-is conditions remained with the range of 10 to 30% (Ham & Golparvar-Fard, 2015; Dall'O', et al., 2013; Fokaides & Kalogirou, 2011). Although thermography-based methods compared to existing approaches, using notional assumptions are more accurate and have their benefits, their application still have limitations (Ham & Golparvar-Fard, 2015):

To measure the actual thermal performance of building elements, conducting several measurements are required (Ham & Golparvar-Fard, 2015). Often because of the different degradation rates in building elements, conducting only a few measurement results in inaccurate representation of the actual thermal properties. Manually analysing the large numbers of raw 2D thermal images is time consuming and subjective and prone to human error. So, to improve the accuracy of thermography-based methods, there is a need for methods to analyse large numbers of thermal images.

Ham and Golparvar-Fard (2015, p. 223) proposed *“an automated approach for updating thermal properties of building elements in the gbXML-based BIM through measuring actual heat transfer condition using 3D thermography.”* This approach improve the decision making process by using the as-is building condition rather than notional assumption as an input for BPS tools, however more experiments are required to validate the applicability of this method (Ham & Golparvar-Fard, 2015).

Conclusion

In the residential sector, 70% of existing UK residential buildings will still exist in 2050 (DECC, 2012). In any one year, 99.7% of CO_2 emissions are related to existing homes constructed in the past years, while 0.03% of CO_2 emissions are related to new dwellings constructed that year (Rickaby & Willoughby, 2014). Therefore, to achieve the climate change targets in the UK, it is necessary to enhance the energy efficiency of the existing UK housing stock (Crosbie & Baker, 2010).

Although there are several motivations to improve the energy efficiency of the retrofit process, the current practices have been faced with several challenges (Mills & Rosenfeld, 1996).

Social barriers to adopting energy-efficient measures include an unwillingness to adopt energy efficient measures and lack of occupants' knowledge, mistrust of energy companies and socioeconomic issues (Crosbie & Baker, 2010). It is essential to understand the vital importance of social barriers to minimise the rebound effects and energy efficiency gap (Pelenur & Cruickshank, 2011). **Financial barriers** are associated with the upfront cost of energy efficiency measures (Webber, et al., 2015), uncertainty about the payback period (Pelenur & Cruickshank, 2011) and ineffective initiatives (Mallaband, et al., 2011). In addition, **building regulations** play a key role to improve the efficiency. In the UK, the energy performance of the dwellings is estimated by SAP calculations, however, those are based on the notional assumptions and do not consider the lifecycle cost of alternatives, frequently leading to suboptimal solutions (Kellya, et al., 2012). **Education and skill barriers** are associated with the knowledge and skill gaps among suppliers, surveyors and installers (Mashford, et al., 2015), and insufficient level of knowledge to implement the state-of-the-art approaches (Lowe & Oreszczyn, 2008). One of the main barriers to improve the efficiency of the retrofit process is related to the **technical barriers**, **late adoption of BPS tools** and **difficulties in effectively measuring energy consumption** which has key role to evaluate the alternative options before implementation (Peltomäki, 2009; Doukas, et al., 2009; Beaven, 2011). The existing simulation methods are very time-consuming, labour intensive, costly and typically adopted at the late stage where fundamental design decisions have been already made. Furthermore, there is Lack of transparent approach to estimate actual thermal properties and these data are usually gained from generic properties of building elements in energy simulation tools (Ham & Golparvar-Fard, 2015).

These challenges have confronted the current practices to improve the efficiency of the retrofit process. In the next chapter, the research method adopted in this research to address the research problem will be discussed.

Chapter Three

Research Methodology

3 Research Methodology

Introduction

The primary aim of this chapter is to provide an overview of the research methodology used in this research. Connecting to the up-to-date review of literature in Chapters 2, this chapter justifies the choice of research methods to achieve the stated research objectives. This chapter presents a brief overview of current research methods in the field of built environment. It then details and justifies the research method adopted in this research. The chapter ends with a description of the methods used in this research include: literature review, interviews with industry and academic experts, and a real world case study and simulation.

Research is defined as a systematic enquiry and examination designed to discover unknown information and relationships using disciplined methods to refine and expand the body of knowledge (Easterby-Smith, et al., 1991; Polit & Beck, 2003). Redman and Mory (1933) defined research as "*systematic effort to gain new knowledge*". Research can be carried out in many diverse ways depending on ontology, epistemology and axiology (Guba & Lincoln, 1994). "*Research approaches are plans and the procedures for research that span the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation"* (Creswell, 2013).

Research in the field of the built environment that interprets real world phenomena has been criticised for its anecdotal approach. Therefore, a coherent and clear definition of a research strategy is an essential requirement for a cogent empirical study in the field of built environment. "*The starting point in research into built environment is to focus clearly on the fact that the ultimate purpose is to add some of value to the body of accumulated built environment knowledge"* (Amaratunga, et al., 2002). The unsolved problem should be identified and reviewed to enable the researcher to seek answers to unanswered questions or solutions to unsolved problems. To produce suitable answers to research questions, and validate the outcomes, it is essential to adopt proper research design, where justifying the rational of the selection of research methods is a fundamental step (Creswell, 2013). Research methods can be categorised in diverse ways; however, many scientist categorise three main research approach: quantitative, qualitative and mixed methods (Kimmance, 2002; Creswell, 2013).

According to Babbie (1983, p. 537), quantitative research refers to *"the numerical representation and manipulation of observations for the purpose of describing and explaining the phenomena that those observations reflect", as opposed to qualitative research, "the non-numerical examination and interpretation of observation for the purpose of discovering underlying meanings and patterns of relationships".*

However, quantitative and qualitative approaches are not as discrete as they first appear, and they should not be considered as rigid categories or dichotomies (Newman & Benz, 1998). One main difference between them lies in their fundamentally diverse assumption about the aim of research (Kimmance, 2002). Since the use of a single methodology often fails to explore all related component to find solution to unsolved problem, mixed methods research, combining elements of both quantitative and qualitative approaches, is recommended to improve the research in to the built environment (Amaratunga, et al., 2002).

Qualitative Research Approach

Qualitative research is an approach to explore and understand the reality of human problems and social phenomena and attempts to describe people in natural situations (Amaratunga, et al., 2002; Groat, 2002). Qualitative research is also defined by the procedures or research methodologies employed to collect the subjective data that form the basis for analysis, analysing data inductively and interpreting of the meaning of the data to obtain general themes from particular situations (Kimmance, 2002; Creswell, 2013).

Qualitative methods have differing weaknesses and strengths. One of the main strengths of qualitative research is its capacity to obtain rich data of real-life circumstances and settings (Groat, 2002). In other words, the richness and holism of qualitative data have considerable potential to reveal complexity and understand the meanings of people's activity and artefacts. This can be considered as one of the significant advantages of qualitative research (Amaratunga, et al., 2002; Groat, 2002).

Although qualitative methods offer great advantages, they come with some costs. Researches employing qualitative research design will find relatively few well-designed guidelines in the literature. So, they have to exercise extra care during the entire research process, and yet still the trustworthiness of the data may remain suspect (Groat, 2002; Amaratunga, et al., 2002). Furthermore, coding and analysing the vast amounts of unstructured data is very time consuming (Groat, 2002).

Groat (2002, p. 199) summarised the strength and weaknesses of qualitative research, as shown in Table 0:1.

Table 0:1 Strengths and weaknesses of qualitative research (Groat, 2002, p. 199)

Strength	**Weakness**
Capacity to take in rich and holistic qualities of real life circumstances	Challenge of dealing with vast quantities of data
Flexibility in design and procedures allowing adjustments in process	Few guidelines or step-by-step procedures established
Sensitivity to meanings and processes of artefacts and people's activities	The credibility of qualitative data can be seen as suspect with the post positivist paradigm

While the classification and the terminology used to describe the qualitative research vary somewhat from author to author, there are three principal categories currently employed: critical, interpretive and positivist (Guba & Lincoln, 1994). Comprehensive discussions on the qualitative philosophy perspectives can be found, e.g. (Easterby-Smith, et al., 1991; Remenyi, et al., 1998; Silverman, 1998; Amaratunga, et al., 2002; Creswell, 2013).

Quantitative Research Approach

Quantitative research is an approach for testing objective theories and discovering underlying relationships through collecting and analysing numeric data using statistical procedures or computational methods (Donmoyer, 2008; Creswell, 2013). Samples in quantitative research can be larger and more representative compared to the qualitative approach (Fitzgerald & Howcroft, 1998). According to Easterby-Smith, et al., (1991) and Amaratunga, et al., (2002) the advantages of quantitative research for built environment research are as follows:

- Analysing the subject is independent of the observer and it is measured through objectives methods;
- The approach enables the researcher to compare and replicate the results;
- It offers great potential to measure descriptive aspects of built environment research, thus the validity can be determined more objectively compared to qualitative methods. For example, measuring variable such as quantitative assumption regarding construction process capability.

The weaknesses of the quantitative research, especially where the resources are limited, are related to collecting large-scale data, analysing at a reasonable time and cost and delivering statistical proof (Amaratunga, et al., 2002). A quantitative approach can be used to measure factors such as physiological, employees’ capability and motivating factors which are important in most of the built environment research. However, their appropriateness to explain these factors are limited (Amaratunga, et al., 2002).

Quantitative research can be classified into five main categories: meta-analysis, quasi-experimental, correlational/predictive, descriptive, and single-subjects (Locke, et al., 1998). More in-depth discussions on quantitative research are available, e.g. (Easterby-Smith, et al., 1991; Horna, 1994; Locke, et al., 1998; Creswell, 2013).

Mixed methods research

Mixed methods research is an approach that combines both qualitative and quantitative data, integrating the two forms of data and employing distinct design to analyse complex phenomena (Creswell, 2013). As discussed in Section 0 and 0, both qualitative and quantitative research approaches have weakness and limitations and thus expecting a researcher to choose one over another seems unjustifiable (Amaratunga, et al., 2002). The crucial aspect in justifying a mixed methods research in the built environment research is that the weaknesses in each single method can be compensated by the counter-balancing strength of another (Yin, 1994). According to Das (1983, p. 311) *"qualitative and quantitative methodologies are not antithetic or divergent, rather they focus on the different dimensions of the same phenomenon".* Blending qualitative and quantitative methods of research enable researchers to use them at different stage of investigation (Rossman & Wilson, 1994; Silverman, 1998). The major strengths of mixed method research follow from its capacity to used combination of quantitative and qualitative elements to simultaneously address a range of exploratory questions (Silverman, 1998), a greater assortment of divergent views (Teddlie & Tashakkori, 2009) and produce a more comprehensive understanding towards a complex phenomenon (Creswell, 2013).

Methodology Adopted

Research studies in the built environment and in the context of digital technologies in the construction domain are not totally technical phenomena - they are also related to human activities, natural science, engineering and management (Whyte, 2000; Amaratunga, et al., 2002). Mixed methods research, combining both qualitative and quantitative methods, has been employed by many researchers to obtain better understanding in this inter-disciplinary field, for example (Kimmance, 2002; Zou, 2017).

Research in this inter-disciplinary area does not deal with a single-aspect problem such as pure engineering, and many other aspects should be covered, e.g. social science and management. To overcome the observed problem in this research which is a lack of a systematic approach to improve the efficiency of energy efficient domestic retrofit, it has been discussed that implementing BIM in energy efficient retrofit process can address the identified problems in practice. The research is closely related to two main aspects: identifying the barriers to improve the efficiency of the energy efficient retrofit process and integrating BIM in building performance simulation process as an enabling technology to improve the efficiency of the retrofit process.

Exploring solutions to address the observed problem needs a thorough understanding of challenges in the energy-efficient retrofit process and also the challenges and potentials to implement BIM to address the identified problems in practice. To explore solutions for the observed problem of this research, the mixed methods research, which can combine both quantitative and qualitative approaches, was employed.

The Centre for Integrated Facility Engineering (CIFE) Horseshoe research framework (Fischer, 2006; Kunz & Fischer, 2007) was adopted to guide the overall direction of this research. The CIFE horseshoe research method has been used for most of the PhD research projects undertaken in CIFE at Stanford University (Fischer, 2006). "*The method supports* *researchers in building on the experiential knowledge and anecdotal evidence that can be gathered on construction sites in the context of existing theory and expert knowledge to carry out practically-relevant and scientifically-sound research"* (Fischer, 2006). As explained in Chapter 1, the existing practices for retrofitting have been facing challenges to enhance the efficiency of the process. Therefore, adopting the CIFE horseshoe research method gives the researcher the opportunity to explore, identify and employ new methods with the potential to address the efficiency problem. The research process follows the adopted CIFE horseshoe research method, and is shown in Figure 0:1.

The process starts with an observed problem in practice. Addressing a problem in practice requires that a problem be identified, described and quantified transparently (Fischer, 2006). In Chapter 2, it was observed that they are several challenges to improving the efficiency of the retrofit process, including behavioural barriers, financial barriers, political barriers, education and skill barriers, disruption to users and technical barriers.

3.1.1 Intuition

Although intuition is the least formalised step in CIFE, it is essential to have a hunch about how to address the problem in a general way (Fischer, 2006). The intuition for the observed problem is to integrate BIM in the energy simulation performance process to improve the efficiency of the process. BIM has benefitted the construction industry through adapting to medium to large-scale projects for new buildings during the last few decades, and it is envisaged as a methodology to change the existing practices (Eastman, et al., 2011).

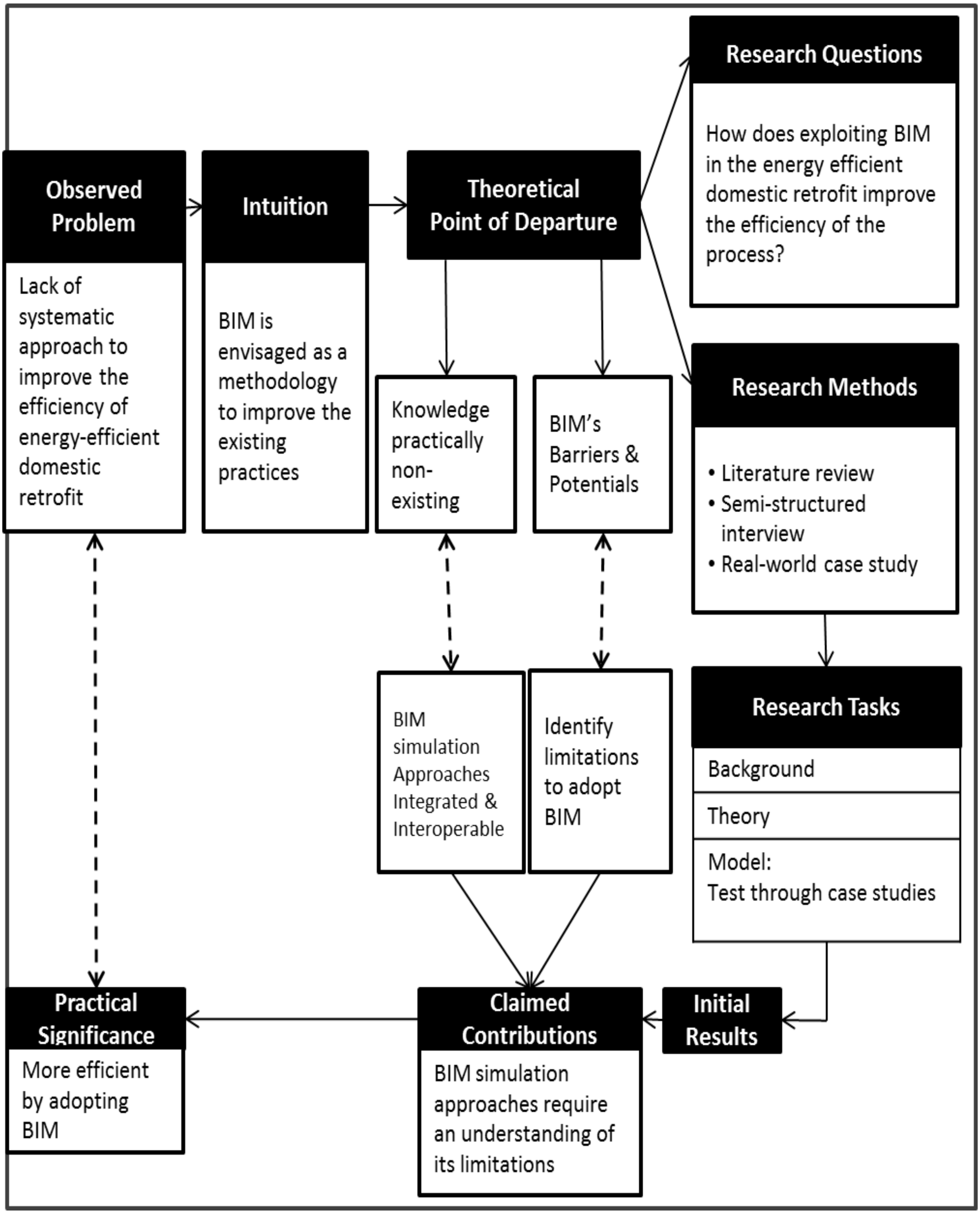


Figure 0:2: The steps of the research process based on CIFE horseshoe research framework

3.1.2 Point of Departure (Theoretical Limitations)

A well-defined statement of the problem and the transparently articulated intuition are required to pave the way to identify the starting point for the research. Therefore, the researcher must critically review the literature, conduct a series of interviews and assess a case study for several grounds in order to (adapted from Fischer, 2006):

- Identify and explore if the problem statement has been identified and mentioned earlier by other researchers, professionals and practitioners. This assists to generalise and quantify the problem statement. This included reviewing the literature to explore the challenges that exist in the current process to improve the efficiency of the retrofit process.
- Identify how researchers and practitioners address the problem through existing theory. This included exploring and identifying the barriers to implement BIM in the energy-efficient retrofit process (will be discussed in Chapter 4).
- Identify how the existing theory, which is partly addressing the problem statement, can be really useful to solving the problem. This required illustrating why the existing building energy modelling practices was deficient or needed to be transformed to solve the problem. This included that how BIM simulation model can be modified and adopted to address the problem.

The researcher’s intuition was that if adopting BIM has improved the existing practices in complex new projects, then it might have the potential to improve the efficiency of small-scale retrofit processes. The theoretical point of departure (POD) of the proposed solution in this research is addressed in Chapter 4.

3.1.3 Research Methods

The adopted research methods and research tasks depend highly on the research problem. As explained, mixed methods research synthesising and combing both qualitative and quantitative approaches was used to find solution for the observed problem.

Qualitative approach: An extensive review of the literature was conducted in two stages in this research to identify the problem and explore how other researchers addressed the problem, which are documented in Chapter 2 and Chapter 4 respectively.

Qualitative approach: A series of semi-structured interviews were conducted to obtain more up-to-date information from leading experts in this field and also to reinforce the findings from the literature review.

Quantitative Approach: The data were collected from a real world case study to investigate the actual energy consumption of the house over a two-year period. The results of the monitored house over a two-year period enabled the researcher to evaluate the accuracy of the experiment by comparing the results of the monitored house with simulated energy consumption predictions of the house through different types of interoperability between BIM and BPS tools.

3.1.3.1 Literature review

The first stage is to identify the research gap, thus the barriers to improve the efficiency of the retrofit process was discussed in Chapter 2. The challenges to improve the efficiency of the retrofit process are categorised into six main groups: behavioural barriers, financial barriers, political barriers, education and skill barriers, disruption to users and technical barriers. After critically reviewing the literature, the researcher identified one of the main barriers to improving the efficiency in the current situation was technical barriers and difficulties in effectively measuring energy consumption at the early stage. In the current practices, the obtained data from BPS tools is frequently subjective, time consuming and evaluative rather than proactive (Torcellini, et al., 2004; Bazjanac, 2008a; Attia, et al., 2012; Kanters & Horvat, 2012).

Building upon the well-defined problem and clearly articulated intuition, the second stage of the literature review (Chapter 4), will explore how BIM implementation could benefit the retrofit process and what are the challenges to exploiting BIM in this process.

3.1.3.2 A series of semi-structured interviews

After reviewing existing research in the relevant literature, it was concluded that there is lack of practical knowledge for implementing BIM in to the small-scale retrofit process. Thus, interviews were carried out to explore professional perspectives towards the challenges in the energy-efficient retrofit process and BIM's potentials and barriers in the energy efficient retrofit process in the residential sector. The semi-structured interviews with nine professionals in this field took place between April 2013 and July 2014 and were carried out either face-to-face or using Skype with nine professionals in Finland, UK, U.S.A and Norway. Participating Interviewees in the interviews are shown in Table 0:1.

Table 0:1: Interview Participants

Name	Job title and expertise	Country	Duration
David Philp	Global BIM/IM Consultancy Director, AECOM	UK	0.5 hour
Mani Golparvar Fard	Director of the Real-time and Automated Monitoring and Control Lab	US	1 hour
Brian Bishop	Chief Executive Officer (CEO) at Data Performance Consultancy Limited	UK	1.5 hours
Tiina Koppinen	Senior Vice President Business Development at Skanska Oy	Finland	0.5 hour
John Lorimer	Director in JLO Innovation Ltd, BIM strategy and implementation	UK	0.5 hour
James Nicholls	Architect and Urbanist in John McCall Architects	UK	2 hours
*	Design Manager at Tønsbergprosjekt, Skanska	Norway	1 hour
Graham Cavanagh	Architect at Ryder Architecture	UK	2 hours
Martin Gladwin	Head of Asset Management in Plus Dane Group	**UK**	2 hours

* Permissions to include interviewees' names was obtained by the researcher, except one marked with *

The interview design, the methodology adopted for the interview, and the result of data analysis will be discussed in Chapter 5.

3.1.3.3 A real world case study

Then, in Chapter 7 a real world case study will be used to explore the potential issues in the current practices of simulation approaches. Although the results of the energy performance simulation of the real world case study through the detailed modelling were accurate, the process is time-consuming, labour intensive and subjective (as discussed in Section 7.3.3.). Therefore, the researcher strove to explore how BIM integration could address those issues to achieve an efficient process for energy efficient retrofit.

After reviewing the extent literature and conducting the interview, it was concluded that an efficient data exchange and interoperability between BPS and BIM tools is critical to improve the efficiency of the energy-efficient retrofit process. The success of data exchange is largely dependent on the quality and transparency of shared information (Nicolaou & McKnight, 2006; Li, et al., 2006). So, to evaluate the efficiency and accuracy of the experimental BIM simulation approach, there are some requirements regarding the different automatic rule-based checking software and BIM platforms which should be discussed. Hence, Chapter 6 will discuss the importance of the quality of shared model, two current commercial applications for automatic rule-based checking and two BIM platforms to select the appropriate software for the experiment.

Although to the best knowledge of the author, this thesis was the first research to implement BIM in the small-scale retrofit process in the residential sector in the UK, in the meanwhile, two other projects commenced implementing BIM in the domestic retrofit process. These two project will be studied in Chapter 8 to explore how these projects have benefitted from BIM implementation in small-scale retrofit projects and also if BIM implementation has faced challenges which are identified by the author in this research. The claimed contribution and practical significance will be discussed in Chapter 9.

Chapter Four

Building Information Management (BIM) in the Retrofit Process

4 Literature Review: Building Information Management (BIM) in the Retrofit Process

Introduction

What has driven the development and adoption of BIM? Towards the end of the 20th century, a mounting concern to save the environment and reduce greenhouse gas emissions emerged as an area of universal concern. Although novel technologies and approaches have been adopted to improve the energy efficiency of existing buildings, the UK's construction industry, with one of the oldest domestic stocks in Europe, is still faced with challenges to reduce CO_2 emissions. BIM is envisaged as a methodology to improve the existing practices (Eastman, et al., 2011, pp. 10-15; Forbes & Ahmed, 2011). To identify how BIM can enhance the efficiency of the retrofit process, BIM needs to be reviewed in terms of its benefits and barriers. This chapter reviews BIM applications in the Architecture, Engineering and Construction (AEC) industry and it is intended to explore how BIM could improve the efficiency of the retrofit process.

The chapter is structured as follows: Section 0 provides a brief introduction to BIM's background, its definitions and the adoption of BIM in the UK. Section 0 discusses BIM's benefits to the construction industry to obtain better understanding of BIM applications in the current practices. Section 0 reviews the potential of BIM implementation in the retrofit process. Section 0 reviews the challenges to implementing BIM in existing building, including data capture techniques and a lack of interoperability between Building performance Simulation (BPS) and BIM tools. Owing to the importance of establishing an open interoperability standard to enable data exchange, three widely open interoperability formats, IFC, gbXML and COBie, is reviewed in section 4.1.6 to choose the interoperability formats to meet the requirements of this research. Section 0 reviews the Characteristics, advantages and disadvantages of four different methods of interoperability between BIM and BPS tools,

What is BIM?

4.1.1 BIM’s Background

The concept of BIM was introduced in 1975 as ‘Building Description System’ (Eastman, 1975). In Finland, the RATAS, a proposed Finnish ‘Building Product Model’ (BPM), had been defined (Björk, 1987). RATAS projects brought together most key players in the Finnish construction industry through a series of Research and Development (R&D) projects (Enkovaara, et al., 1988). Then, in 1989, new concept called BPM was introduced in the international research journals, a prototype as a proof of concept. (Björk & Penttilä, 1989). Thereafter, *Jerry Laiserin widely publicised* ‘Building Information Modelling’ (BIM) *in the industry in 2002*” (Bazjanac, 2004).

4.1.2 BIM Definitions

BIM has many definitions, which vary in their complexity. The definition primarily depends on the perspective of what is being sought to be gained from the approach. Two of the most widely adopted BIM definitions are given below.

The National BIM Standard-United States® (NBIMS-US™) defined BIM as “*a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward*” (NBIMS-US™, 2007).

buildingSMART International defines BIM as Building Information Management which “*is the organisation & control of the business process by utilising the information in the digital prototype to effect the sharing of information over the entire lifecycle of an asset*" (bSI, 2012).

According to Kiviniemi (2010), BIM can be defined in several ways. Firstly, as a ‘Building Information Model’, such as the digital representation of a building to interoperate and exchange data in digital format. Secondly, as ‘Building Information Modelling’, including the procedure of creating and managing a building’s information throughout its lifespan; and thirdly, as ‘Building Information Management’, covering the procedure of generating, utilising and managing digital information for integrated design, construction process, operational and maintenance phases of buildings. According to Kiviniemi (2010), Building Information Management is considered to be the best approach to defining BIM. At a broader level, since it is not just limited to buildings, it can be considered as Asset Information Management (AIM), which also covers infrastructure (Kiviniemi, 2010). This research considers BIM as ‘Building Information Management’ to cover the process of managing digital information during design, construction and retrofit phase of buildings. Considering BIM as a technology is a common misconception of BIM within the AEC industry. While the digital representation of a building is one of the fundamental parts of BIM, it is more than just this application (Krygiel, et al., 2008).

4.1.2.1 BIM is a Sociotechnical System

BIM *“describes the process of designing a building collaboratively using one coherent system of computer models”* (Kennerley, 2013). BIM is a socio-technical system and is about process and people as much as it is about technology (Harty, et al., 2010) as technological tools are dependent heavily and mutually on social practices (Trist & Bamforth, 1951). Harty (2010) describe BIM *“as ‘sociotechnical’ because it has social components, complementing the technical core like the leaves on a tree. The social parts influence the evolution of the technical core through feedback loops”* as shown in Figure 0:1.

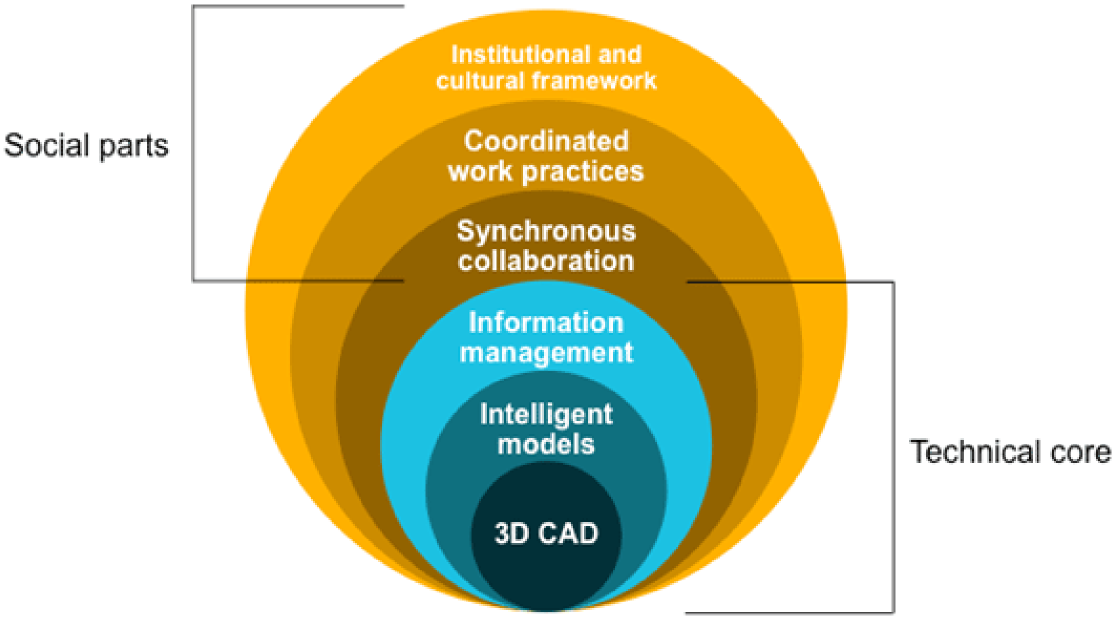


Figure 0:1: Sociotechnical system with a technological base and layers of social components (Kennerley, 2013)

4.1.3 BIM Adoption

As construction projects increase in complexity, alternative modern methods of construction and design have increased in popularity. Suermann (2009) pointed out that designers, construction managers and contractors, who have the ability to accomplish tasks more efficiently than ever before, have used BIM. Furthermore, clients increasingly require BIM services from designers and contractors and it is constantly becoming a better-known established collaboration process in the design and construction process of buildings (Azhar, et al., 2008). In 2008, Mervyn Richard and Mark Bew provided a BIM Maturity Diagram to describe the different levels of BIM and it forms the basis for the UK's government's phased implementation of BIM, as shown in Figure 0:2. "*Government will require fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016*" (Cabinet Office, 2011).

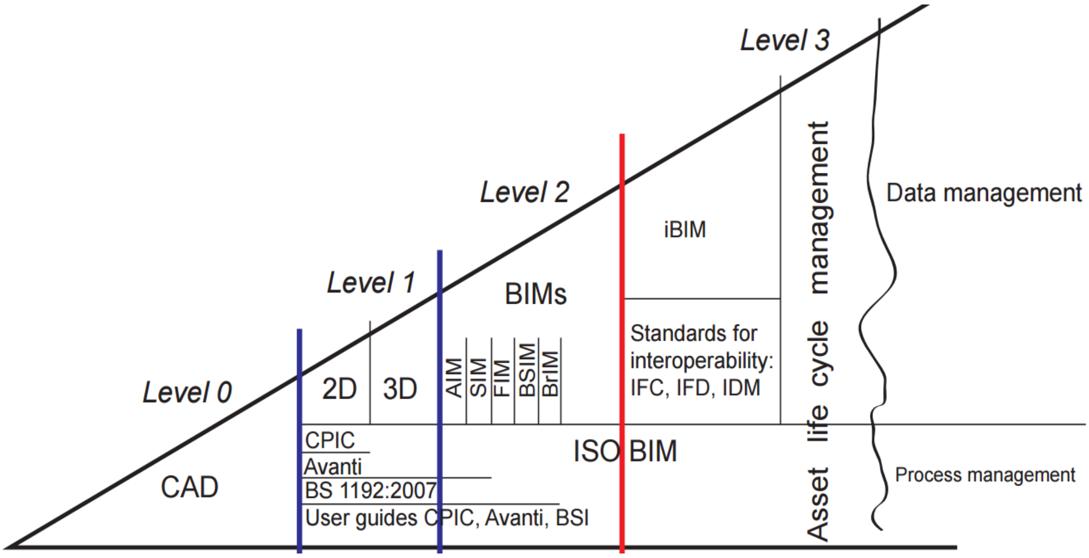


Figure 0:2: BIM Maturity Diagram (Bew & Richards, 2008)

According to the NBS National BIM Survey, BIM adoption has increased in the UK from 2010 onwards as shown in Figure 0:3 (NBS, 2016). The result of NBS shows:

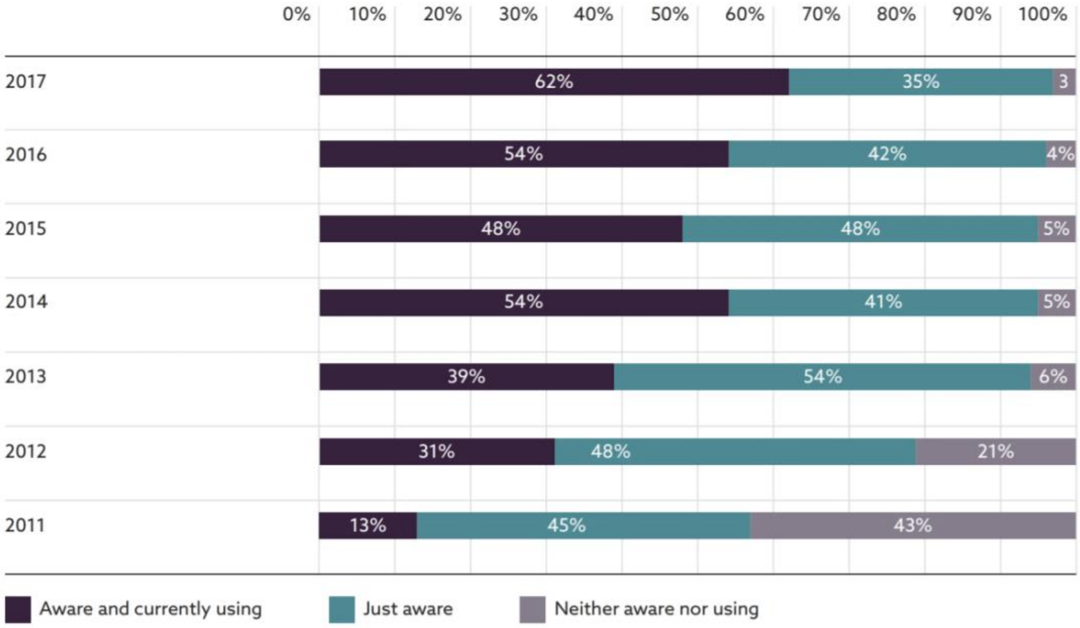


Figure 0:3: BIM awareness and usage, adopted from (NBS, 2017)

54% of respondents have utilised BIM for at least one project in 2015. It increased to over 40 % from 2010, when only 13% used BIM in their projects.

BIM awareness has risen dramatically from 2010. In 2010, 43% of participants did not know what BIM it was, while it was only 4% by 2015 (NBS, 2016; NBS, 2015).

In 2014, there was a slight dip in BIM usage compared to 2013. Although it increased to 54% in 2015, it shows that the rate of usage has moderated from 2013 onwards (NBS, 2017).

BIM Benefits

The construction industry already has benefited from BIM implementation, although its fragmentation has influenced the heterogeneous adoption of IT. BIM not only assists those involved bodies to simulate their projects, but also provides a built environment with digital prototypes of buildings prior to the first pile being driven into the ground (Weygant, 2011). The primary advantage of BIM is associated with its potential to represent the physical and functional characteristics of the whole lifecycle of buildings, from inception through demolition, and embracing construction, operation, maintenance and retrofit (Eastman, et al., 2011, pp. 19-26). Diverse phases in a building's lifecycle have different advantages attributed to different phases (Forbes and Ahmed 2011). Intelligent objects with 3D models, including geometric or non-geometric attributes with topological or functional data and parametric rules for each component through the whole life cycle, enhance the project delivery and decision-making process. Decision-making processes can be improved through the extraction and analysis of information based upon the requirements of various clients and users to provide a comprehensive definition of BIM as modelling, a repository of functional and environmental data, collaboration, integration, schedule of performance, cost estimation and facility management (Succar, 2009). Constant and coordinated views and representations of the digital model, including reliable and updated data, can be easily interrelated with the specification, procurement information and processes (Khemlani, 2007). The benefits of BIM that are currently in use, and the potential merits of BIM implementation in the construction industry, are listed in Table 0:1.

Table 0:1: BIM's Potentials

BIM's Potentials	Description
Quality Control of Design and Construction Process	• Improving the building performance through assessment of design processes at the early stages (Browne & Menzel, 2012; Konstantinoua & Knaacka, 2011). • Enhancing the quality of products such as unwarranted maintenance (Eastman, et al., 2011, p. 155); • Providing more accurate visualisation at the early stages (Eastman, et al., 2011, pp. 331-333); • Discovering of design clashes at early phases (Azhar, et al., 2008).
Cost Management	• Obtaining cost reliability and decreasing financial risk (Eadie, et al., 2013); • Alleviating cost of project through prefabrication offsite (Iturralde, 2012; Eastman, et al., 2011, pp. 321-348); • Reduce construction costs (Eastman, et al., 2011, p. 156)
Time Management	• Reducing time to market (Eastman, et al., 2011, pp. 156,165); • Generating accurate construction drawings at any stages of design to reduce time and errors related to generating 2D (Jalae & Jrade, 2015; Eastman, et al., 2011, pp. 157-162); • Improving the fabrication offsite and shorten the time by automated fabrication facilitated for the 3D model (Migilinskasa, et al., 2013).
Improved Sustainability	• Improving energy efficiencies by linking the building model to energy analysis tools at the early design stages (Browne & Menzel, 2012; Eastman, et al., 2011, p. 23); • Developing a schematic model before generating an elaborated building model to meet the functional and sustainable requirements (Eastman, et al., 2011, p. 156); • Improving the coordination among contractors and sub-contractors to implement lean construction techniques through reducing the requirements for onsite equipment and materials inventories, scheduling of sub-contractors to assure just-in-time arrival of involved bodies (Migilinskasa, et al., 2013; Arayici, et al., 2011).

The benefits of BIM implementation have been proved to people who have adopted BIM in their projects (NBS, 2015). According to a survey conducted by NBS in 2014, 92% of interviewees will use BIM within three years in the UK. Based on the NBS report, cost efficiencies are improved by 59% and the delivery process is sped up by 51% and profitability increased by 48% (NBS, 2015).

However, BIM implementation in the retrofit process is almost a reverse engineering process and, consequently, the capabilities and barriers to BIM implementation in the retrofit process are, to some extent, different.

Adopting BIM through the Retrofit Process

Depending on the requirements of stakeholders and projects, potential applications and functionalities of BIM in retrofit processes are numerous (Volk, et al., 2014). One of the essential criteria to implement BIM successfully in a project is to have a clear understanding of the reasons to adopt BIM, thereby avoiding wasting time and cost on irrelevant detailed information which cannot be useful to achieve intended functionality. According to ISO 2481-1:2010 (2010), *"functionalities are either inherent in 3D, 4D or 5D BIM (e.g. quantity take off, scheduling or cost calculation) or they are attached to BIM as independent expert applications. Expert functionalities use the underlying BIM data to support, extend, calculate or simulate specific business requirements (e.g. perform structural analyses). Results are either reintegrated into BIM or reported separately. Functionalities are based on process maps, which describe the logical flow of information and activities as well as the stakeholders' roles within a particular functionality."* Implementing BIM in the retrofit process has numerous benefits such as support of decision–making process, reduced retrofit schedules onsite, minimised costs, improved collaboration, documentation and more accurate visualisations (Volk, et al., 2014). Also, BIM implementation in existing buildings can assist to extend current assessment criteria for sustainability ratings and certifications (U.S. Green Building Council, 2013). BIM through integration with collected data, such as maintenance costs, energy consummation and so forth, can monitor and verify the cost and energy performance of buildings and expand the depicted environmental effects of buildings (U.S. Green Building Council, 2013). Although the potential functionalities of BIM in existing building are manifold, it is not yet widely used in the AEC industry (Volk, et al., 2014).

Challenges to Exploit BIM in Small-scale Retrofit Process

There are some challenges to implement BIM in the AEC industry. For example, there are some issues to achieve effective collaboration. If the architect's model does not have adequate information for contractors, they may need to create a new model. Also, if involved bodies within a project use different BIM platforms and tools then importing and exporting a model from one to another or combing models is required. These issues may result in adding complexity, increasing errors and increasing the time to market (Eastman, et al., 2011). The Industry Foundation Class (IFC) standard and model servers allow communication with all BIM applications and this may reduce the potential problems (Eastman, et al., 2011). Furthermore, team members are confronted with undefined ownership of documentation, the legal and contractual implication of BIM (Ashcraft, 2008; Eastman, et al., 2011, p. 27). The ownership of multiple designs and construction data files and also, the responsibility of financing, the accuracy of the model and maintaining information through the whole process are not explicit so far. Using new technologies and shared building models within companies is challenging and, like other changes in workflows and technologies, requires investment, time and education. Moreover, shifting to BIM implementation is not only about buying software and training the whole workflows in companies need to be shifted, which requires a comprehensive understanding of BIM process and BIM technologies. Any firm should make their own plan for implementing BIM by considering their intended aims (Rezgui & Miles, 2011; Eastman, et al., 2011, pp. 258-261).

Implementing BIM in existing buildings might improve the data management and delivery of better projects. However, BIM adoption in existing buildings is confronted with shortcomings as there are no pre-existing models of buildings. The UK's existing housing stock is one the oldest in Europe and almost 13 million dwellings were built before 1960 (Baeli, 2013) and almost no building has building documentation in BIM format for the retrofit process (Akcamete, et al., 2010; Dickinson, et al., 2009).

4.1.4 Capturing initial Data and uncertainty of captured data

One of the major obstacles to adopting BIM in the retrofit process is associated with the initial captured data (Penttilä, et al., 2007). BIM creation and processing are varied for existing and new buildings owing to diverse information availability, required functionality and quality of information (Hajian & Becerik-Gerber, 2010; ISO Standard, 2008; Volk, et al., 2014). Dealing with inaccurate and uncertain data create challenges for a collaborating team trying to implement BIM in their retrofit projects. Certainty about the captured data is crucial regarding all the functions for BIM applications. Evaluating building fabric is very important to execute energy efficient retrofit process owing to the importance of estimating how thermal performance should be enhanced (Ham & Golparvar-Fard, 2015).

As shown in Figure 0:1, model creation in a new building and existing building are different. The model creation in the new building is an interactive and iterative process and it can be created in different lifecycle stages including inception, brief, design and production (Volk, et al., 2014). However, model creation in an existing building is a reverse engineering process and a building’s geometric and topologic information has to be captured and modelled (Mill, et al., 2013; Volk, et al., 2014; El-omari & Moselhi, 2008; Klein, et al., 2012; Akbarnezhad, et al., 2012).

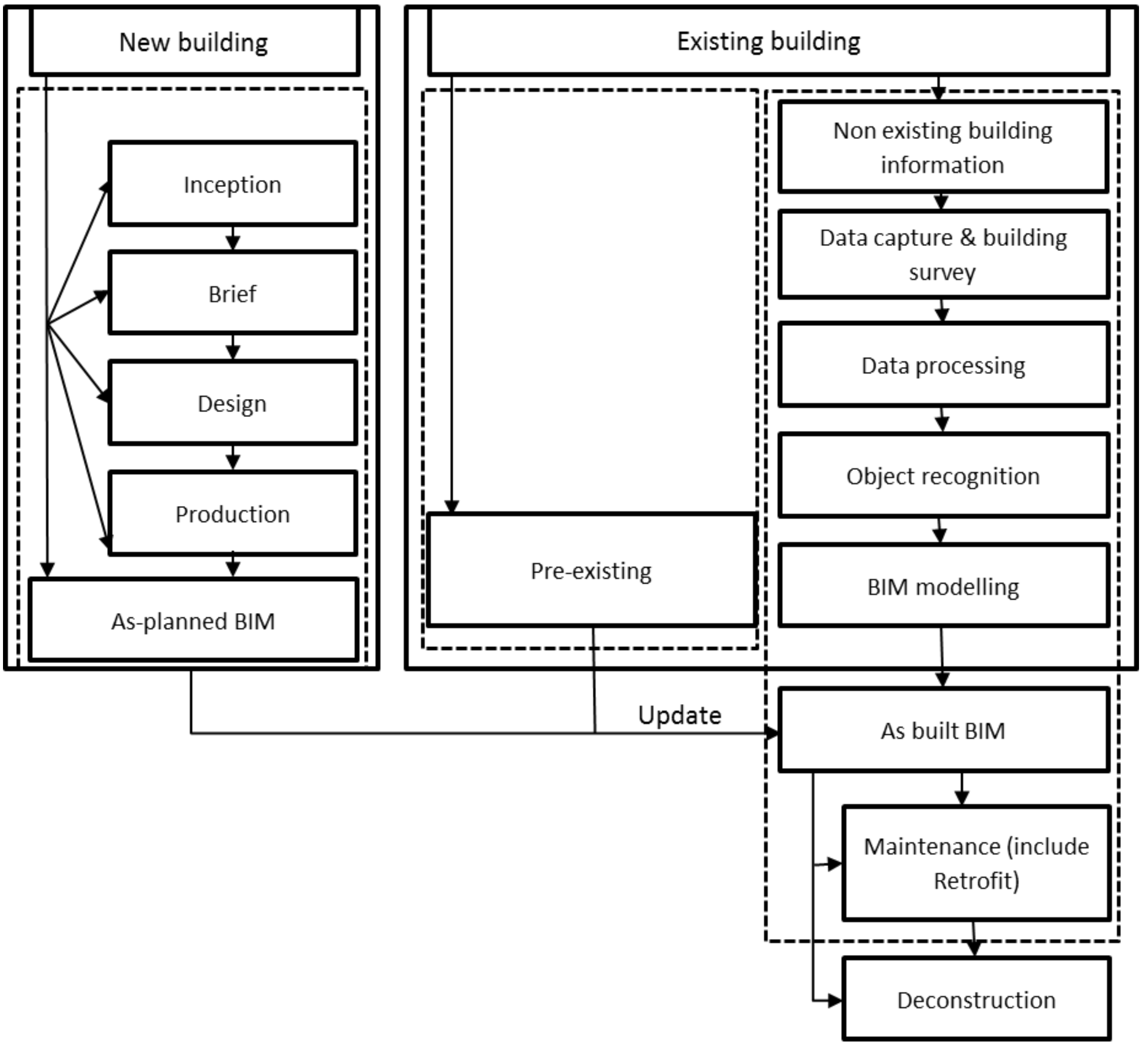


Figure 0:1: Model creation process in new and existing building, adopted from (Volk, et al., 2014)

Also, thermal data and semantic attribute/property data should be integrated in to model, but this must be done manually (Volk, et al., 2014). The accuracy of captured data is very important to deliver accurate outputs, and information should be precise, relevant and up-to-date to fulfill requirements for the intended functionalities (Gray, et al., 2013; Hajian & Becerik-Gerber, 2010).

According to Volk, et al., (2014) the *"main characteristics for data capturing technique selection are cost, time, the level of details and environmental condition during data capture (e.g. light, weather, vegetation, concealments, clutter)".* Data capturing and building surveying techniques can be classified into two main categories: non-contact techniques and contact techniques, as shown in Figure 0:2.

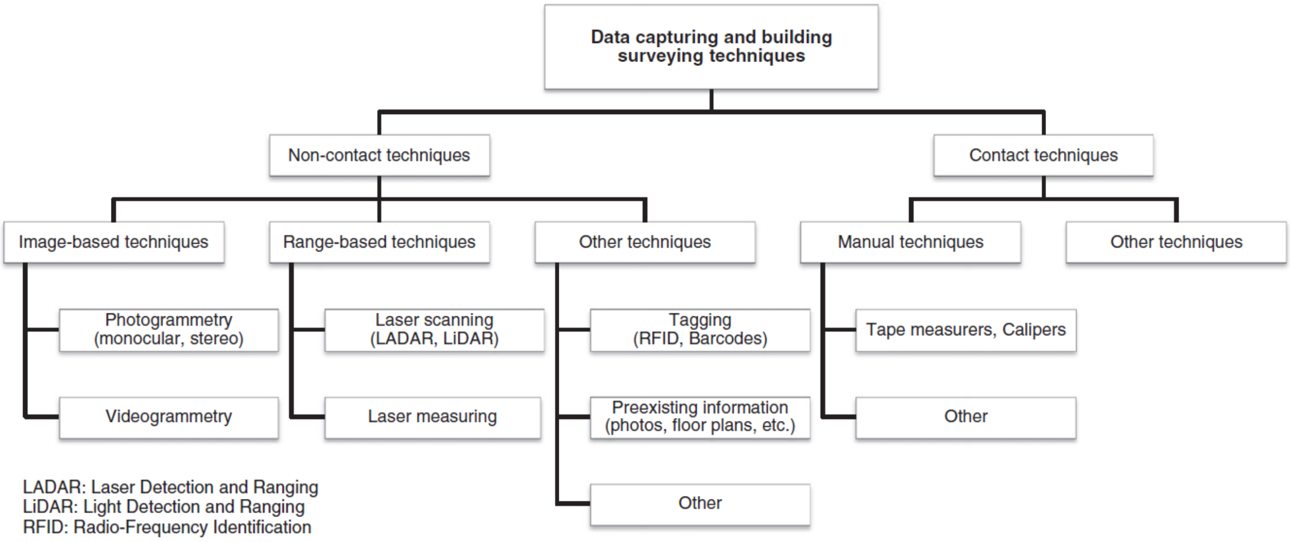


Figure 0:2: Systematic overview of data capturing and surveying techniques to gather existing building's information (Volk, et al., 2014)

Two main data capturing techniques, laser scanning and photogrammetry, are summarised in the following sections.

4.1.4.1 Laser scanning

Laser scanning has been one of the most common and popular approaches to data capture and has been broadly applied as a surveying tool within the AEC industry (Kim, et al., 2016; Wang, et al., 2016; Laefer & Truong-Hong, 2017). The collected data of the geometric surfaces of an object by laser scanners can be reconstructed to create digital 3D models (Frohlich & Mettenleiter, 2004). Flawless data collection of all surfaces has made laser scanning a prevalent technique in the AEC industry to collect a building's and infrastructure's dimensions for as-built documentation (Bhatla, et al., 2012). One of the main advantages of laser scanning is recording all physical dimensions of the environment without accidentally omitting required data from the survey. Compared to manual surveying, laser scanning eliminates errors, and mostly there is no need to assess the accuracy of results (Drago, 2010).

Although this technology has high spatial accuracy for existing building, its usage has been confronted with several challenges, especially until a few years ago (Hajian & Becerik-Gerber, 2010; Bhatla, et al., 2012; Golparvar-Fard, et al., 2011). The main drawback of laser scanning has been associated with its costs, such as investing upfront for training operators and purchasing the required equipment (Bhatla, et al., 2012; Klein, et al., 2012). Also, analysis of the output of the point clouds has required manipulation and it has been more time-consuming in comparison with other remote sensing technique like photogrammetry (Golparvar-Fard, et al., 2011). Environmental conditions, such as sun and rain, and object characteristics, such as texture, colour and reflectivity of objects, affect the precision of the point clouds acquisition (Kavulya, et al., 2011; Klein, et al., 2012). These factors have had major effects on the accuracy of the as-built model, and post processing has been required to provide reliable and acceptable recording quality (Kavulya, et al., 2011). Also, processing the results has required proper hardware and software to be able to process and manipulate a large amount of data to create the as-built model. It could be an upfront investment for some of the small companies to invest in hardware and software (Drago, 2010; Klein, et al., 2012).

Nevertheless, the hardware and software tools of laser scanning have been rapidly developing recently and the laser scanners are seen as surveying instruments which meet the requirements of industrial applications, and most of the above challenges have met over the last few years. A number of service providers offer laser scanning services, and small companies do not need to invest in the hardware, software and learning (Fabbri, et al., 2017). For example, to survey a cave, Fabbri, et al. (2017) used the service provided by FARO (FARO, 2016). Transportation of equipment was not an easy task a few years ago (Bhatla, et al., 2012), but using FARO Laser Scanner CAM2 Focus^{3D} with 240 × 200 × 100 mm dimensions and restrained weight (5 kg) allowed it to be carried in to the cave. Also, automated and semi-automated products, such as Geomagic software (2014), can be used to deal with extremely large point clouds, and post processing procedure is not time-consuming nowadays (Bouzakis, et al., 2016). However, due to the problems of laser scanning, when the researcher was surveying the case study, laser scanning was not a feasible option.

4.1.4.2 Photogrammetry

"*Photogrammetry involves deriving geometric information about an object using information derived from photographs*" (Klein, et al., 2012). Photogrammetry is a portable remote sensing technique that creates a 3D model of an object by using 2D photos (Bhatla, et al., 2012; Mikhail, et al., 2001). There are several steps to deriving geometric information through photogrammetry technique. "*Generally, it includes selecting common feature points in two or more images; calculating camera positions, orientations, and distortions; and reconstructing 3D information by intersecting feature point locations*" (Klein, et al., 2012). Commercial software packages are available to generate 3D point clouds by detecting common features in a sequence of images, such as 123D Catch by Autodesk (James, et al., 2015; Autodesk, 2015) Agisoft Photoscan (Agisoft, 2015; James, et al., 2015), Microsoft Photosynth (Photosynth, 2011) and Autodesk Photofly (Photofly, 2011). Although photogrammetry technique offers a lower cost and lower skill in comparison to 3D laser scanning, its application in the AEC industry is limited (Golparvar-Fard, et al., 2009). Environmental and site conditions, such as lighting conditions, affect the image processing for accurate photogrammetry (Remondino & El-hakim, 2006; Golparvar-Fard, et al., 2009). Especially when affordable handheld digital cameras are used to take photos, the availability of natural lighting is essential and the technique cannot be used in the presence of severe shadow line and insufficient lighting (Bhatla, et al., 2012; Omar & Nehdi, 2016). Also, dynamic objects, such as people, vehicles and people, can influence the correspondence of feature points and occlude critical building geometry. These issues can be alleviated by the right planning before taking images (Remondino & El-hakim, 2006). Another limitation is the lack of feature points caused by the appearance of similar features points in photographs or surfaces with a slight difference in texture (Remondino & El-hakim, 2006; Markley, et al., 2008). Klein (2012) summarised the advantages and limitations of 3D laser scanning and photogrammetry in Table 0:1.

Table 0:1: Comparison of 3D laser scanning and photogrammetry for remote sensing (Klein, et al., 2012)

Technology	**3D laser scanning**	**Photogrammetry**
Accuracy	Millimetre	Centimetre
Resolution	Millions of points	Hundreds of points
Equipment cost	Tens of thousands *	Hundreds
Required Skill	Medium-high	Low
Portability	Bulky*	Handheld
3D data generation	Automatic capture	Post-processing
Commercial software	Yes	Yes
3D modelling	Automatic meshing & shape extraction	Manual modelling*
Environmental challenges	Reflectivity, surface texture, weather, target movement, edges, line of sight	Feature repetition, surface texture and material, view angle, line of sight

* The equipment costs and portability of laser scanning have changed. Also, creating 3D modelling from photogrammetry has improved over the last few years.

However, due to the rapid evolving hardware and software of laser scanning over the last few years, the information provided by Klein (2012) in Table 0:1 has changed, including portability and equipment cost. Service providers like FARO (2016) have overcome the cost of equipment and training and recent laser scanners are hand-held and portable. In addition, 3D modelling for photogrammetry has improved over the last years. Golparvar-Fard, et al., (2011) presented an image-based reconstruction approach that, automatically overlayed hi-resolution photographs to 3D point cloud models. Since the accuracy of photogrammetry survey is less than a manual survey (Klein, et al., 2012), and post-processing of images have been taking considerable time, photogrammetry is not applied in this research. Due to the problems associated with laser scanning and photogrammetry a few years ago, the researcher applied the manual techniques and used SAP 2009 to fine-tune and check the accuracy of input data to an energy simulation tool (BRE, 2011) which will be explained in Chapter 7.

4.1.5 Interoperability and Interdisciplinary in BIM

The lack of interoperability between BPS tools and BIM is claimed as the reasons for scarce use of BPS tools in the early design stage (Venugopal, et al., 2012). The exchange information formats are diverse in BIM and BPS tools. Since most of their exchange information formats are proprietary, due to their commercial nature, degrees of accessibility are varied (Dimyadi, et al., 2008). Therefore, an efficient information exchange can assist project partners to achieve streamlined workflows and smooth the use of BPS tool at the early design stage (Eastman, et al., 2011, p. 100; Bazjanac, 2004). This can help to avoid data repetition and redundancy between BIM and BPS tools (Cemesova, et al., 2015).

To support multitasking within the construction industry, various applications with partly different and partly overlapping information specifications are required. Eastman (2011, p.

99) defined interoperability as *"the ability to exchange data between applications, which smoothes workflows and sometimes facilitates their automation".* Conventionally, interoperability has been based upon file-based exchange formats like DXF (Drawing eXchange Format) and limited to geometry. The earliest interoperability relied on Application Program Interfaces (APIs), which are still vital approaches for interoperability (Eastman, et al., 2011, p. 99). In the construction industry, design and construction are teamwork. To enable collaboration and communication amongst involved bodies in a project, compatible tools and broadly accepted BIM platforms are a prerequisite (Laakso & Kiviniemi, 2012). An efficient exchange can assist in achieving streamlined workflows and reduce steps for design and management. Different design and construction domains have different specification requirements supported by their own software applications. "*Interoperability, at the minimum, eliminates the need to manually copy data already generated in another application. Manual copying of partial project data greatly discourages iteration during the design, as required for finding best solutions to complex issues, such as structural or energy design*" (Eastman, et al., 2011, p. 100).

Furthermore, a fragmented construction industry had been reported as a problematic area to achieve interoperability and, in consequence, this has led to the heterogeneous adoption of information technology amongst these actors (Laakso & Kiviniemi, 2012; Tang, et al., 2010). According to Eurostat (2017), 93.3% of companies in the European construction industry have less than 10 employees. In the UK, where the total enterprises were 270,770 in 2014, the enterprises with less than ten employees accounted for 252,744 (Eurostat, 2017). "*The dominance of small actors is also common on the project level where the work of numerous sub-contractors must be coordinated. To bridge the gaps created by this challenging environment, new types of software and electronic services have been* *introduced in an attempt to unify core processes in construction projects. While only a minority of innovations stick and become integral parts of the construction process, those that do can disrupt otherwise cemented stakeholder patterns"* (Laakso & Kiviniemi, 2012). BIM data is aimed to be shared and the access control is meant to manage who can write (create or edit) or just read the data. Also, users' involvement, access and actions within the project should be traceable so that the workflows can be coordinated and managed. In addition, to improve the interoperability and create seamless workflows it must be readable and manageable with the open standard model (Eastman, et al., 2011, pp. 99-148). Although the new type of software and innovations has been introduced constantly during the past decades, adoption of IT has been uneven in the AEC industry (Laakso & Kiviniemi, 2012). The vast majority of the workforce is employed in small firms which have limited resources (Eurostat, 2017). Thus, adoption of new technologies is slow and transitions from traditional manual workflows to new collaborative processes relying on sharing interoperable data is a challenging issue (Laakso & Kiviniemi, 2012). Thereby, the heterogeneous adoption of information technologies is a natural consequence of the fragmented nature of the construction industry. However, interoperability based on an open standard, file-based exchange or server-based exchange, enjoys many theoretical advantages. "*With use of open standard, the mappings only need be translated back and forth from that single format in order to be compatible with all other applications supporting that same standard"* (Laakso & Kiviniemi, 2012). The capability of open interoperability standard and how it can assist to achieve streamlined workflows is illustrated in Figure 0:3.

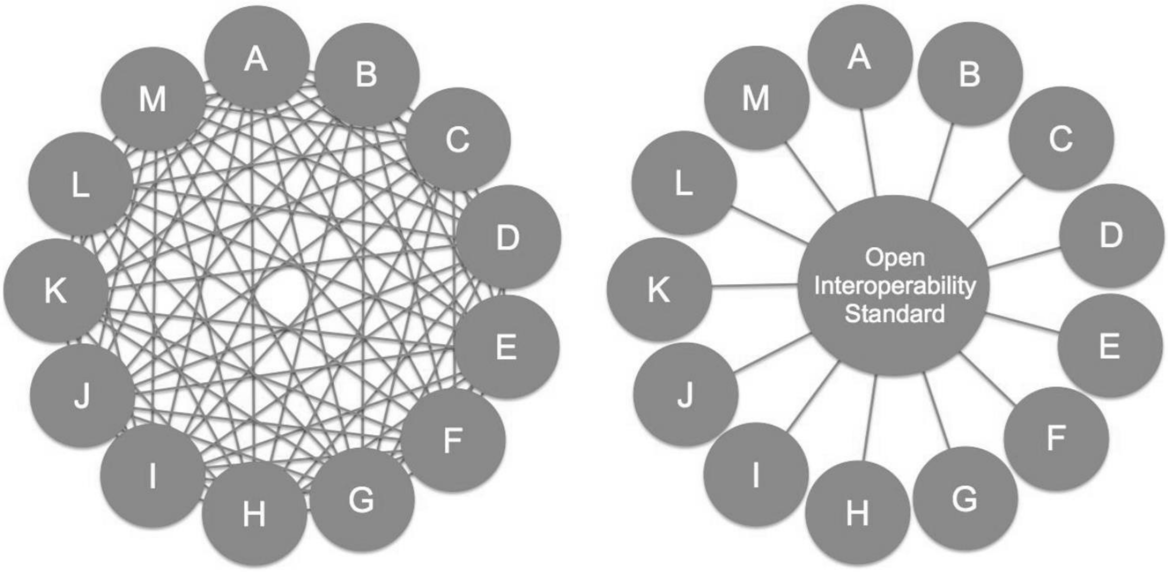


Figure 0:3: Interoperability: direct translators vs. an open interoperability standard *(Reproduction by* (Laakso & Kiviniemi, 2012) based on sources: (Gielingh, 2008, p. 755)

Use of neutral data exchange is the common practice between BIM tools and building performance analysis tools to support activities such as energy analysis, quality takeoff, cost estimation and so forth (C. Eastman, et al. 2011).

4.1.6 Open Interoperability Standards

Prior to understanding what open standard means, it is important to understand why the open standard format is important. There are three means to apply communication platforms, Bespoke, Single (Closed) and Common (Open) (Open BIM Focus, 2012). To clarify the concept a United Nations communications is used as an example. *"To function properly in the United Nations, with 192 member states and more than 50 languages, it is essential that everyone can understand what others are saying."* There are three means to reach this (Open BIM Focus, 2012):

Bespoke: "*Everyone has to learn everyone else's language".* It would be possible for four official languages, but it is impossible for more than 50 official languages. In terms of software, it is not a feasible option since it would need a dedicated protocol to translate data among enormous platforms in the AEC industry. Also, it would need to make sure that whenever a new version of a software is released, these data translations are updated as well (Figure 4.5:4).

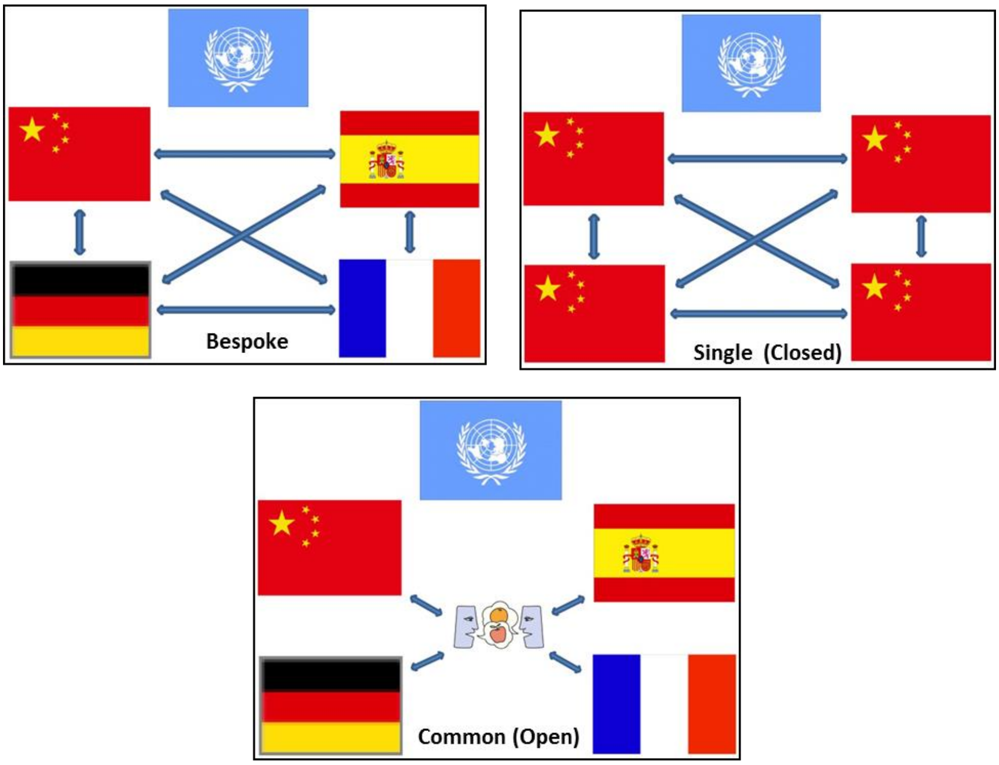


Figure 0:4: Communication Platforms

Single (Closed): "*Everyone, bar one, has to change their language*". This approach would force all delegates to speak one language which is not politically acceptable and possible. In terms of software, since there are more than one hundred BIM applications, it would mean that one vendor must dominate and impose other vendors to its specific format and functionality for all involved disciplines (Open BIM Focus, 2012). Although it is possible that one vendor could dominate other vendors, like Microsoft, it can pose serious challenges to users (McKenzie & Shughart II, 1998; Anton & Biglaiser, 2013; Flowers, et al., 2010). It might result in the growth of unfair trade practices and delay for further development of software (Anton & Biglaiser, 2013; Flowers, et al., 2010). Therefore, it is not an acceptable approach.

Common (Open): "*everyone uses their own languages with a common interpreter*." In this way, there is no need to change delegates' languages. This approach is very practical and works in the United Nations. There are six official languages (Arabic, Chinese, English, French, Russian and Spanish) of the UN, and when delegates speak their own languages, they must provide an interpretation to translate in one of the official languages (United Nations, 2013). In other words, everyone speaks their own language and all the words are going directly to a common "pool" that translates each language into every delegate's native language. In terms of software, it means that every discipline uses their own software applications, and data is translated to a common format (Open BIM Focus, 2012). This approach is the optimal solution as users do not have to understand the data format used by other disciplines and other software applications (IBC., 2011; Open BIM Focus, 2012).

There are several open BIM interoperability standards used in the AEC industry across the world. It is essential to compare different methods of data exchange and their capabilities to provide the researcher with the knowledge to find out appropriate data exchange format between BIM and energy analysis software, which is also capable for the automation of rule checking. In the AEC industry, several open BIM interoperability standards have been used, such as The Green Building XML schema (gbXML), Construction Operations Building Information Exchange (COBie) and Industry Foundation Classes (IFC).

4.1.6.1 The Green Building XML schema (gbXML)

"*gbXML is an industry supported schema for sharing building information between disparate design software tools*." (gbXML, 2013). It was developed to facilitate transmission of the information between sophisticated BIM models and various building analysis applications to improve the integration and interoperability between them (gbXML, 2014). It is one of the most broadly supported data format for exchange data between BIM models and energy analysis tools such as Ecotect, EnergyPlus and DesignBuilder (Sokolov & Crosby, 2011; GSA, 2015). gbXML enabled project participants to transfer data directly from BIM models to building energy analysis tools, therefore this open interoperability format was used for BIM simulation approach in Chapter 7.

4.1.6.2 Construction Operations Building Information Exchange (COBie)

"*COBie is an information exchange specification for the life-cycle capture and delivery of information needed by facility managers*." (East, 2013). COBie is a formal scheme to organize data from design and construction to facility management purposes, and it provides a standardized level of detail for materials, maintenance information, serial numbers, location, tag, and performance data (East & Carrasquillo-mangual, 2013). However, it does not include any geometrical or architectural data, such as walls, roofs, stairs and slabs, which are crucial for energy efficient retrofit processes. Hence, it cannot be used for this research.

4.1.6.3 Industry Foundation Class (IFC)

The IFC specification is a comprehensive data scheme and a neutral data format for exchanging and sharing information within the building and facility management industry sector (buildingSMART, 2011). IFC is the international standard for openBIM and is also registered by the International Standardization Organization (ISO) as International Standard ISO16739 (ISO, 2010). This non-proprietary data model provides an excellent framework to manage and exchange data throughout the lifecycle of a building that are used by software applications during construction or facility management processes (bSI, 2015; Khemlani, 2004). It represents geometry, performance, process and other features required for building planning, construction and management (Laakso & Kiviniemi, 2012). However, its efficiency has not ultimately achieved by various uneven implementations (buildingSMART, 2011) and its main specification does not cover an energy domain’s description (buildingSMART, 2013), Rose and Bazjanac (2015) proposed an algorithm generating space boundaries for energy analysis application from IFC descriptions of buildings.

The focus of the IFC data model is on those classes that are needed to share information rather than processing it proprietary software (ifcwiki, 2015). There are two main reasons why the IFC format as data exchange format can be used in this research. Firstly, not only is it comprised of definite components, such as walls, windows, beams and door, but also it covers the necessary concepts, including materials, activities, geometry and space which is crucial for energy efficient retrofit process (Kumar, 2008). Secondly, it is a well-suited format for the automation of rule checking and it has been globally accepted (Malsane, et al., 2015).

Interoperability between BIM and BPS tools

BPS tools to evaluate buildings performance are widely used in the later design stages, but their integration is still limited in the early design stages where design decisions have the highest impact on the final building performance (Mondrup, 2014; Hygh, et al., 2012). For example, if a design concept with a highly transparent façade for providing daylight was decided in the early design stage by combining external shading and hybrid ventilation without considering the potential issues such as glare and cooling energy, it may result in major impact on design and cost when it turns out that the initial conditions are not realistic, e.g. venting and solar shading are in use more than expected to provide thermal comfort (Østergård, et al., 2016). Despite the potential of evaluating building performance, the data obtained from BPS tools are frequently evaluative rather than proactive (Attia, et al., 2012; Kanters & Horvat, 2012). Even advanced, accurate software capable of providing a wide range of assessments and various performance indicators is usually well suited for quality control, benchmarking, and code compliance rather than accurate prediction of the performance (Østergård, et al., 2016).

There is a lack of building simulation tools providing active support and well-timed feedback on performance implications of various design variations and measures (Kanters, et al., 2014; Attia, et al., 2012). The ability of software to provide timely feedback is often referred to as "intelligence" (Batueva & Mahdavi, 2015; Attia, et al., 2011). According to a survey conducted by Attia, et al., (2011) among 230 architects to rank BPS tools selection criteria, "*usability and information management of interface*" and "*integration of intelligent design knowledge-base*" ranked higher than "*accuracy and ability to simulate detailed and complex building components*" and "*interoperability*" (Attia, et al., 2011). This means BPS tools providing feedback and guide on the performance implications have the overriding priority for most of the architects (Østergård, et al., 2016). However, according to Batueva and Mahdavi (2015), less than 8% of BPS tools listed by the International Building Performance Simulation Association (IBPSA) (2014) in the United States have the potential for early integration to provide guidance and feedback. As mentioned previously, informed decision-making at the early stages has a significant impact on final performance, but the integration of BPS tools has faced challenges that need to be overcome. *"The challenges to early stage deployment include lack of information, uncertainties, model resolution, and rapid changes of design. In addition, general challenges include interoperability, time-consuming modelling, stricter and opposing requirements, limited reuse of knowledge, and simulation guidance" (Østergård, et al., 2016).* Interoperability between BIM and BPS tools has addressed several mentioned challenges to integrating BPS tools in the early design stages, including time-consuming modelling, continuity, and interdisciplinary collaboration

(Østergård, et al., 2016). Data exchange and interoperability between BPS tools and BIM can be executed in different methods. Østergård (2016) studied the characteristics of four different approaches to combining BPS tools and BIM. These four methods were categorised by Citherlet (2001) and Petersen (2011) and included stand-alone, integrated, run-time interoperable and file exchange. These different methods, their characteristics and pros and cons are presented in Table 0:1.

Table 0:1: Characteristics, advantages and disadvantages of four different simulation methods, Adapted from (Citherlet, 2001; Petersen, 2011; Østergård, et al., 2016)

Method	Characteristics	Advantages	Disadvantage
Stand-alone	Several unrelated applications are used separately. Data interpreted by users.	Problem specific application.	No dynamic data exchange. Several interfaces. New model per application.
File exchange	Common file exchange format readable and sometimes writable from both BIM and BPS tools	Single data model. Model consistency	No dynamic data exchange. Maintenance of the data transaction feature. Several user interfaces.
Run-time interoperable	The connection (or linking) of applications at run-time. Information is exchanged in a co-operative way.	Data and model consistency. Single user interface. Dynamic data exchange. Physical model.	Maintenance of the data transaction feature.
Integrated	Applications merged at algorithmic level (Numerical calculations integrated into BIM environment).	Data and model consistency. Single user interface. Dynamic data exchange. Application maintenance.	Require knowledge in various domains.

4.1.6.4 Integration and direct links in early design

This section focuses on the integrated and run-time interoperable approaches to improving interoperability at the early design stage and adopting BIM. The challenges identified in Chapters 2 would be addressed, such as uncertainty about the quality of retrofit measure, lack of interoperability between BPS tools and BIM and time-consuming iterative modelling.

The BIM industry has evolved over the last decades and semantic data have been integrated in to the BIM software packages for analyses such solar analysis, energy analysis and so forth (Østergård, et al., 2016). Also, some software vendors, like Graphisoft and Autodesk, dynamically couple tools or add-ons to facilitate BPS (Østergård, et al., 2016). For example, Graphisoft (2015) integrates algorithms directly into the BIM software (EcoDesigner Star for ArchiCAD) and Autodesk (2015) develop their proprietary BPS tools (Green Building Studio for Revit). In addition, third party vendors such as IESVE (2015), Sefaira (2015), and OpenStudio (2015) would improve the decision making process at the early stage by providing direct links to BPS via application programming interfaces (Østergård, et al., 2016). However, the common file formats, such as gbXML and IFC, are required for some of these couplings. Several detailed simulation engines which are computationally intensive, such as Radiance (2015), Daysim (2015) and EnergyPlus (2015), can be used through various plug-ins. However, they need many inputs assigned to default values associated with particular building types (Østergård, et al., 2016). Applying cloud computing may overcome the challenges of run-time analysis by enabling rapid feedback, saving time through reducing (re)modelling and easing iterations (Østergård, et al., 2016). Graphisoft's EcoDesigner in ArchiCAD provides effortless interoperability. However, this type of integrated framework needs more intelligent guidance and basically depends on vendors to integrate performance simulation into the BIM environment (Graphisoft, 2015; Batueva & Mahdavi, 2015).

Conclusion

Many clear benefits have been reported by adopting BIM in new buildings (Browne & Menzel, 2012; Konstantinoua & Knaacka, 2011; Eastman, et al., 2011; Eadie, et al., 2013; Migilinskasa, et al., 2013). Exploiting BIM has improved sustainability, energy efficiencies, cost reliabilities, decision-making and reduced time-to-market at the early stages of new buildings projects (Tanga, et al., 2010; Eastman, et al., 2011).

However, BIM implementation in the retrofit process is almost a reverse engineering process and, consequently, the capabilities and barriers to BIM implementation in the retrofit process are, to some extent, different.

The potential benefits of BIM implementation in the retrofit process are manifold, such as the support of a decision-making process through cost and energy performance analysis, minimised costs, reduced time on site, improved collaboration, accurate visualisation (Volk, et al., 2014) and supporting sustainable design and certifications (Jalae & Jrade, 2015). However, it is not widely used in the AEC industry since its adoption has been confronted with several barriers (Volk, et al., 2014). Although a broad range of add-on applications are rapidly evolving to provide run-time coupling providing fast feedback (Østergård, et al., 2016), their applications are confronted with sociotechnical issues due to the fragmented building industry (Negendahl, 2015) and technological tools are dependent heavily and mutually on social practices (Trist & Bamforth, 1951).

Another challenge is related to the fact that there are no pre-existing models of buildings (Akcamete, et al., 2010), particularly of UK housing built before 1960 (Baeli, 2013; Dickinson, et al., 2009). One of the main barriers to implementing BIM in the retrofit process is related to the initial captured data and dealing with inaccurate and uncertain data (Penttilä, et al., 2007). Created BIM results are varied regarding information availability, required functionality and quality of information in new and existing buildings (Hajian & Becerik-Gerber, 2010; Volk, et al., 2014). The model creation in an existing building is reverse engineering process and topologic and geometric information of building have to be captured (Akbarnezhad, et al., 2012; Klein, et al., 2012; Volk, et al., 2014).

Two main capturing data techniques, laser scanning and photogrammetry, were studied in this chapter. Flawless data collection of all dimensions of the environment to create digital 3D models (Bhatla, et al., 2012) without omitting required data have made laser scanning techniques the most prevalent in the AEC industry (Frohlich & Mettenleiter, 2004; Laefer & Truong-Hong, 2017). However, a few years ago, when the researcher was exploring the benefits and barriers of each surveying techniques, applying laser scanning was confronted with several challenges including its costs (Klein, et al., 2012), being time-consuming and requiring manipulation process to analyse the point clouds (Golparvar-Fard, et al., 2011), sensitivity to the environmental conditions affecting the accuracy of the as-built model (Kavulya, et al., 2011), upfront investment on required hardware and software to manipulate large amount of data (Drago, 2010; Klein, et al., 2012). Nowadays, most of the aforementioned challenges have been met over the last few years (Fabbri, et al., 2017). Photogrammetry techniques offer a lower cost and skills requirement in comparison to 3D laser scanning (Golparvar-Fard, et al., 2009). However, due to the time-consuming post-processing and inadequate accuracy (Klein, et al., 2012) it was not applied in this research. Due to the problems associated with laser scanning and photogrammetry a few years ago, the researcher applied the manual techniques and used SAP 2009 to fine-tune and check the accuracy of input data to energy simulation tool (BRE, 2011). In addition, other challenges to improve the efficiency of the retrofit process are related to the lack of interoperability between BPS tools and BIM and the scarce use of BPS tools in the early design stage (Venugopal, et al., 2012). BPS tools play a key role in choosing optimal solutions, leading to informed decisions (Beaven, 2011; Doukas, et al., 2009). Despite the potential of evaluating building performance, the obtained data from BPS tools are frequently evaluative rather than proactive (Attia, et al., 2012; Kanters & Horvat, 2012). Even advanced, accurate software providing wide range of assessments and various performance indicators is usually better suited for quality control, benchmarking, and code compliance rather than accurate prediction of the performance (Østergård, et al., 2016). An efficient information exchange such as IFC and gbXML can assist project partners to achieve streamlined workflows and avoid data repetition and redundancy between BIM and BPS tools (Eastman, et al., 2011, p. 100; Bazjanac, 2004; Cemesova, et al., 2015).

By improving interoperability at the early design stage and implementing BIM, challenges identified in Chapters 2, such as uncertainty about the quality of retrofit measures and time-consuming iterative modelling, would be addressed.

Open interoperability standards and widely adopted open interoperability formats, including gbXML, COBie and IFC and their capabilities, have been studied. COBie does not include any geometrical or architectural data, which are crucial for energy efficient retrofit processes. Hence, it cannot be used for this research. gbXML one of the most broadly supported data format for interoperability between BIM and BPS tools is chosen for BIM simulation approach. IFC is chosen as it is the well-suited format for the automation of rule checking and it has been globally accepted (Malsane, et al., 2015).

Interoperability between BPS tools and BIM can be executed in four methods, as categorised by Citherlet (2001), including stand-alone, integrated, run-time interoperable and file exchange (Østergård, et al., 2016). The pros and cons of each approach were summarised in Table 0:1. Also, the integrated and interoperable approaches, two adopted BIM simulation approach, were critically reviewed regarding their advantages and disadvantages. These two methods will be studied in Chapter 7 through a real-world case study.

Chapter Four

Primary Data Collection

5 Primary Data Collection

Introduction

After reviewing existing research in the relevant literature, it was concluded that the knowledge of the BIM implementation in small-scale retrofit projects is practically non-existent. Thus, interviews were carried out to explore professional perspectives towards the challenges in the energy-efficient retrofit process and BIM's potentials and barriers in the energy efficient retrofit process in the residential sector.

In this research, semi-structured interviews with nine professionals in this field were conducted to explore the expert opinions of the topic. This chapter is structured as follows: Section 0 provides an introduction to the interview design and how questions were crafted, followed by the methodology adopted for the interview in section 0. Section 0 presents the approach for data analysis through NVivo data analysis software. The results of data analysis are discussed in section 0.

Interview Design

In building energy research, semi-structured interviews have often been adopted to answer the research questions (Galvin, 2015). This approach has been adopted in many prominent energy and building journals, including *Building Research and Information*, *Energy Policy*, *Energy and Buildings, Sustainable Cities and Society, Building and Environment,* and *Energy Efficiency* (Galvin, 2015).

In this research, the qualitative semi-structured interviews took place between April 2013 and July 2014 and were carried out either face-to-face or using Skype with nine professionals in Finland, UK, U.S.A and Norway. The data were collected through a recorder, and then the data were transcribed, analysed and interpreted. The intention of the interview was to explore practical applications and challenges, as well as investigating professionals' viewpoints towards the potential and challenges to exploit BIM in the process. The interview questions were designed to prompt interviewees to speak broadly about the topic area and to obtain wide-ranging insights into the technical, economic and social factors affecting the adoption of BIM in the energy efficient retrofit process.

Semi-structured interviews with open questions allow the researcher to obtain new insights and ideas which may not have been thought of the researcher. This requires that the researcher has diverse research skills, as well as technical and social background knowledge about the research topic; in this case about BIM and an in-depth knowledge about the retrofit process in the current situation. Hence, as explained in Chapters 2 and 3, the researcher strived to seek a broad knowledge about the BIM application and energy efficient retrofit process through an existing literature review and participating in international conferences to obtain sufficient knowledge and skills before carrying out the semi-structured interviews with professionals. This was an essential element to enable the researcher to pick up leads emerging within the interviews. In this research, similarly to other research in building energy consumption, the sample size was small. However, common assumptions are typically formed for interventions in the light of findings and inferences, and the findings can be generalised to the wider population (Galvin, 2015). The findings were analysed and interpreted through the coding method in NVivo to identify the main concepts to address the research questions. The interviewees were informed that their participation in the interview was voluntary. Also, they were advised that interviews included open-ended questions and the duration of the interview was no more than 15-20 minutes. However, there was no time limit to answer the questions and they were free to answer questions with their own pace. The findings of the interviews, together with results of the literature review and simulation of a real world case study, were used to develop a framework to make correct decisions during the retrofit process through BIM adoption.

The open-ended questions were classified into three sections. In the first section, interviewees were asked about their professional backgrounds, experiences, projects and their roles in delivering projects. Obtaining knowledge from professionals with diverse backgrounds assisted the researcher in exploring practical barriers and motivations to implement BIM in the retrofit process from different perspectives. Therefore, speaking about their professional background and the type of involved projects (residential, non-residential, retrofit projects, and new build projects) was important to find out how they observe barriers and motivations for BIM implementation. Also, it helped to analyse how identified barriers are associated with their background.

The second section included seven questions which were crafted to explore current trends in retrofit regarding energy efficiency and CO_2 emissions. Interviewees were asked about the driving factors and challenges in the energy-efficient retrofit process. It was essential to identify how occupants and stakeholders could be motivated to invest in energy efficiency measures and what barriers have confronted them in executing the energy efficient retrofit process. Interviewees were asked about any tools used to achieve the energy efficient process. Finally, they were questioned regarding any suggestion to improve energy efficiency or to implement BIM in the efficient process for energy-efficient retrofit, including any case study, tool, contact, reference and so forth. See appendix A for interview questions.

Snowball sampling

Researchers carry out interviews to seek useful information for a comprehensive analysis to conclude the best possible solution which could be reached (May, 2011). Nevertheless, researchers are confronted with challenges to carry out such research, including estimating the number of respondents to provide sufficient information and choosing a proper process to generate necessary information to address the requirements of their research objectives (Sarantakos, 1998). The targeted population who researchers are interested in studying and obtaining their views can be very large. However, it is not practical to study the whole group due to time and other resource limitations. *"A sample is a subset of the population that is usually chosen to serve as a representation of the views of the population"* (Ahmed, et al., 2016). A sampling technique with appropriate criteria can assist researchers to obtain thorough knowledge from a reasonable number of people in a targeted group (Burgess, 2001; Bryman, 2001). A sampling technique has been considered as one of the most proper approaches by which such information can be achieved in a way enabling the researcher to address research questions (Ahmed, et al., 2016).

Snowball or chain referral sampling has been widely used in qualitative research as a technique to obtain data from extended associations through people who share and know of others possessing specific ranges of knowledge and skills which are of interest in the research (Biernacki & Waldorf, 1981). To provide reliable information, the interview can be conducted using snowball sampling to reach relevant people in the study (Patton, 2002; Morgan, 2004). Since the number of people who are familiar with BIM in retrofitting a residential building was limited, and there is no available source for finding participants of this specific matter, snowball sampling was a useful technique to build up a network of professional contacts. Building up a network of initial contacts, connections and locating correct target areas has a profound impact on the success and accuracy of the sampling results as it is essential to find relevant credible people for inclusion in the study (Morgan, 2004; Patton, 2002). Therefore, the first rounds of interviews of relevant academic and industry BIM experts were conducted. To explore the potentials and barriers from a diverse background, interviewees were chosen based on their expertise and experiences in varied backgrounds i.e. BIM coordinator; business development director; architect; global BIM/IM Consultancy Director; structural engineer; Green Deal manager and civil engineer.

In qualitative research, to obtain the optimum data of a particular context in depth, smaller groups of professionals and practitioners are chosen based on the sound criteria to address the research objectives (Borrego, et al., 2009). In this research, the sample size was chosen based on the eventual data saturation addressing research questions. Data saturation in qualitative research means that the author reaches a point in their data analysis where it becomes “counter-productive” and additional data cannot necessarily add anything to the overall story or develop a framework, model or theory (Strauss & Corbin, 1998, p. 136). In this research, the author reached the point where similar data were observed over and over again and additional data did not add anything new and the categories were saturated – hence, sampling data was stopped to conclude the analysis.

Data Analysis Software: NVivo

The integrity of data collection, analysis and the sturdiness of processes are essential to achieve trustworthy qualitative research (NVivo, 2014; Smyth, 2004). NVivo 10 was used in this study to analyse semi-structured interviews to organise and analyse the qualitative data more efficiently and to identify potential avenues for further research. NVivo is a software developed by QSR International for use in qualitative research working with very rich text-based and/or multimedia information. “*Fundamentally, NVivo does two things: it supports the storing and manipulation of texts or documents; and it supports the creation and manipulation of codes, known in NVivo as nodes*” (Gibbs, 2002). Nodes connect the theoretical concepts or ideas, and it is an effective way of analytical thinking, which is essential in qualitative research (Gibbs, 2002).

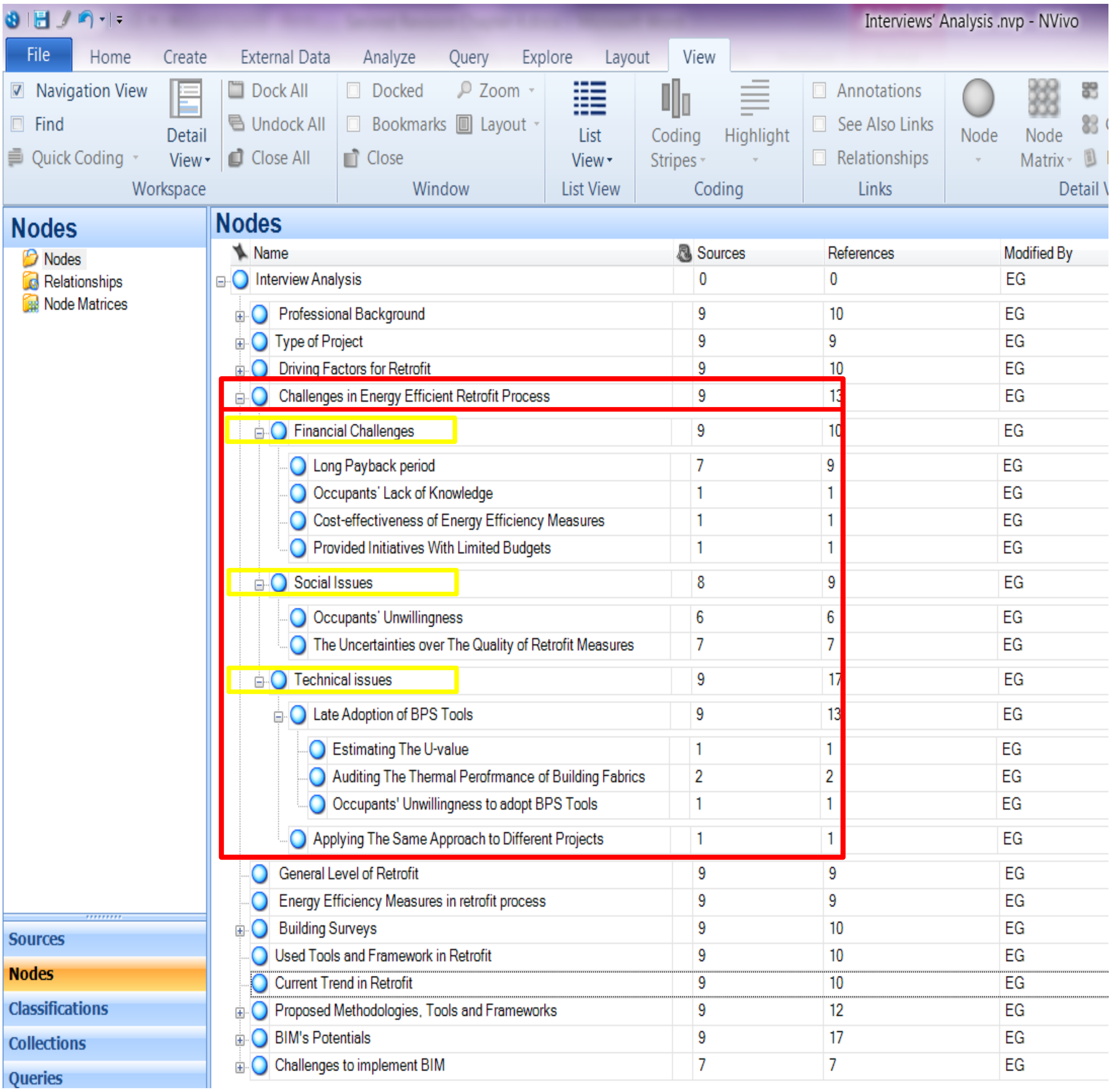
Unstructured and semi-structured interviews were analysed effectively in NVivo through analytical coding data, reviewing and exploring coding by the coding query and a classification scheme that paves the way for identification, exploration and retrieval of qualitative data (Auld, et al., 2007). In addition, the word frequency query was run to reveal the main themes in the interviews as shown in Figure 5.4:1.

Figure 0:1: Result of word frequency queries in NVivo

5.1.1 Coding

“Coding is an essential procedure. Any researcher who wishes to become proficient at doing qualitative analysis must learn to code well and easily. The excellence of the research rests in large part on the excellence of the coding” (Strauss, 1987). Coffey et al (1996) believe it is one of the principal activities in qualitative research. Many researchers start coding while they start thinking about their collected data until they have finalised the research (Gibbs, 2002). Some researchers conclude that coding is necessary (Strauss, 1987) and some realise that it is one of the central activities in qualitative research (Coffey, et al., 1996). So, it can be concluded that coding in qualitative research is essential to obtain an effective relational database to explore relationships for data analysis and to carry out trustworthy qualitative research. One of the benefits of NVivo is using a coding system to establish the relationships between principles in the data (Smyth, 2004). Coding is not about the label or name - the label is just an abstract of the concept (Gibbs, 2002). Researchers have used different words for coding such as category, index, node and code. However, NVivo has kept it simple and used just node and code terms.

Once the interviews were collected and transcribed, coding took place in NVivo 10 software. The selection of quotes during the coding process was guided by the interview questions. The quotes that shared similar characteristics were grouped under the generic characteristics of their context. For example, 11 diverse categories emerged in relation to three main issues including “*financial issues*”, “*technical issues*” and “*social issues*” under the heading of “challenges for energy efficient retrofitting in residential sector”, as shown in Figure 0:2.



Name	Sources	References	Modified By
Interview Analysis	0	0	EG
Professional Background	9	10	EG
Type of Project	9	9	EG
Driving Factors for Retrofit	9	10	EG
Challenges in Energy Efficient Retrofit Process	9	13	EG
Financial Challenges	9	10	EG
Long Payback period	7	9	EG
Occupants' Lack of Knowledge	1	1	EG
Cost-effectiveness of Energy Efficiency Measures	1	1	EG
Provided Initiatives With Limited Budgets	1	1	EG
Social Issues	8	9	EG
Occupants' Unwillingness	6	6	EG
The Uncertainties over The Quality of Retrofit Measures	7	7	EG
Technical issues	9	17	EG
Late Adoption of BPS Tools	9	13	EG
Estimating The U-value	1	1	EG
Auditing The Thermal Perofrmance of Building Fabrics	2	2	EG
Occupants' Unwillingness to adopt BPS Tools	1	1	EG
Applying The Same Approach to Different Projects	1	1	EG
General Level of Retrofit	9	9	EG
Energy Efficiency Measures in retrofit process	9	9	EG
Building Surveys	9	10	EG
Used Tools and Framework in Retrofit	9	10	EG
Current Trend in Retrofit	9	10	EG
Proposed Methodologies, Tools and Frameworks	9	12	EG
BIM's Potentials	9	17	EG
Challenges to implement BIM	7	7	EG

Figure 0:2: Coding in NVivo

Interviews of professionals in retrofit process and/or BIM

As explained earlier, the interview was semi-structured with a list of questions. According to participants' backgrounds and experiences, and depending on the situation, the questions were modified to allow sufficient flexibility. Participants were chosen based on two main professional backgrounds: BIM experts and retrofit experts.

As shown in Figure 0:1, the BIM experts group was divided into two main groups, professionals with experiences to implement BIM in new small-scale projects, and professionals exploiting BIM in retrofit projects but complex ones. To the best knowledge of the author, practical BIM knowledge is non-existent in the small-scale retrofit process, thus the researcher strived to obtain knowledge from these two groups.

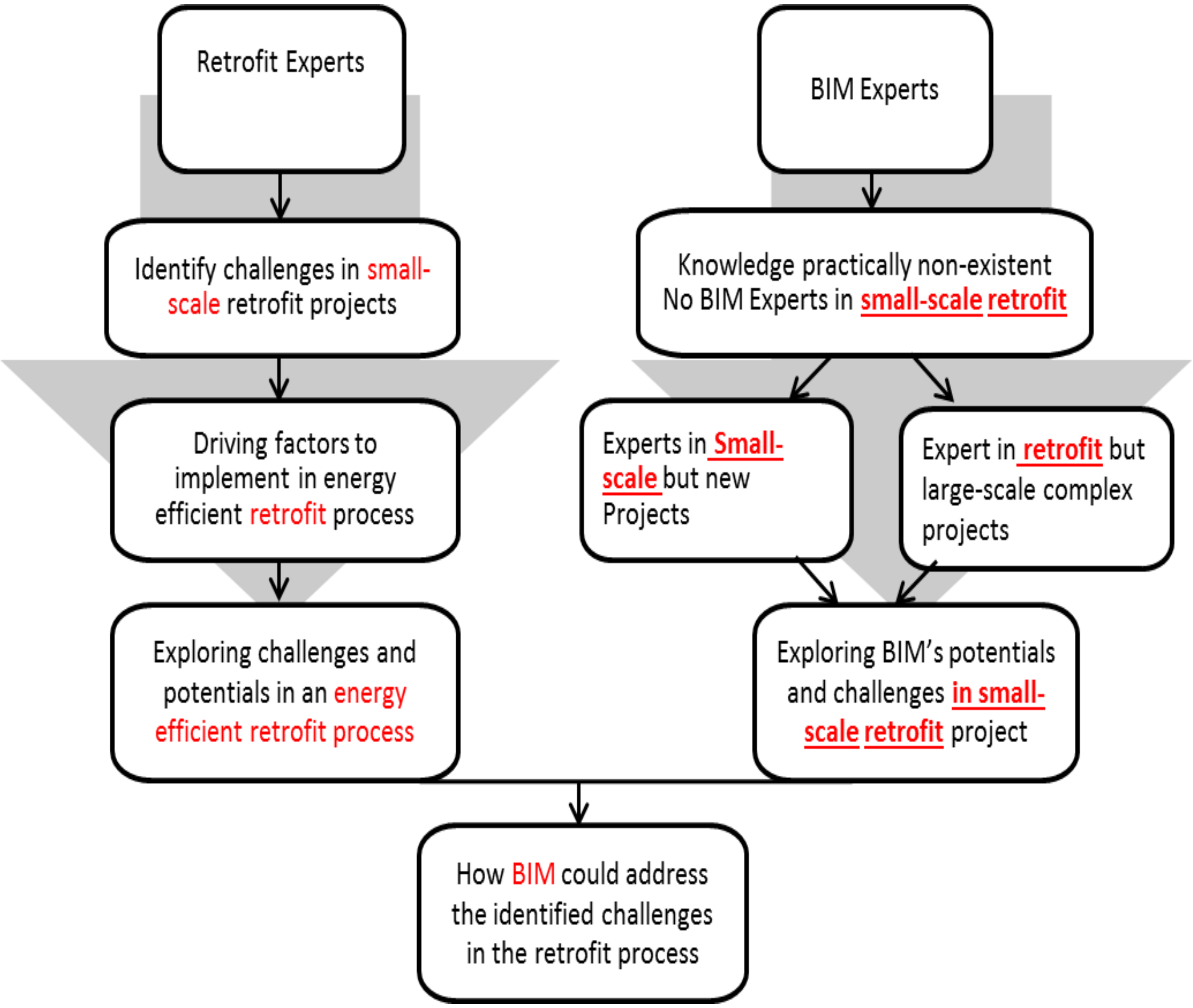


Figure 0:1: Classifying participants based on their professional backgrounds to address the challenges

Energy efficiency experts were interviewed to explore the practical challenges in retrofit projects and to evaluate if BIM's potentials could address identified challenges. Participating Interviewees in the interviews are shown in Table 0:1

Table 0:1: Interview Participants

Job Title	Country	Expertise	Duration
Global BIM/IM Consultancy Director, AECOM	UK	BIM implementation	0.5 hour
Director of the Real-time and Automated Monitoring and Control Lab	US	BIM implementation	1 hour
Chief Executive Officer (CEO) at Data Performance Consultancy Limited	UK	Experienced in the retrofit process	1.5 hours
Senior Vice President Business Development at Skanska Oy	Finland	BIM implementation	0.5 hour
Director in JLO Innovation Ltd, BIM strategy and implementation	UK	BIM implementation	0.5 hour
Architect and Urbanist in John McCall Architects	UK	Experienced in the retrofit process	2 hours
Design Manager at Tønsbergprosjekt, Skanska	Norway	BIM implementation	1 hour
Architect at Ryder Architecture	UK	BIM implementation	2 hours
Head of Asset Management in Plus Dane Group	UK	Experienced in the retrofit process	2 hours

The Interviews were analysed using a thematic approach, classifying the data into identified main issues. The results of the interviews are analysed as follows: the challenges and driving factors in energy efficient retrofit process in residential sectors, BIM's implementation potentials and challenges in the energy efficient retrofit process.

5.1.2 Challenges for energy efficient retrofitting in residential sector

Based on the interviews' data analysis, irrespective of their professional backgrounds, all participants emphasised that BIM implementation in the energy efficient retrofit process benefits the residential sector. However, its adoption has been confronted with several economical, technical and social barriers.

5.1.2.1 Financial issues

The majority of participants highlighted the importance of financial issues to achieve energy efficient retrofit process for several compelling reasons.

- Most of the **provided programs and initiatives with limited budgets** could not address the homeowners and tenants requirements (Interviewee A, 2013).
- The **cost-effectiveness of energy efficiency measures** are a very complex issue to determine and "*it is hugely complicated to balance investments against the savings*" (Interviewee E, 2014).
- Due to the **occupants' lack of knowledge** about the investment, most retrofit projects are not as efficient they could be, since the majority believe in investment in the level of just simple cost rather than an understanding of being cost effective throughout the lifespan of projects (Interviewee B, 2013).
- **Long payback periods** and the **lack of clients' knowledge** in private house ownerships over provided incentives have faced the retrofit process with challenges (Interviewee H, 2014).
- The long payback period could be considered as a **socioeconomic issue**. When the payback period is not short enough for customers to appreciate the benefits of extra investments, there would be a lack of customer demands for investments and motivations for contractors to achieve high energy-efficiency (Interviewee D, 2014).

5.1.2.2 Technical issues

All participants believe that late adoption of Building Performance Simulation (BPS) tools in the retrofit process is one of the most critical issues in achieving the energy efficient retrofit process. There are several reasons for late adoption of BPS tools in the retrofit process.

- Interviewee B (2013) emphasised one of the most serious technical challenges is **estimating the U-Value** of building fabrics precisely and it is not just associated with the retrofit projects, even simulation results of new buildings do not always reflect the reality and the assumed consumption could be completely wrong.
- **Assessing and auditing the thermal performance of building fabrics** is still a challenge (Interviewee H, 2014). There is a lack of clear qualitative and quantitative practical knowledge and evidence for **input data in BPS tools** since the theoretical evidence does not support the practical evidence if the variables are not all met on the site (Interviewee B, 2013). The problem is that the current approach to model energy consumption of existing buildings is not imparted from reality (Interviewee B, 2013; Interviewee I, 2013). Some people argue that since creating simulation environments requires many assumptions, one of the most important factors is estimating U-Value, and there is no accurate approach to do it, hence they do **not perform energy simulation** (Interviewee B, 2013). The Horizon 2020 program made an announcement recently that accuracy of energy analysis based on the assumptions is a major issue. Some argued that the simulation could be 60% off and it is very hard to rely on it (Interviewee B, 2013).
- In addition, **applying the same approach to different projects** regardless of their unique characteristics, age and construction types. leads to making inappropriate decisions in the retrofit process which is one of the main challenges in the current situation (Interviewee I, 2013).

5.1.2.3 Social issues

The occupants' unwillingness to adopt energy efficiency measures are considered as a fundamental issue in improving the uptake of energy efficient retrofit as reported by the majority of the participants.

- Interviewee A (2013) mentioned his/her experiences as a contractor in social housing projects, stating that "*despite the fact that energy efficiency measures were supposed to be done for free for them,* ***people were unwilling to adopt*** *them as these measures were disrupting their daily life. Informing occupants about the potential benefits versus their investments over the lifespan of the house and minimising the disruption time could increase the demand to deliver energy efficient retrofit process*" (Interviewee A, 2013).
- Another issue is related to the **uncertainties over the quality of retrofit measures** and mistrust of energy companies, contractors and their services highlighted in the interview by the majority of participants.
- An additional barrier is due to **the lack of occupants' knowledge** about the potential benefits of different energy efficiency measures versus their investment (Interviewee I, 2013; Interviewee F, 2013). Interviewee B (2013) stated, "*customers are more interested in upgrading mechanical systems as the lowest hanging fruits compared to improving the building fabrics to improve the energy performance*". "*Although improving building fabrics could usually cause more disruption, it offers greater opportunities to reduce* CO_2 *emissions*" (Interviewee E, 2014).

5.1.3 Drivers to improve the energy efficiency

- **Reusing and retrofitting** a building that could otherwise be demolished provides substantial economic and environmental benefits and it has been considered a strong motivation for retrofitting (Interviewee E, 2014). Retrofit projects have a set of constraints compared to new building projects, such as load-bearing structures, however involved bodies should consider them as opportunities to cut down the carbon footprint. For example, reusing load-bearing structures, steel and concrete, offer economic and environmental opportunities compared to the new projects as reusing the structure by itself reduces the carbon footprint (Interviewee G, 2014).

- Driving factors to retrofit housing is highly depend on the type of housing, for example, driving factors for social housing are very different compared to privately owned houses (Interviewee A, 2013). In social housing, mostly **legislation** is the motivation to perform retrofitting, however in private ownership, the motivation might be interior **re-planning, requiring more efficiency, reducing the energy bills and changing the use of space**, for example reconfiguration suiting the requirements of an ageing population (Interviewee H, 2014; Interviewee A, 2013; Interviewee E, 2014). Another example of changing the use and function as a motivation to retrofit, was Manchester Central Library. The functionality of the library has been changed throughout the years and it required reassessment to address the requirements of the library's function for the 21st century with a large number of digital media, different research methods, different interaction approaches of people with books (Interviewee H, 2014).
- All participants highlighted the importance of **saving energy and requiring more energy efficiency** to perform retrofit. For example, in Manchester Central Library, the old boiler with limited control options was replaced with a high-energy efficient boiler. The building fabric was insulated, glazing was replaced and other energy

efficient measures were implemented to achieve Excellent BREEAM rating (Interviewee I, 2013; Interviewee H, 2014).

- One of the main driving forces for more energy efficient homes is the **government**, through introducing a **range of schemes** to reduce CO_2 emissions to achieve the climate change target by 2050. Many schemes have been introduced to improve energy efficiency within domestic households in the UK, such as the Carbon Emission Reduction Target (**CERT**), Community Energy Saving Programme (**CESP**), Energy Company Obligation (**ECO**) and **GREEN DEAL** (Interviewee C, 2014). However, the 44.4% of participants mentioned that those schemes have to be improved to address the occupants' requirements, for example, GREEN DEAL is not very appealing in practice (Interviewee H, 2014; Interviewee I, 2013; Interviewee C, 2014; Interviewee F, 2013), as explained in chapter 3, section 3.4.2.
- The majority of interviewees highlighted the importance of **financial incentives** to improve energy efficiency in the UK. **VAT recovery** and more financial incentives could be beneficial to achieve the energy efficient retrofit process (Interviewee A, 2013; Interviewee B, 2013). However, "*there is no practical approach to measure and compare the* ***tax incentives versus the cost associated with the retrofit measure****, and owners are often left to deal with this fundamental question as to whether retrofit is cost effective for them*" (Interviewee B, 2013). Nevertheless, the **high price of energy bills** has forced occupants to implement energy efficiency measures, such as upgrading the heating systems, heat recovery and monitoring the energy performance of the building (Interviewee A, 2013; Interviewee I, 2013).

5.1.4 BIM potentials in energy efficient retrofit process

- Interviewee D (2014) highlighted the importance of BIM in the small-scale project and stated that in many cases, it might be more useful to start with **small simple residential projects and after learning BIM potentials**, implement it in huge complex projects. We have been implemented BIM for new residential construction in Finland, Norway and Sweden. We do not believe that BIM should be implemented in massive and complex projects only. Although BIM does not necessarily bring new creative ideas to the project, it allows those creative ideas to be **communicated in a transparent way** people understand (Interviewee G, 2014).
- The majority of participants highlighted the importance of **adopting BIM at a very early stage** of the retrofit process where design decisions have the highest impact on the final building performance. Implementing BIM just as a modelling tool improve the energy performance analysis through getting **access to the geometry information** for energy simulation, which is extremely helpful to expedite the retrofit process. However, exploiting BIM as a federated model could improve the energy efficient retrofit process to a greater extent (Interviewee E, 2014; Interviewee B, 2013).
- One of the main advantages of exploiting BIM is providing the opportunity to **compare different solutions and choose optimal options**, leading to an informed decision and determining in the early design stage what level of retrofit is required (Interviewee A, 2013; Interviewee D, 2014). Informing clients about the possible options, such as different insulation, heating systems, glazing systems, and providing them with accurate results via digital tools addressing predefined performance

criteria assist in making clients sure about the quality of retrofit measures (Interviewee A, 2013; Interviewee E, 2014; Interviewee D, 2014).

- In addition, BIM could **speed up the retrofit process on site**. Although the setup phase might take more time than traditional process, it speeds up the retrofit process on site to **minimise the disruption** where the house is occupied (Interviewee F, 2013).
- For example, BIM implementation in the retrofit process of Manchester Central Library offered many benefits to the project from thermal performance and facility management perspectives. Interviewee H (2014) stressed that retrofitting the Manchester Central Library without BIM would have been very challenging. **Collaborating with involved bodies** in three-dimensional coordination to improve the retrofit process predominantly with phasing and feasibility of services in the lower ground floor to integrate into the building. Obtaining a clear understanding of certain elements of services in the very early stage of the retrofit process saved time considerably. Also, from a thermal performance point of view, comparing different glazing elements, their **performance and cost analysis** on different options assisted the involved bodies in realising the advantages and disadvantages of the various applications within the Manchester Central Library project. In addition, from a facility management (FM) perspective, all information, including services, floor finishing, lighting fixtures and so forth, assisted the team to **visualise, control and monitor all aspects** of the project through the three-dimensional model (Interviewee H, 2014). Analysing the **energy performance, acoustics performance and fire design** were considered as factors in the potential of BIM to retrofit the Manchester Central Library, although due to the lack of cross-compatibility between

the software at the time retrofit was done, 2010-2014, not all BIM potentials were achieved (Interviewee H, 2014; Interviewee E, 2014).

All participants believed BIM could assist in achieving an efficient process for energy efficient retrofit process. However, they noted that there are also some challenges to implement it in the retrofit process.

5.1.5 Surveying approach in retrofit process

- The majority of interviewees stated that **laser scanning** has been one of the most common and reliable surveying approaches that has been broadly adopted in the AEC industry. The data collected from laser scanning technology can be used to create a 3D model and achieve accurate data of buildings' dimensions. Two interviewees underlined several advantages of laser scanning. One of the biggest advantages of laser scanning technology is **eliminating errors and omissions** in the required data from the survey, and accessing a rich data model (Interviewee D, 2014). Also, using laser scanning could **save time and be very cost effective** especially for listed buildings, since an error in heritage buildings could not only cost a lot on the entire project but also, it might be impossible to rectify an occurred error. Although laser-scanning technology can be used to recreate three-dimensional model, the process of scan to BIM is not completely automated. There is room for improvements in automation of capturing the geometry for energy analysis (Interviewee H, 2014).
- The other surveying approach is using the **Ground-penetrating radar (GPR)** to infer information on the physical and geometrical condition of the building fabrics, as it was used in Manchester Central Library (Interviewee H, 2014). GPR has been

recently established as one of the most powerful and effective approaches in building and road-surveying (Benedettoa, et al., 2017). According to interviewee H (2014) GPR is ultrasound scanning of structure and although it does not provide us with the specification of materials, for an example it provides how the moisture works in the fabric, and the data can be used to plot the thermal path.

- The other adopted survey approaches in the retrofit process include **blower door tests** to measure the airtightness of buildings (Interviewee B, 2013; Interviewee G, 2014), thermal images to explore opportunities for improvement in the building façade (Interviewee I, 2013), and **SAP** and **PAS2030 guidelines** which can be used to produce **EPC** or a required Green Deal Assessment report (Interviewee C, 2014; Interviewee F, 2013). However, three out of nine interviewees believe that SAP calculations cannot accurately be relied upon (Interviewee F, 2013; Interviewee C, 2014; Interviewee I, 2013). Interviewee F (2013) mentioned, *"clients expect to see SAP calculations and EPC, regardless of accuracy. Although the physical challenges are associated with the specific requirements of the buildings in terms of age, construction, type, orientation and so forth, SAP calculations do not consider these factors. However, SAP calculations are a compulsory measure to sell or rent property, so SAP is used although it is not useful at all".* Interviewee C (2014) highlighted the same concern by saying energy performance simulations based upon the SAP calculations have standard occupancy and usage patterns which are typical values of quantities. However, in real life, they vary substantially. Therefore, capturing data techniques should be improved to be beneficial in exploiting BIM in the retrofit process.

5.1.6 Challenges to implement BIM in small-scale retrofit in residential sector

- One of the nine participants believed that BIM can benefit complex projects as more cooperation and collaboration is required due to the complexity of projects. Small-scale projects such as **housing with no complexity cannot benefit from BIM implantation** as much as complex projects do (Interviewee F, 2013). However, 78% of participants disagreed and stated that this **misconception** is one of the main barriers to the implementation of BIM in the AEC industry.
- All participants believe the **lack of interoperability** between architectural models and BPS tools at the early stage of the retrofit process is one of the main barriers to evaluating energy performance where design decisions have the highest influence to achieve energy efficient process. The lack of cross compatibility was reported by interviewee H (2014), who was involved in retrofitting Manchester Central Library. As he underlined, Due to the **lack of cross-compatibility of softwar**e, much more information should be disseminated. In most cases, any output from Revit model faced the complexity of modelling for thermal, acoustic, and CFD analysis and fire design. All those elements and strands need to be done individually and we didn’t make benefits of the actual model information as it should be from live model. Furthermore, interviewee F (2013), who strives to implement BIM in their company through a bottom-up approach, made a similar point regarding interoperability: We confront challenges to implement BIM due to incapable interoperability amongst software in our company and since we work with private sector there is no pressure in terms of **clients’ demands**, BIM is used as a stand-alone for majority of projects.
- “To perform energy analysis, the geometry of the building, U-value of building fabrics and the inlet and outlet of the building systems are essential. A lot of existing

buildings do not have even blueprints and recreating the geometry of the model via traditional survey devices is very time consuming" (Interviewee B, 2013). **Capturing data from existing buildings** and uncertainties over the accuracy of captured data were highlighted by the majority of participants as a barrier to implementing BIM at the early stage of the retrofit process. **Inaccurate and questionable assumptions in BPS** tools might result in misleading involved bodies to execute insufficient energy efficiency measures (Interviewee C, 2014).

- BIM being mandatory for government projects can be considered as a driving factor to implement BIM. However, there is a **lack of customer demand** within SMEs for exploiting BIM (Interviewee F, 2013). BIM is currently used mostly as a stand-alone tool in companies since there is no customer demand to implement BIM as a collaborative process. A large amount of data from building fabrics and openings should be captured to create the model, and it is challenging without the collaboration of clients providing required data. More collaboration with clients would allow companies to achieve information packages and pave the way for the model to compare various potential options and choose the optimal solution from the outset of the project. Gaining a **clear understanding of BIM benefits, and its socio-economic potentials in projects by clients** would be a key driving factor in order to implement BIM (Interviewee F, 2013).
- Implementing BIM in Manchester Central Library is a good example to prove retrofit projects can benefit considerably by BIM implementation. Although the adopted surveying approach in Manchester Central Library, which was renovated 2010-2014, was almost 10 times more expensive than traditional ones, it allowed a federated model to be built which was very cost effective as it was used for various

performance simulations and also enabled facility management through the 3-dimensional model (Interviewee E, 2014).

5.1.7 Suggestion to implement BIM in the energy efficient retrofit process

- Three out of the nine interviewees underlined that one approach to implementing BIM in retrofit projects was to incorporate it into a **more definitive EPC at the point of sale with a database set up at the Land Registry** for open resourcing (Interviewee C, 2014; Interviewee F, 2013; Interviewee H, 2014). Access to the building construction and occupancy assessment information would allow for better data mining for a more effective analysis of energy efficiency measures (Interviewee H, 2014). The setup database would be extremely important to integrate into BIM and combining buildings into a larger database make also the city smarter (Interviewee C, 2014).
- **Educating occupants** to interact with energy efficiency measures can be very constructive. Occupants often struggle to use the services in the way they have been designed (Interviewee E, 2014). **Enhancing end-users' knowledge** about the benefits of energy efficient measures, for example how much could be saved on energy bills, and having a clear understanding how and why inhabitants react to the measure is critical to improve energy efficiency (Interviewee F, 2013; Interviewee G, 2014).
- **Improving interoperability between architectural models and BPS tools** would pave the way to improve the energy efficiency of the retrofit process. Providing a practical example of BIM implementation in the small-scale energy efficient retrofit process could be used as a framework or as guidelines for SME to adopt BIM (Interviewee I, 2013; Interviewee C, 2014).

Discussion and conclusion

The qualitative semi-structured interviews were conducted with nine academic and industry experts in Finland, the UK, US and Norway to explore BIM's potential to address the identified challenges in the energy efficient retrofit process and the challenges to implementing BIM in the process. The interview questions were designed to prompt interviewees to speak broadly about the topic area. To provide reliable information, the interviews were conducted using snowball sampling to reach relevant people in the study (Patton, 2002; Morgan, 2004). Since the number of people who are familiar with BIM in retrofitting a residential building is limited and there is no available source for finding participants of this specific matter, snowball sampling was a useful technique to build up a network of professional contacts. The sample size was chosen based on the eventual data saturation addressing research questions.

The theoretical concepts and ideas were connected by coding to explore the relationships between principles in the data. Therefore, the coding of collected and transcribed interviews took place in NVivo 10. The coding process of quotes was guided by the interview questions. The quotes that shared similar characteristics were grouped under the generic characteristics of their context. Using NVivo assisted the researcher to group the similar characteristics easier by classifying them in codes and sub-codes. This helped the researcher to simply organise and discuss the shared similar ideas under their main headings.

The results of the interviews were as follows:

To achieve the energy efficient retrofit process, three main barriers were identified - financial, technical and social issues. According to the participants, ineffective programmes and initiatives, lack of lifecycle cost analysis, long payback period, late adoption of BPS tools, uncertainty over the quality of the retrofit measures, lack of clients' demand in non-governmental projects, lack of occupants' knowledge over the potential benefits versus their investments, and inaccurate SAP calculations have been reported as the main challenges in achieving energy efficiency.

Modelling, as one element of BIM, expedites the energy performance analysis through access to the geometry information. It provides the opportunity to compare different potential options and choose the optimal solution at the very early stage of the retrofit process, where design decisions have the highest impact on the final performance. Comparing different options with 3D visualisations, and obtaining a clear understanding of procedures, ensure the clients about the quality of the retrofit process leading them to make informed decisions. Speeding up the retrofit process on site and minimising the disruption for occupants is very important to implementing energy efficiency measures especially for aged people.

Although eight of the nine participants believed that BIM implementation benefits the energy efficient retrofit process in the residential sector, there are some challenges to implementing BIM. A lack of interoperability between BIM and BPS tools at the early stage of the retrofit process was reported as the main barrier to implementing BIM in the retrofit process. In addition, the majority of participants underlined the uncertainty of captured data and using questionable assumptions in BPS tools created a misleading decision-making process. Furthermore, there is a lack of client demand with SMEs for exploiting BIM in the domestic retrofit process.

Several suggestions were recommended to implement BIM in the small-scale retrofit process. Improving the interoperability between the BIM and BPS tools would assist to improve the energy efficiency. Providing a practical example of BIM implementation in small-scale energy efficient retrofit process could be used as a guideline for SMEs to adopt

BIM. In addition, involving and interacting with clients through 3D visualisation and providing them with a clear understanding of the potential benefits versus their investments at the early stage would improve the occupants’ knowledge about the energy efficiency measures and reassure them about the quality of measures. Incorporating BIM into a more definitive EPC at the point of sale, with a database set up at Land Registry for open sourcing for better data mining, could improve BIM implementation in the retrofit process.

Although several challenges were identified through the interviews, the interoperability between BIM and PBS tools was identified as the main challenge. Improving it would also build the foundation to solutions of the other challenges.

Chapter Six

Requirements for the Experiment

6 Requirements for the Experiment

Introduction

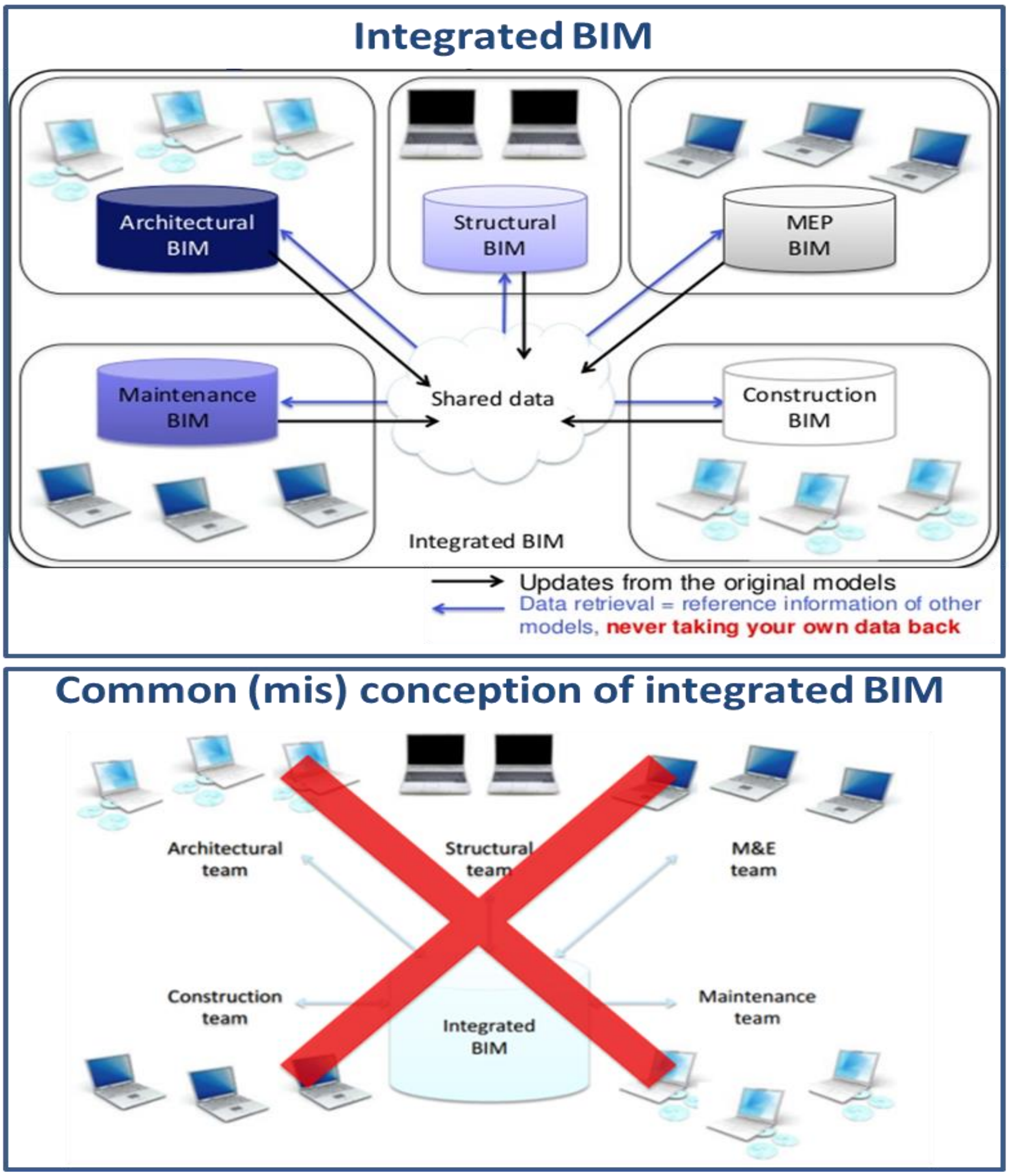
Gaining a good knowledge about the BIM tools and quality checking software, their applications and potentials in building design will assist to select an appropriate data quality checking software and BIM tool which fulfils the requirements of the research.

In Chapter 5 the importance of the data exchange and interoperability between BPS and BIM tools to improve the efficiency of the energy-efficient retrofit process was discussed. The success of data exchange is largely dependent on the quality and transparency of shared information (Nicolaou & McKnight, 2006; Li, et al., 2006). Therefore, this chapter reviews the quality of shared model in several sections as follows: Section 6.2 reviews the importance of the quality of the shared model, automated rule checking and rule-based checking. Section 0 compares two commercial applications for automatic rule-based checking to select the right model checking software for this research. BIM's tools and platforms, as well as two widespread BIM tools, including Revit and ArchiCAD, are reviewed regarding their file formats and their interoperability with energy simulation tools in Section 0.

The Importance of the Quality of Shared Information in the Model

Prior to understanding the importance of the quality of shared information in a model, it is essential to understand what 'model' refers to. "*Model in its broadest sense is the cost-effective use of something in place of something else for some cognitive purpose. It allows us to use something that is simpler, safer, or cheaper than reality and enables us to cope with the world in a simplified manner, avoiding the complexity, danger, and irreversibility of reality*." (Rothenberg, 1989). The shared model must provide the necessary information for the intended aims, despite the common misconception of integrated BIM being one model where everyone is working with the same data (Kiviniemi, 2005). Since different domains in the architecture, engineering and construction (AEC) industry perform different tasks, therefore the model for each of these diverse domains must be different.

As shown in Figure 6.2:1, each domain imports the required data from the reference models to their models (Berlo, 2015). In other words, integrated BIM refers to the whole concept of using shared data by each domain, instead of working on one BIM model by all domains.



Integrated BIM

Common (mis) conception of integrated BIM

Figure 0:1 Sharing information/data between domains and common (mis)conception of integrated (Kiviniemi, 2005)

This is inevitable owing to the fact that "*a model represents reality for the given purpose; the model is an abstraction of reality in the sense that it cannot represent all aspects of reality*."' (Rothenberg, 1989).

Several studies have been conducted in operations management, business and marketing over the role of data quality for data exchanges (Nicolaou & McKnight, 2006; Mukhopadhyay, et al., 1995; Hartonoa, et al., 2010). More research in the built environment would be needed to identify the importance of quality of shared information. Nicolaou and McKnight (2006) studied the role of data quality in the success of early stage interorganisational data exchanges. Their study suggested the success of using the exchanged data can be improved by applying the appropriate control system over the quality and transparency of information (Nicolaou & McKnight, 2006). Also, Li, et al. (2006) concluded that the success of data exchanges depends strongly on the quality of shared information, where quality refers to accuracy, accessibility and usefulness of the shared information. Researches in other fields with some similarities with the built environment show the significant role of the quality of shared information in the initial stage of the process to make a proper decision (Nicolaou & McKnight, 2006; Mukhopadhyay, et al., 1995; Hartonoa, et al., 2010; Ding, et al., 2006).

The following sections review how automated rule-based quality checking in the built environment has been initiated, processed and improved to be implemented in building design. Respectively the automated quality checking and rule-based checking applications are critically reviewed.

Automated rule checking

There is clear evidence of BIM's potential in the AEC industry, and users have commenced using one or more BIM platforms, fabrication and supporting the design (NBS, 2015; Solihin & Eastman, 2015). With the production of more detailed and complex building models offered by BIM tools, visual inspection is no longer sufficient to ensure the quality of BIM models (Solihin & Eastman, 2015). So, an automation of checking with minimum user interventions is required to identify potential issues at the early stage of design (Ding, et al., 2006). As the AEC industry is shifting toward more semantically rich BIM from 2D Computer Aided Design (CAD), the development of automated rule checking of building designs using model checking software is becoming a realistic prospect (Malsane, et al., 2015).

However, computerising rule-based checking presents a major challenge to the AEC industry. Consequently, automated rule checking of building designs has been an active field of research since the 1960s (Nawari, 2012a). In 1996, Fenves (1996) made the initial effort and introduced a decision table formulation for rule checking. The brief history of efforts in automation building code-checking is covered by Eastman et al. (2009) and Nawari (2012). Eastman (2009) surveyed some progress over rule-based checking system in the last few years. A survey of extent literature review has shown several research activities in this field. Some have put focus into the interpretation of rules into computable forms, such as using RASE (Requirement, Applicability, Selection, Exception) tagging mechanism (Hjelseth, 2011). Some focus on the implementation of computable rules applying specific rule engines or standard techniques. For instance, Beach et al. (2013) used DROOLS open source rule engine through extending the RASE mechanism, and Nawari (2012b) introduced the use of the SmartCode tagging. Others focused on the rule-checking for very certain problem domains such as a code-checking application for building envelop designs (Tan, et al., 2010).

One of the recent projects is the AutoCodes project developed by Fiatech to enable a digital review process (Fiatech Regulatory Streamlining Committee, 2012). "*However there is some level of inconsistency because of human judgement that fills in the ambiguities, incorporating experience and unwritten local adaptation of the rules*." (Solihin & Eastman, 2015).

Studying the history of automated code checking with the initial effort in 1996 indicates that this is not a new concept in the built environment. However, there are barriers to the wider spread of its use in the AEC industry. All project participants need to be educated to understand the process of shifting from inefficient 2D paper-based checking process to efficient and consistent use of BIM (Fiatech Regulatory Streamlining Committee, 2012).

6.1.1 Rule-based Checking

According to Eastman et al. (2009), as BIM's role itself has evolved, rule checking has covered a wide scope of several specialized types of rule checking within the AEC industry. They classified scope of the rules into the following categories:

- *"Check for well-formedness of a building model. These rules primarily check syntactic aspects of model against set of standards for the IFC or for other model views.*
- *Building Regulatory code checking.*
- *Specific client requirements such as requirement for hospital design.*
- *Constructability and other contractor requirements.*
- *Safety and other rules with possible programmed corrective actions.*
- *Warrantee approvals.*
- *BIM data completeness for handover to the facilities management (FM)." (Solihin & Eastman, 2015).*

Effective rule checking software has been developed during last two decades, although it is still evolving. Rule checking systems are large applications and need considerable software utilities to offer the functionality in rule derivation, building model preparation, rule execution, and rule reporting, and their needed internal capabilities (Figure 6.3:1) (Eastman, et al., 2009).

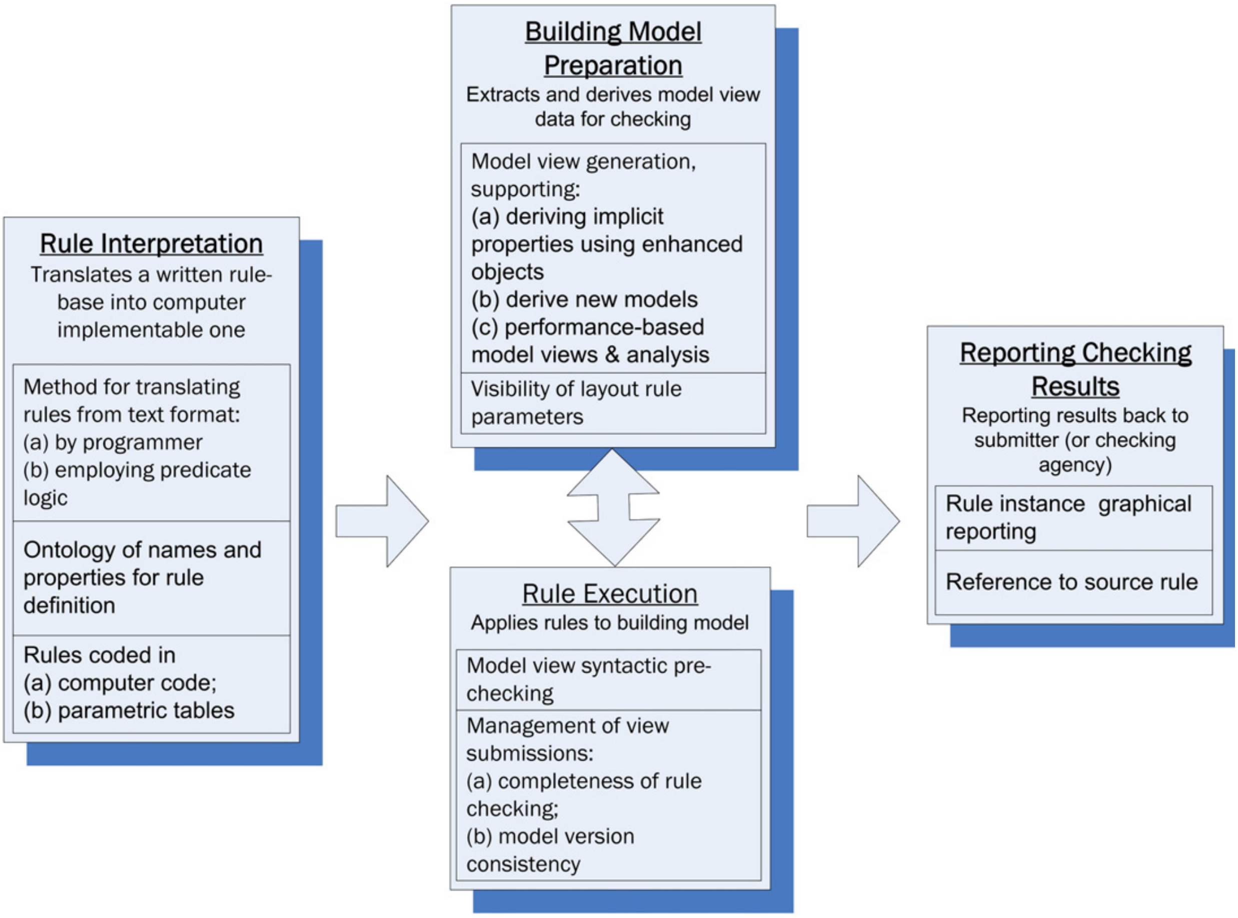


Figure 0:1: The four classes of functionality a rule checking system should support: Rule derivation, building model preparation, rule execution, and rule reporting, and their needed internal capabilities.

In the model structure, the fundamental operation is the reading of attribute values such as material type, a reference to geometric placement and so forth. Therefore, the model structure can be simple (just reading of attribute values of material type) or complex (reading of attribute values of both material type and geometry) (Solihin & Eastman, 2015). Solihin and Eastman (2015) classified rule checking into four general classes of rules according to their typical uses and complexity involved for each classification of the rules (Figure 0:2). It assisted the researcher to understand each class of rules and its involved complexity level to identify which data quality checker application can be adopted to address the requirements of this research.

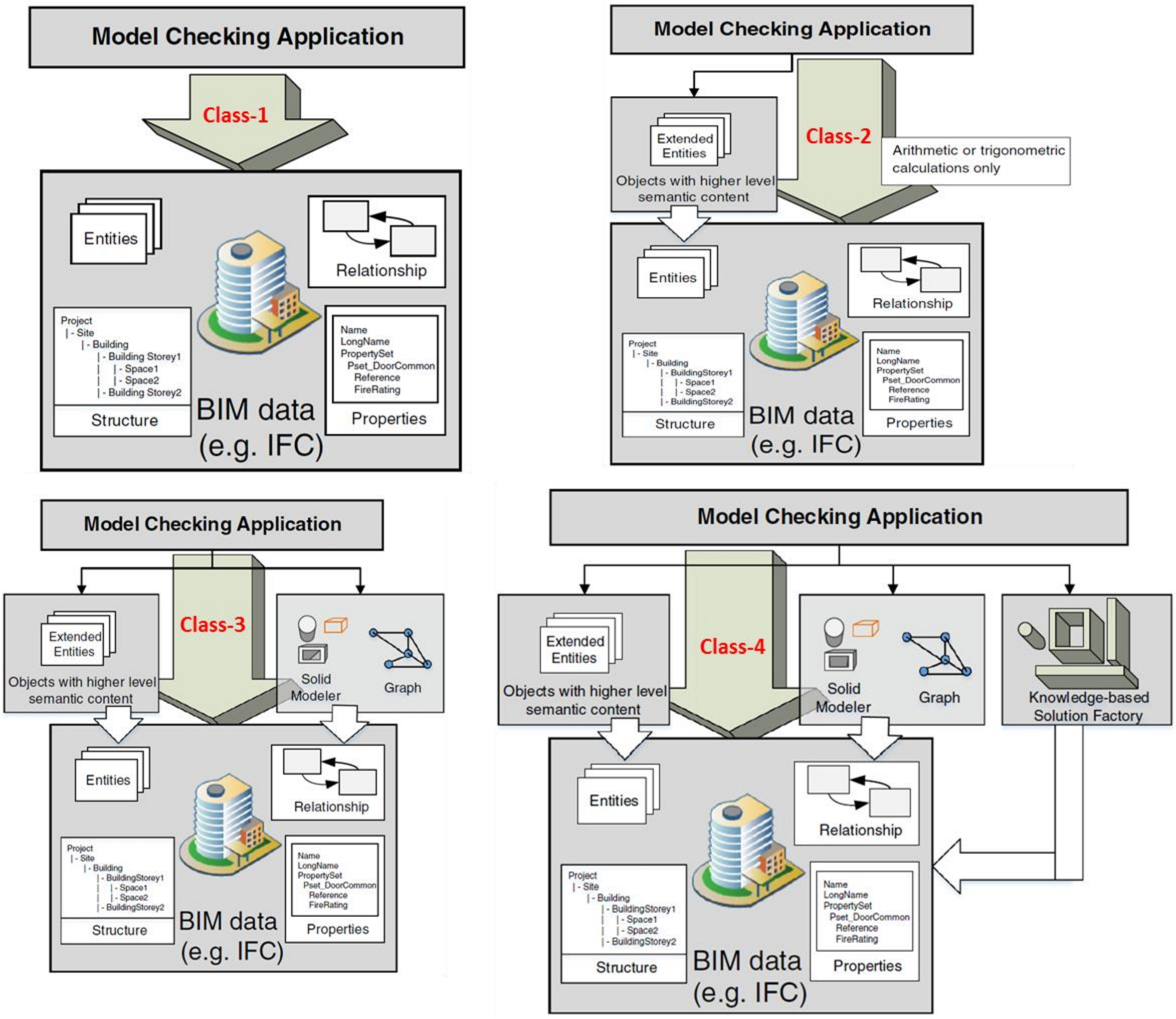


Figure 0:2: Diagram for typical application implementing in four classes of rules. Adopted from: (Solihin & Eastman, 2015)

Class 1- This class of rules checks a single or a small number of explicit data that exist within the BIM database. Typical applications of this class of rule include checking the correctness of required attribute setting of entities, the attribute values required for deriving value on other class of rules, and basic building code checking (Solihin & Eastman, 2015).

Class 2- This class of rules checks single value or a small set of derived attributes; however, it does not create a new data structure. "*This class of rule involves a trade-off between requiring the user to derive the data vs. rule checking-derived data."* (Solihin & Eastman, 2015).

Class 3- "*This class of rule requires an extension to the data structure that encapsulates higher level semantic conditions of building data. The main idea is to be able to 'compute once, use many' since such information typically requires extensive computation often involving geometry operations*." (Solihin & Eastman, 2015).

Class 4- This class of rules focus more on how building model prove compliance requiring "proof of solution" rather than only fulfilling assigned criteria. It usually assigns performance based codes. "*Generally, the application of this class of rules is more interested in the solution, which may have more than one acceptable answer, all of which eventually can be traced to the final answer of whether a design (or the design with additional information added into the design) complies with what the rules expect. The source of the solution is typically a knowledge-based facility that is coded into the system.*" (Hu, et al., 2008; Zhang, et al., 2013).

The above rule classification assisted the researcher to evaluate which class of rules are addressing the required checks to perform energy analysis for the research to choose an appropriate software application (More explanation is in section 0).

6.1.1.1 Automated compliance checking

Automated compliance checking is one type of rule checking where model checking validates the building designs (Hjelseth & Nisbet, 2010). To automate rule checking of building designs, building rules require interpretation from human-readable text rules into a set of computer-implementable rules (Nawari, 2012a). To meet legislation requirements, building designs for compliance need to be checked against extensive building codes. The manual checking and validation of building design against building regulation are currently applied in almost every country (Malsane, et al., 2015). The manual validation is not only an extensive task for designers and involved bodies who oversee enforcing the building regulations, but also it is subjective and can lead to inconsistency and ambiguity in assessments, increased cost and delays in the entire construction process (Malsane, et al., 2015; Ciribini, et al., 2016). For example, failure to properly check designs for compliance in a large complex housing project in London cost £800,000 owing to changing the design and construction of steep and narrow wheelchair ramps (Building.co.uk, 2003). This type of rule checking is not applied in this research as the research does not aim to check the building designs for compliance against building regulations and it aims to check the quality of architectural design model to be used for energy analysis.

6.1.1.2 Model Checking for Data Quality

The main aims of quality checking are twofold: first, improving the quality of BIM files of each designer and secondly, enhancing information exchange between project participants, and therefore making the entire design process more effective (Kulusjärvi, 2012).

Improving the quality of BIM model: Model checking is a rule-based framework to validate and check a proposed design against the required rule sets according to diverse validation domains. It does not modify a building design, but rather evaluates a design based on objects, their relations and/or attributes. It enables users to conduct a check, with results such as “pass,” “fail,” “warning,” and “unknown,” where the required data is missed or incomplete (Zhang, et al., 2013). Model checking enables users to check the quality of design content and internal consistency of a Building Information Model in relation to defined requirements (Kulusjärvi, 2012). It is essential to stress that quality checking it is not about design quality since it is impossible to check non-quantifiable quality. Data quality is intended to ensure that the BIM file is built based on the specific requirements which are necessities to fit its intended purpose (Kulusjärvi, 2012). A BIM file can be analysed for building code checking, deficiency detection, spatial requirements and so forth (Kulusjärvi, 2012). To have an accurate output of BIM model, it is essential to have accurate and correct input data into the model. As this research wanted to achieve accurate energy simulation results, it is essential to check whether the model has correct data for this purpose.

Enhancing information exchange between project participants: BIM is essentially a means to share information to facilitate communication and collaboration between various disciplines. Therefore, it is essential to establish an open interoperability standard to enable data exchange or reuse among different domains (IBC., 2011; Open BIM Focus, 2012). Open interoperability standards and widely adopted open interoperability formats including, gbXML, COBie and IFC, and their capabilities are discussed in the following sections.

Commercial application for automatic rule-based checking

Currently, there are two commercial applications providing reasonable capabilities for automatic checking in the market (Solihin & Eastman, 2015). These two applications are Solibri Model Checker (SMC), and FORNAX™ ePlanCheck (Automated Building Plan Checking Expert System) with more focus on regulatory authority for large-scale turnkey implementation (Solihin & Eastman, 2015). The following sections provide the knowledge regarding the capabilities of these two commercial applications.

6.1.2 Solibri Model Checker

Solibri Model checker (SMC) is a java-based desktop platform application, commercial software tool, to analyse Building Information Models for physical security, quality, quantity and integrity (Solibri, 2014; Eastman, et al., 2009). Quality Assurance (QA) and Quality Control (QC) process are conducted through "X-raying" the building model to reveal potential weaknesses and flaws in the design (Solibri, 2014). "*SMC highlights the clashing components and checking that the model complies with the building codes and organizations' own best practices*" (Solibri, 2014). The SMC process is shown in Figure 6.4:1.

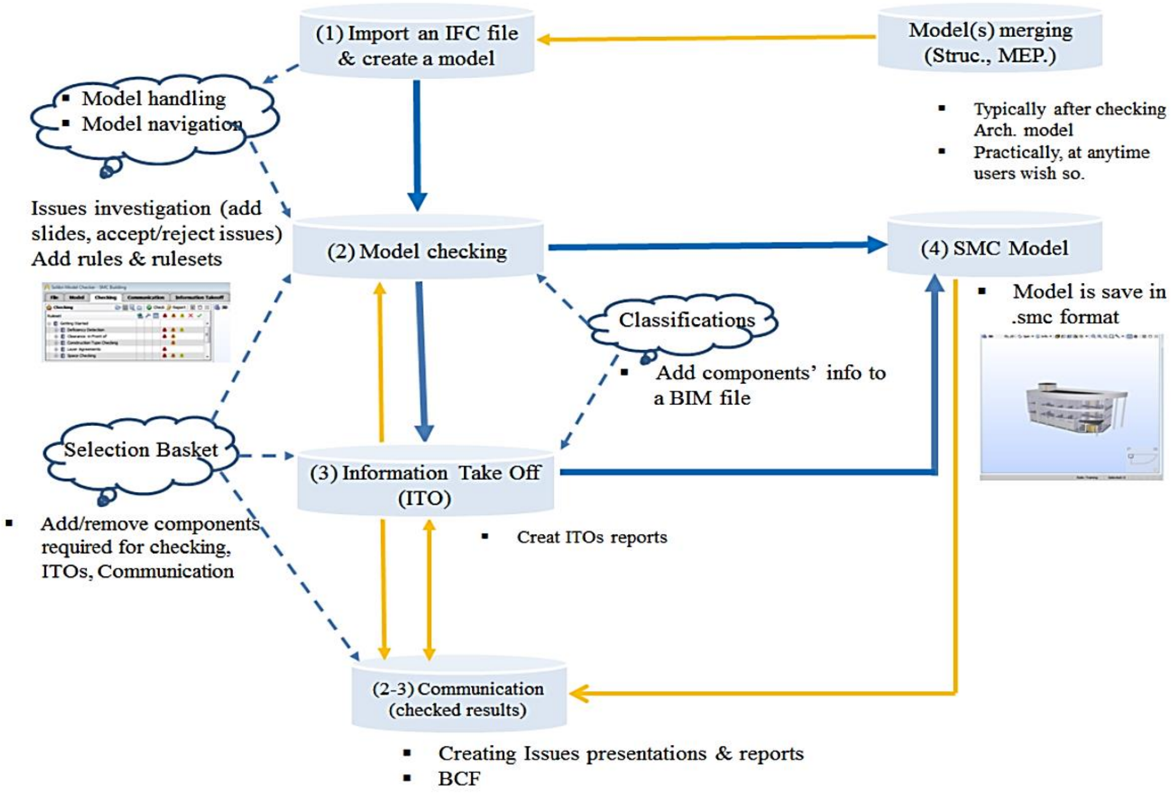


Figure 0:1: Overview of SMC QA/QC Process (Solibri, 2014)

SMC can open and check models from any IFC compliant BIM software (Solibri, 2014). Using neutral and interoperable data format plays a key role in validation phase through formalized information and exchange procedure (Dave, et al., 2013). SMC can be used for an IFC-based rule checking procedure to provide a clear idea of the potential critical issues associated with missing or incomplete data and potential problems on site (Solihin & Eastman, 2015). Users can customise the parameters in SMC rules library according to their imposed requirements and computational complexity (Solihin & Eastman, 2015). Checking and evaluating of design information using IFC files makes the process transparent to all parties, and gives a clear view of the progress, leading to better client satisfaction (Kulusjärvi, 2012). In addition, BIM files in IFC format improve the exchange information between parties and decrease the risk of misinterpretation; although the effectiveness of this process requires more emphasis on the quality and correctness of the information (Kulusjärvi, 2012).

A BIM Validation rule set in SMC can check the IFC models for internal consistency, quality, modeling procedure and parametric attributes. To assure the quality of the proposed design solutions, BIM files can be checked according to various validation domains and parametric rule set which should be customised and organised in required consequential checking phases (Khemlani, 2009; Dave, et al., 2013).

To gain a better understanding of the potential issues and address them, generated issues are grouped and categorised into categories (Solibri, 2014). A systematic control of parametric models enables users to improve the quality of proposed design, consistency of required information, minimize the changes over the construction phase and enhance the transparency of the whole process (Kulusjärvi, 2012). Quality assurance methods fall into two main principle methods for BIM files: checking and analysis (Kulusjärvi, 2012).

6.1.2.1 Checking

This method verifies the accuracy and correctness of data in BIM files. Determining the accuracy and correctness of data requires some reference information to compare and measure the information contained in a BIM file against of them (Kulusjärvi, 2012). A SMC library with capabilities for pre-checking a model provides rules to check shape overlaps, name and attribute conventions as a precursor of a more accurate check (Eastman, et al., 2009). A BIM file or parts of it can be checked programmatically using so-called rules such as “Clash Detection”, “Deficiency Detection”, “Accessibility Rules” and so forth (Kulusjärvi, 2012).

Visual review is one form of checking that usually compares the geometry of items which are visible in the BIM against the viewer’s concept of ‘what is correct’. Also, ‘technical visualization’ is the most effective way and it focuses on identifying components. This approach is very effective and easily mastered; however, it is subjective and prone to human error (Kulusjärvi, 2012). In addition, using this approach is difficult to process bigger quantities of data and numerical data (Kulusjärvi, 2012). Due to the nature of the potential challenges in the AEC industry and because each building has its own specific characteristics and requirements, definite results cannot be concluded in this approach and it requires further actions to be agreed among the parties (Kulusjärvi, 2012).

6.1.2.2 Analysis

To provide more reliable results, performing analysis is usually most practical after the completion of the checking tasks. The analysis makes an interpretation, an assessment the quality of information easier due to producing information refined from the BIM (Kulusjärvi, 2012). For example, area calculation analysis can be done to compare how the current status of design corresponds to the set target (Kulusjärvi, 2012). Also, the accessibility in a model can be checked based on the ISO (SMC, 2009; Lie, 2008). This enables involved bodies to explore any substantial difference and to examine the underlying reasons. Then, they must determine whether the difference refers to issues that require more actions (Kulusjärvi, 2012). An analysis reveals the order of magnitude level problems, small issues and underlying reasons for which must be studied in further details on a case-specific basis. However, it does not offer 'correct' or 'incorrect' solutions for problems (Kulusjärvi, 2012). Quality model checker evaluates a model based on objects, their relations and/or attribute, rather than modifying a model since there might be several viable solutions to one issue (Zhang, et al., 2013).

6.1.3 FORNAX

The FORNAX platform is suitable for large-scale turnkey implementation with more focus on regulatory authority (Solihin & Eastman, 2015). It was established by CORENET in Singapore, and developed by nova CITYNETS Pte. Ltd. on top of EDM Model Checker (novaCITYNETS, 2002; Solihin & Eastman, 2015). FORNAXt is C++ object library, which drive new data and extends IFC model data with a new structure that defines greater level abstractions of the building model (Solihin, et al., 2004; Solihin & Shaikh, 2005). FORNAX objects have the capability to carry rules for checking themselves (Solihin & Eastman, 2015). The extension to the data structure provides involved bodies with an opportunity to 'compute once, use many'. This potential makes the platform suitable for building code checking requiring complex tasks (Solihin & Eastman, 2015; Khemlani, 2005). Figure 0:3 illustrates the FORNAX™ system architecture with the use of solid modeller as its geometry engine to deal with complex geometrical and spatial operations.

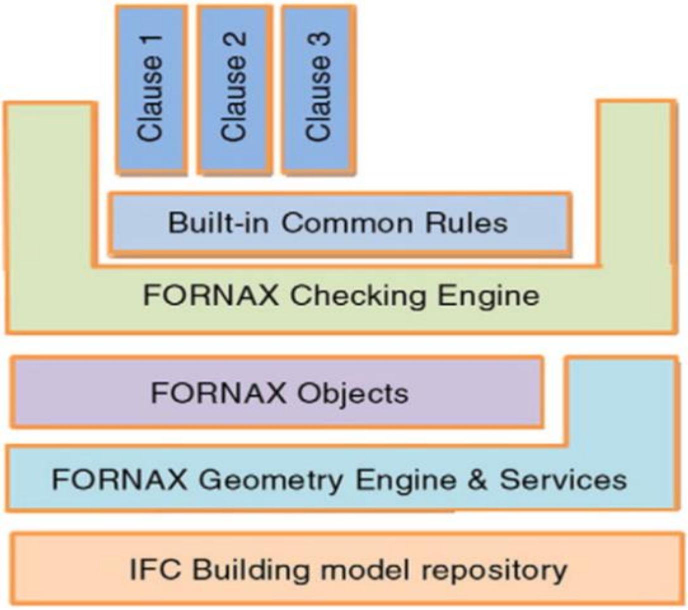


Figure 0:3: FORNAX system architecture

Quality Model Checker Software

Leveraging required data from BIM to energy performance analysis tools minimises the effort and time needed to build energy model (Ham & Golparvar-Fard, 2015). However, expected energy performance results from this approach may vary from actual energy performance due to several errors and clashes in a model. To select an appropriate quality checking model software for this research, two commercial applications for automatic rule-based checking were critically reviewed according to the classification developed by Solihin and Eastman in Table 0:1 (2015).

Table 0:1: Implementing different classes of rules in Solibri Model Checker and FORNAX (adopted from Solihin and Eastman (2015))

	Class 1: Checks based on explicit data	Class 2: Checks based on simple Derived attribute values	Class 3: Checks based on extended data structure	Class 4: Checks and suggests corrective actions or solutions
Solibri Model Checker	✓	✓		
FORNAX		✓	✓	

To achieve an energy efficient building solution, accurate analysis is required based upon the data in the BIM model that is already included in the design. The quality and accuracy of the outputs depend on the quality and clarity of the provided information. The required level of data and accuracy to run the energy performance is explained to define what classes of rules are covering these requirements and which software complies with those rules. To run energy performance software it is essential to check the attributes and attribute values. For example, space boundaries must be defined properly. It must be a member of ifcZone and named and classified based on the standardized categories. Also, checking the correctness of required attribute setting of entities is crucial to run the energy performance. For example, an energy model is required to check for well-defined entities such as walls that their components and their relationships with door and windows must be correct. This type of information is obtained from the explicit relationship entities in the model. In addition, checking the derive values and attributes save time and effort across all applications and avoids repeating the process in each BIM platform.

Checking the correctness of required attributes of entities, attributes and attribute values, and derived values shows that SMC covered in class 1 and class 2. Hence, Solibri Model Checker covering these classes of rules was chosen as an application to check the quality of data for this research.

BIM's Tools and Platforms

Eastman, et al., (2011) defined BIM tool and BIM platform as follows:

BIM tool: *"A task-specific software application that manipulates a building model for some defined purpose and produces a specific outcome. Examples of tools include those used for drawing production, specification writing, cost estimation, clash and error detection, energy analysis, rendering and visualisation."* (Eastman, et al., 2011, p. 586)

BIM platform: “*A BIM design application that generates data for multiple uses and incorporates multiple tools directly or through interfaces with varying levels of integration. Most BIM design applications serve not only a tool function, such as 3D parametric object modelling, but also other functions, such as drawing production and application interface, making them also platforms*” (Eastman, et al., 2011, p. 586)

The idea that a single application could cover all specific requirements as a tool, which existed in the beginning of the BIM age, has slowly waned (Eastman, et al., 2011). There is no one ideal application for all enterprises and projects since the choice of a BIM application should be based on their intended use within an organisation. An ideal compromise would be to adopt several tools to support the project-specific requirements regarding collaboration, communication, fabrication and so forth. Since adopting any tools and platforms within an office is a considerable undertaking, before adopting any application, the intended aim and capability of the BIM applications should be elucidated.

Two BIM tools widely used in the construction industry are reviewed with regard to their file formats and their interoperability with energy simulation tools.

6.1.4 Autodesk Revit

Revit was originally developed by Charles River Software, founded in 1997 and later renamed to Revit Technology Corporation. The first version of the software was published in April 2000. In 2002 Autodesk bought the company (Wikipedia, 2015). Revit is based on a totally different file structure and code base than Autodesk’s earlier product, AutoCAD. Currently, Revit is the BIM market leader; it is easy-to-use and well-known for implementing BIM in architectural design. This research reviewed Revit 2016, which can be installed on Windows and Mac computers. Revit is an integrated software that has the potential to combine features within Revit Architecture, Revit MEP, Revit Structure and Revit

Construction. Revit as a tool supports drawing generation with the bidirectional potential to manage and update drawings and model. Hierarchical parametric relations between objects and sub-objects are supported by Revit and its rule set has been developed with each new version. Revit as a platform can be linked to other applications through exchange format such as IFC or Revit's Open API. File formats supported by Revit Architecture include CAD formats (DWG, DXF, DGN, ACIS (SAT)), WDF/DWFx, ADSK (for building site), FBX (for 3D view), txt, gbXML, IFC, ODBC, HTML (for room/area report), AVI, JPEG, TIFF, BMP and PNG (Autodesk, 2015; Eastman, et al., 2011). As a result of supporting a wide range of file formats and applications, Revit is of the leading BIM software platforms in the AEC industry. In Revit 2015, Autodesk provided Autodesk Vault 2015 Server to manage, organise and track data, documentation process and simulation. In Revit 2016, Autodesk moved ahead to improve the previous version and released Autodesk Vault 2016 and also Revit Interoperability for Vault Professional (Server) to index Revit family files with objects and parameters. The capability of Autodesk Vault Server and Vault Professional Server to manage data is not evaluated in this research as it is released recently (Autodesk, 2015). Also, Autodesk has faced with few hurdles on parametric rules and parametric relations that are improved in the new release (Eastman, et al., 2011; Autodesk, 2015).

The interoperability between Revit model and energy analysis tools is supported with gbXML, DOE and EnergyPlus (Autodesk, 2015). Also, Autodesk Green Building Studio (GBS) is the integrated energy simulation for Autodesk Revit (Autodesk, 2017).

6.1.5 ArchiCAD Graphisoft

Graphisoft commenced marketing ArchiCAD in the 1980s and is the earliest constantly marketed BIM platform (Eastman, et al., 2011). ArchiCAD can be run on Windows and MAC platforms. Eastman et al, (2011) described the strengths of ArchiCAD as "*it has intuitive* *interface and is relatively simple to use. It has large object libraries, and a rich suite of supporting applications in construction and facility management".* File formats supported by ArchiCAD 20 are as follows: CAD format (DWG, DXF, DGN), BIM format (IFC, IFCXML, IFCZIP, NWC (Naviswork model file), SMC (Solibri Model Checker), BCF), Image format (BMP, DIB, RLE, JPEG, JPG, JPE, GIF, TIFF, TIF, PNG, JFIF, ICO, PCT, JP2, LWI, HDR, EXIF), PHPP, gbXML, GDL, GSM, EMF, WMF and PDF (Götz, et al., 2016). Autodesk Revit and GraphiSoft ArchiCAD are the two leading BIM software platforms for the architects. Although both BIM tools can be achieve the same goal in a BIM projects, they have different approach (Abanda, et al., 2015).

The interoperability between ArchiCAD model and energy analysis tools is supported with gbXML, PHPP, SBEM, VIP-Energy (Graphisoft, 2016). Also, GRAPHISOFT EcoDesigner STAR is the integrated energy simulation tool for Graphisoft ArchiCAD (Graphisoft, 2016).

This PhD research chose Graphisoft ArchiCAD as it is the leading BIM software (Eastman, et al., 2011) in supporting open interoperability formats, such as IFC and gbXML (Eastman, et al., 2011; Abanda, et al., 2015), and it has not been reported for any antitrust issue in software markets as opposed to Autodesk (Katz & Shapiro, 1998).

Conclusion

As the AEC industry is shifting toward more semantically rich BIM from 2D Computer Aided Design (CAD), the manual validation and visual inspection are not sufficient to ensure the quality of BIM models (Solihin & Eastman, 2015). The manual validation is not only an extensive task for project participants, but also error-prone and subjective and may lead to inconsistency and ambiguity in assessments and delays in the entire construction process (Malsane, et al., 2015). Therefore, the development of automated compliance checking of building designs using model checking software is becoming a realistic prospect in the AEC industry (Malsane, et al., 2015).

Two model rule-based checking, ‘automated compliance checking’ and ‘model checking for data quality’ were studied. Automated compliance checking is one type of rule checking where the model needs to be checked against extensive building codes to meet legislation requirements (Malsane, et al., 2015). This type of rule checking is not applied in this research as the research does not aim to check the building designs for compliance against building regulations and it aims to check the quality of architectural design model to be used for energy analysis. ‘Model checking for data quality’ is chosen for this research for two main reasons: improving the quality of BIM files and enhancing information exchange between BPS and BIM tools, and therefore making the entire design process more effective (Kulusjärvi, 2012). It is essential to stress that quality checking it is not about design quality since it is impossible to check non-quantifiable quality. However, it intends to ensure the BIM file is built based on the specific requirements which are necessities to fit its intended purpose (Kulusjärvi, 2012).

By adopting the quality model checker, the construction industry has benefited significantly from including improved quality of BIM files of each users, enhancing information exchange between users, their consistency with the information requirements, and increasing the effectiveness and transparency of entire design process (Kulusjärvi, 2012; Ciribini, et al., 2016; Malsane, et al., 2015). Therefore, two commercial applications, Solibri Model Checker and FORNAX, were reviewed in terms of their capabilities and potentials offering for quality checking of data in BIM files. Rule checking classified into four general classes of rules according to their typical uses and complexity involved for each classification of the rules (Solihin & Eastman, 2015). It assisted the researcher to understand each class of rules and its involved complexity level to identify which data quality checker application can be adopted to address the requirements of this research. Checking the correctness of required attributes of entities, attributes and attribute values, and derived values illustrates that Solibri Model Checker can address the requirements of the case study in this research.

The capabilities of two widespread BIM tools, Revit and ArchiCAD, in the construction industry were reviewed regarding their file formats and interoperability with energy simulation tools which is the focus of this research. The researcher chose Graphisoft ArchiCAD as it is leading BIM software (Eastman, et al., 2011) in supporting open interoperability format, such as IFC and gbXML (Eastman, et al., 2011; Abanda, et al., 2015).

Chapter Seven

Data Collection and Analysis from The Real World Case Study

7 Data Collection and Analysis from the Real World Case Study

Introduction

Prior to evaluating the usability and efficiency of BIM implementation in the energy efficient retrofit process, it is essential to understand the potential issues in existing methods for calculating and simulating the energy performance of buildings through a real-world case. Exploring the potential issues is important to learn how BIM integration could address those issues to achieve an efficient process for energy efficient retrofit. Two Existing methods for calculating the energy performance (SAP and PHPP), detailed modelling simulation approach using stand-alone BPS tool (DesignBuilder) and BIM simulation approaches were compared with the results of monitored house over a two-year period to evaluate their accuracy and efficiency.

This research does not aim to provide a technical comparison of different energy simulation software. However, it strives to compare the potential benefits and barriers of BIM approaches based on the extant literature review, primary data collection from the survey and studying a real world house. The major contribution of this research is the development of a framework for the evaluation of benefits and limitations of approaches and providing a practical example of how BIM can be integrated in energy performance simulation.

The chapter is structured as follows: section 0 provides a description of energy efficient retrofit measures incorporated in to a 19th century Liverpool terraced house, including openings, walls, floors, roof, mechanical ventilation with heat recovery, heating system and hot water system, since the energy efficient measures, their parameters and specifications are critical to build an energy simulation model. The potential issues and efficiency of existing approaches to predict energy performance including SAP, PHPP and detailed modelling simulation using DesignBuilder, are evaluated and compared with monitored results in section 0.

To address the identified challenges in existing approaches to predict energy performance, two BIM simulation approaches, “integrated BIM tools” and “interoperable BIM”, and the potentials and limitations of each approach are critically reviewed in sections 0 and 0.

Case Study: 2 Broxton Street, Liverpool, United Kingdom

The UK government was committed to providing 1.5 million solid wall homes with insulation (DECC, 2011). In 2009, the ‘*Technology Strategy Board*’ (renamed ‘*Innovative UK’* in August 2014) launched a competition called ‘*Retrofit for the Future’* to motivate and encourage retrofit and reduce CO_2 emissions (Innovate UK, 2014). One of the case studies was a 19th century Victorian terraced house at 2 Broxton Street, Liverpool in the UK, shown in Figure 0:1 (Gladwin, 2011).

Figure 0:1: 2 Broxton Street House before retrofit

It was retrofitted by the Plus Dane Group to near Passivhaus standards by integrating energy efficient technologies into the house (Gladwin, 2011). The two-storey Victorian property has three bedrooms and a traditional pitched roof and it was built circa 1900-1929 with no roof insulation, single glazed windows and a poor loft structure. Two open front gas fires were used for space heating and an electric immersion heater provided hot water. The property was in a poor state of repair and had a very low SAP score, primarily due to a lack of any thermal insulation (Gladwin, 2011).

This case study was chosen for this research for several important reasons: (i) *"The Victorian housing stock is certainly the most 'energy-hungry' of all housing stocks in the UK."* (Baeli, 2013); (ii) The 130-year-old Victorian house is considered to be 'hard-to-treat' with solid walls; 38.3% of the English housing stock is considered 'hard-to-treat', with 29.8% having solid walls (CSE, 2011); (iii) Access to analysed monitored data provided by the Technology Strategy Board (2013) enabled the researcher to compare the existing simulation method and BIM simulation method to evaluate the accuracy and potentials of each approach; (iv) Having direct contact with Martin Gladwin, head of asset management in Plus Dane Group, who adapted Passivhaus techniques in an innovative approach to a retrofit project, assisted the researcher to have a deep understanding over various challenges they confronted to deliver energy efficient retrofit project. The simulation models were built based on energy efficiency measures that their details and specifications described in section 7.1.1 Technical details of mechanical systems, building fabrics and openings are essential to create the simulation model.

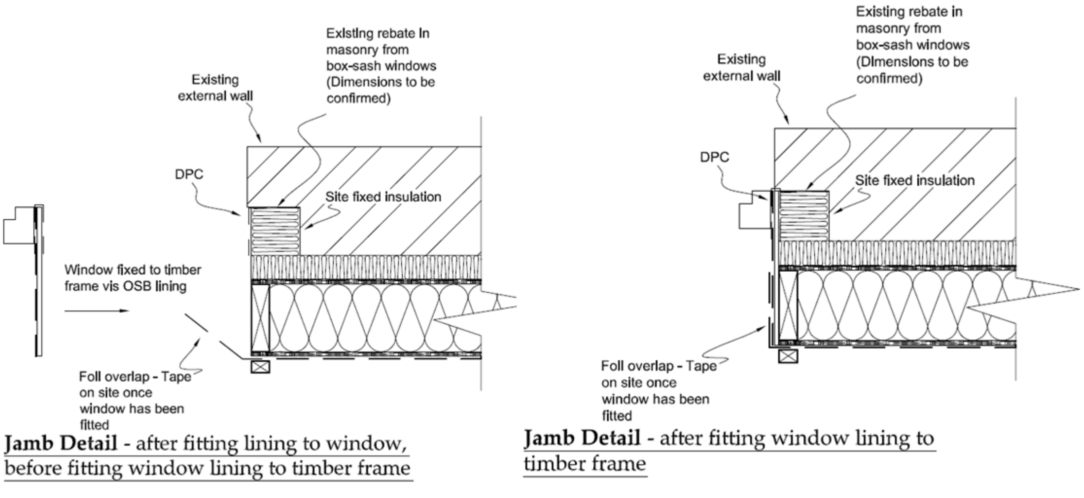
7.1.1 Retrofit Process of 2 Broxton Street House

Plus Dane Group incorporated the principles behind Passivhaus to its retrofit. The Plus Dane Group used "existing technology for new application" as they described their innovative approach (Gladwin, 2011). The measures to retrofit the house included replacing windows, insulating walls, floors, roofs, installing Mechanical Ventilation with Heat Recovery (MVHR), replacing heating systems and hot water systems.

7.1.1.1 Openings

Single glazed windows were replaced with triple glazing with Low-E glass. At the early design stage, NorDan's New NTech Passive windows were proposed to achieve high thermal performance of dwellings; however, NorDan did not deliver the windows in time (Gladwin, 2011).

To avoid delay in the project, Passivhaus accredited West Port triple glazed windows were installed (Gladwin, 2011). External and internal doors were replaced and the sealing process was undertaken to eliminate air paths and achieve good air tightness. The details of before and after fitting windows lining to timber frame are shown in Figure 0:2.



Jamb Detail - after fitting lining to window, before fitting window lining to timber frame

Jamb Detail - after fitting window lining to timber frame

Figure 0:2: Detail of Windows before and after fitting lining to timber frame (Larrosa Marshall and Associates, 2010)

7.1.1.2 Walls

According to Plus Dane, *"it was the first time to use Modern Method of Construction (MMC) system in a retrofit project, in this case through Maple SupaWall system."* All external walls were insulated internally by SupaWall, a closed timber-frame panel. The external walls consist of the existing external walls, 140 mm studs sheathed with 9mm Oriented Strand Board (OSB) both sides with polyurethane as insulation and two-coat plasterwork as finishing. The U-value of SupaWall for this project is 0.11 W/m^{2}k (LEB, 2010). The SupaWall system is illustrated in Figure 0:3.

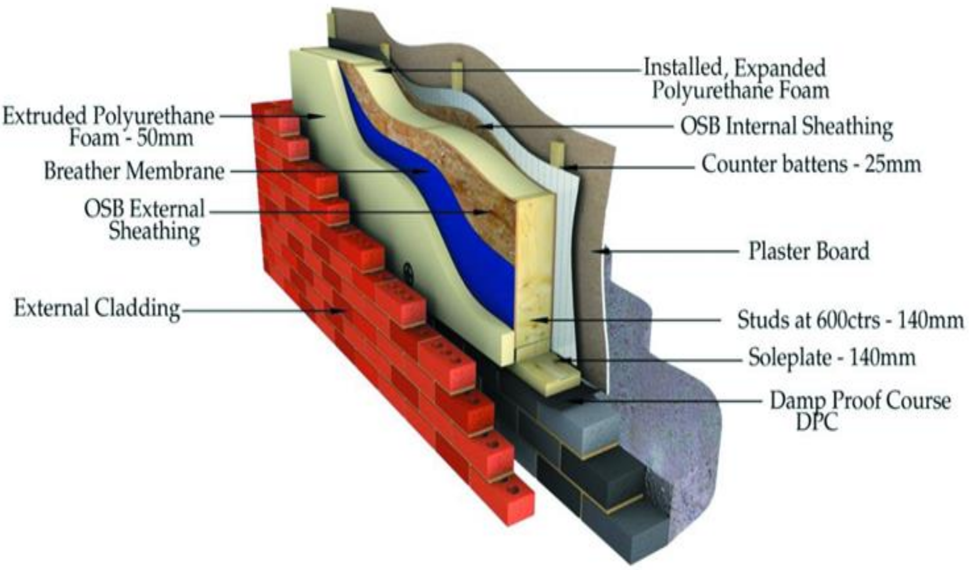


Figure 0:3: SupaWall System (Larrosa Marshall and Associates, 2010)

7.1.1.3 Floors

The ground floor was reconstructed with new sleeper walls, concrete floor and SupaFloor after removing the existing joists and board (LEB, 2010). The close-tolerance interlocking insulated floor and ready-finished board were replaced (LEB, 2010). The subfloor consists of 10mm C20 concrete, 1200g polythene as a Damp Proofing Membrane (DPM), 50 mm fine aggregate, and 150mm crusher run (Larrosa Marshall and Associates, 2010). A prefabricated SupaFloor by Maple Timber Frame was installed consisting polyurethane foam insulation sheathed by 9mm OSB both sided. The U-value of SupaFloor is 0.12 W/m^{2}k for this project (LEB, 2010; Larrosa Marshall and Associates, 2010).

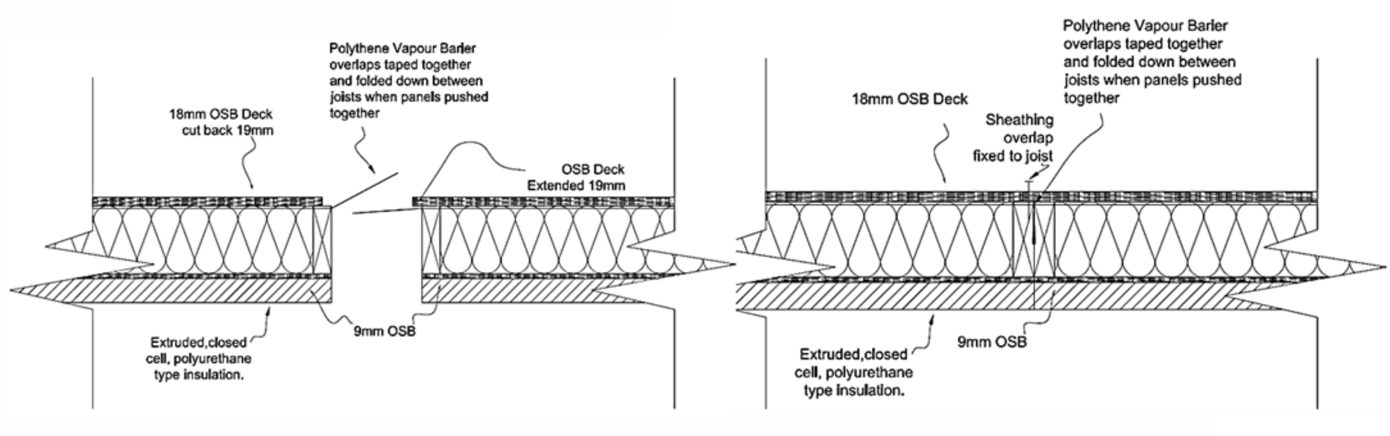


Figure 0:4: SupaFloor: Plan section at panel Junction before and after location (Larrosa Marshall and Associates, 2010)

7.1.1.4 Roof

The traditional pitched roof with no insulation was reconstructed. Chimney stack and breasts were removed from the dining room and living room. Gyproc MF ceilings and 200mm mineral wool insulation were installed at 2600mm height achieving 0.15W/m^{2}K U-value (LEB, 2010).

7.1.1.5 Mechanical Ventilation with Heat Recovery (MVHR)

A good air-tightness was achieved through eliminating air paths by having continuous insulation (to avoid thermal bridges) and sealing the building to reduce energy bills, heating demand and improve thermal comfort. However, very high airtightness results in under-ventilation, leading to providing additional ventilation sources rather than natural ventilation as suggested by Part F of the Building Regulation 2013. It suggests "*ventilation provisions for dwellings with a design air permeability tighter than or equal to 5 m^3/(h.m^2) at 50 Pa is recommended*" (GOV.UK, 2013). The Passivhaus-certified MVHR unit with high efficiency counter-flow channel-type heat exchanger with an airflow rate of 80 to 300 m^3/h was ordered from Germany, as it was not available in the UK in 2010 at the time of the retrofit process (Gladwin, 2011). The unit is SAP Appendix Q certified and well heat-insulated with a heat recovery efficiency rate of 94.4% @ 145m^3/h or 93% @ 200 m^3/h

(Gladwin, 2011). The MVHR unit is located in the conservatory and the system is controllable via the local control panel. Plus Dane provided the occupants with a user-friendly guide and a 10-inch home user display monitor located in the kitchen to display the energy usage and generation in real time (Gladwin, 2011). The unit is fully automatic and there is no need for attention unless defects occur.

7.1.1.6 Heating System

As explained in 7.1.1.5 section, MVHR is installed to extract and supply ventilation. The MVHR unit and condensing boiler as a back-up system with thermostatic radiator provide space heating (Larrosa Marshall and Associates, 2010). The boiler is a high efficiency condensing type and its heat output is much larger than the required heating to provide adequate tap hot water. Radiators can be operated via the boiler control unit and there are four options to control; Timed, Once, On, and Off. ‘Timed’ option or pre-set option enables occupants to set the radiators on at the specific time. ‘Once’ option enables users to set the heating system on for one period during the day. ‘On’ and ‘Off’ options to set the heating system on or off continuously. Also, thermostatic radiator control valves switch the heat on or off automatically in each room upon reaching the temperature they have been set for (Gladwin, 2011).

7.1.1.7 Hot Water System

A solar thermal system, the Worcester Greenskies, was installed on the south facing rear roof slope to support the hot water provision (Larrosa Marshall and Associates, 2010). Solar panels contributed almost 10% of hot water heat in winter, and on warm summer days solar panel system provides almost all the hot water heat depending on hot water usage. In winter condensing boiler heats the water mainly (Gladwin, 2011).

Figure 0:5 shows the mechanical system installed in the house.

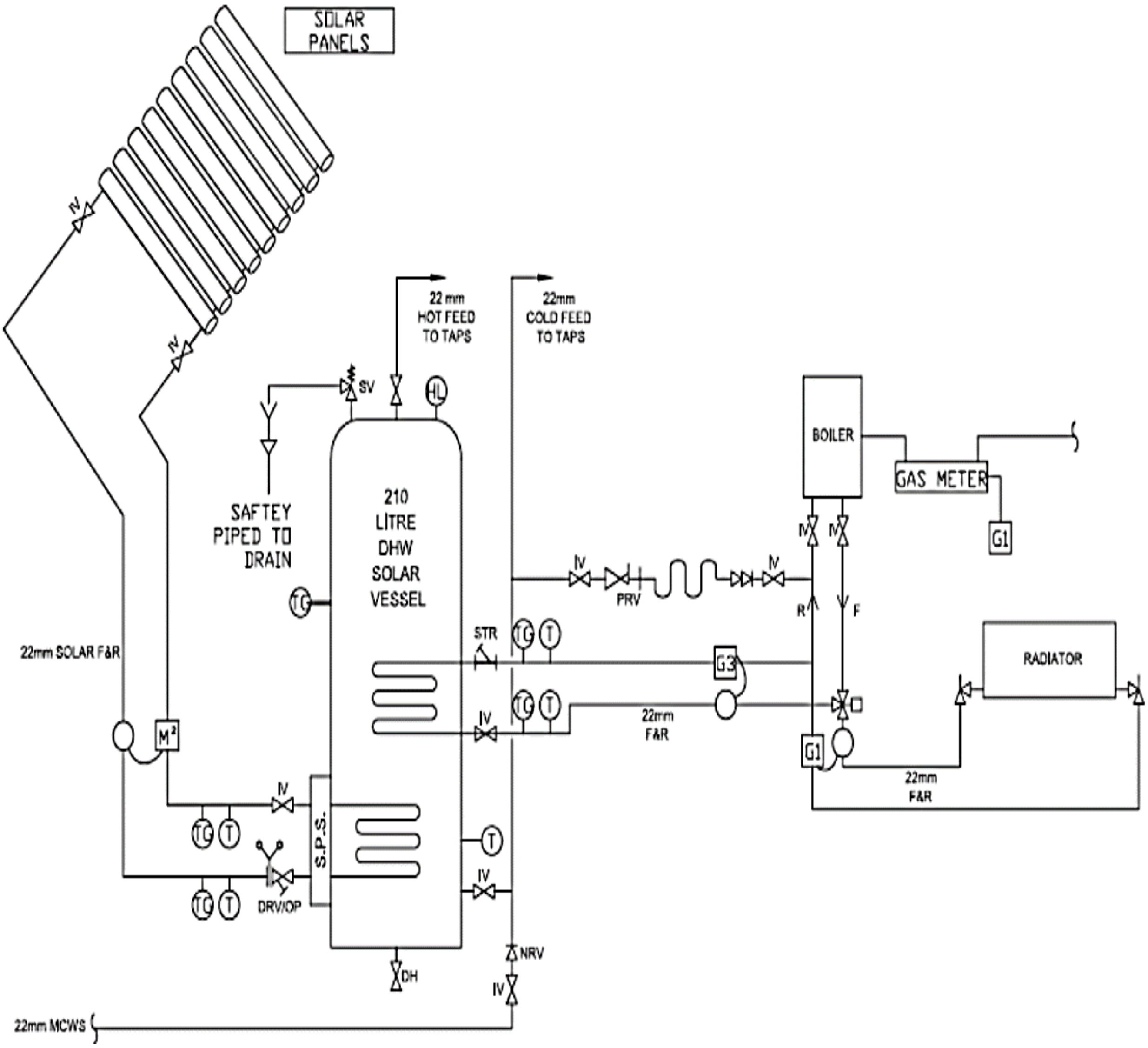


Figure 0:5: Mechanical system in 2 Broxton Street, Liverpool

Although thermography analysis and fan pressurisation were carried out to identify the heat loss path and air leakage, not all required information was available from the manual survey, house SAP (See Appendix C) and drawings. SAP 2009 was used to fine-tune and check the accuracy of input data to energy simulation tool (BRE, 2011). The main features of the house before and after retrofit are summarised in Table 0:1.

Table 0:1: Input data before and after retrofit

Input value	Before Retrofit	After Retrofit
Orientation	Front elevation faces North East	Front elevation faces North East
Windows	U-value 4.80 W/m^{2}K Single glazed timber frames	U-value 0.78 W/m^{2}K Triple glazed timber frames
Doors-unglazed solid timber	U-value 3.00 W/m^{2}K	U-value 1.00 W/m^{2}K
Roof	U-value 2.30 W/m^{2}K Pitched, slates or tiles, With 100mm mineral wool between rafters	U-value 0.15 W/m^{2}K Insulated roof-200mm mineral wool
Solid wall	U-value 2.10 W/m^{2}K 215mm thick brick work	U-value 0.11 W/m^{2}K internal insulation SupaWall
Suspended floor	U-value 1.20 W/m^{2}K Un-insulated suspended timber floor	U-value 0.12 W/m^{2}K SupaFloor panels
first floor	U-value 1.47 W/m^{2}K	U-value 0.12 W/m^{2}K
Total floor area	89.20 m^2	89.20 m^2
Ventilation	Natural	MVHR
Airtightness	14.53 m^3/hr@50pa	2.75 m^3/hr@50pa
Heating	Boiler to radiators	MVHR with air flow rate of 80 -300 m^3/h and electricity efficiency of 0.23 W/(m^{3}h). Gas-fired Boiler to radiators
Hot water	From boiler	Solar thermal panels and boiler
Appliance		A-rated, low energy appliances

7.1.2 Results of long term monitoring

To assess and measure the building performance, Energy Saving Trust protocol undertook long-term measurements by a wireless data logging and monitoring system.

During the two years of monitoring, all data and parameters have been recorded at five minute intervals to provide data regarding external temperature and relative humidity; internal room temperature and relative humidity; ceiling, floor and wall surface temperatures; air temperature of MVHR ducts; utility metering of water, gas and electricity; and energy produced by solar panel.

- **Internal temperature:** the data logger was installed on the top corner of the living room to measure the internal temperature. Hence, it shows very high temperature. To evaluate the internal temperature, the readings from thermistor sensor in the side wall were used.
- **Gas:** The average gas consumption was 49kWh/m^2 in 2011. According to the occupancy patterns, two adult and two children (2.8), the per capita gas consumption was 1568 kWh. The average gas consumption was 71kWh/m^2 in 2012 and per capita gas consumption was 2271kWh.
- **Electricity:** The average electricity consumption was 30kWh/m^2 in 2011and 2012 for the MVHR, lighting, central heat pump and appliance socket loads.
- **Total primary energy used:** To calculate the primary energy use, the PHPP primary energy factors were presumed, 2.70 for electricity and 1.10 for gas (Ridley, et al., 2013) . The total primary energy use was 136.5kWh/m^2 in 2011 and 156.6 kWh/m^2 in 2012 as shown in Table 0:2.

Table 0:2: Primary energy use in 2011 and 2012 for the Broxton Street house

Type of energy used		Grid energy use (kWh/m^2)	PHPP primary energy factor	Primary energy use (kWh/m^2)	Total primary energy use (kWh/m^2)
2011	Gas	49.2	1.1	54.1	136.5
	Electricity	30.5	2.7	82.4	
2012	Gas	71.3	1.1	78.4	156.6
	Electricity	28.9	2.7	78.2	

- **CO$_2$ emissions:** to estimate the CO$_2$ emissions for the Broxton Street house, CO$_2$ emission factors from BRE project were used which is 0.195kgCO$_2$/kWh from gas and 0.422kgCO$_2$/kWh from electricity (Pout, 2001). The house emitted

22.40kgCO$_2$/kWh.m^2 in 2011 and 16.09 kgCO$_2$/kWh.m^2 in 2012 as shown in Table 0:3.

Table 0:3: Total CO2 emissions in 2011 and 2012 for the Broxton Street house

Type of energy used		Grid energy use (kWh/m^2)	CO$_2$ emission factors (kgCO$_2$/kWh)	Primary energy use (kgCO$_2$/kWh.m^2)	Total CO$_2$ emissions (kgCO$_2$/kWh.m^2)
2011	Gas	49.2	0.195	9.6	22.40
	Electricity	30.5	0.422	12.8	
2012	Gas	71.3	0.195	13.90	26.09
	Electricity	28.9	0.422	12.19	

Existing Methods for Assessing and Simulating the Energy Performance of Buildings

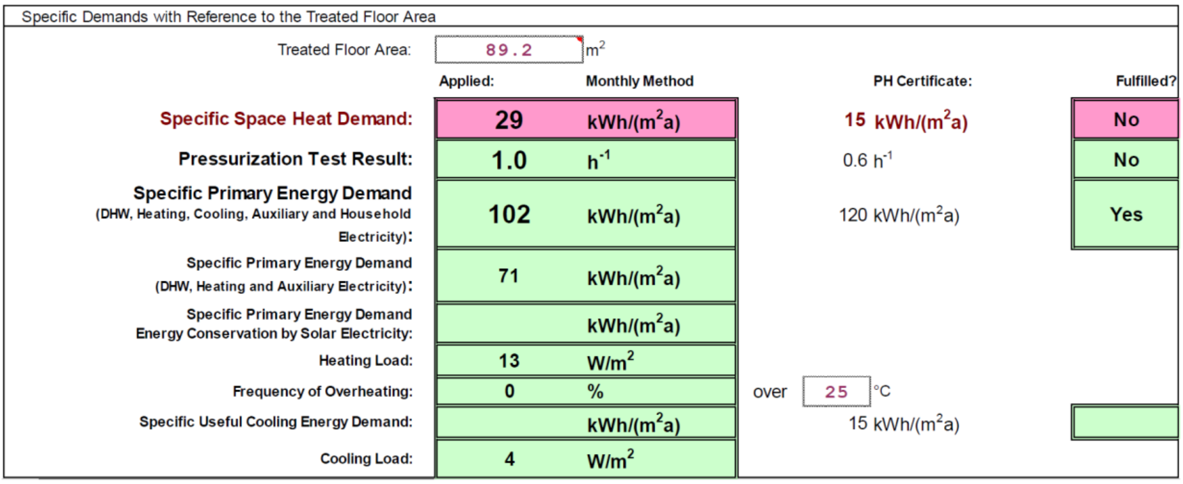
The retrofit process of 2 Broxton Street can be categorised by several main themes: reducing heat loss from building fabric consisting of the openings, roofs, floors and walls by insulation and installing new glazing; improving airtightness to reduce unwanted airflow; installing MVHR to recover heat to warm fresh air; improving services by installing solar panels and energy efficient lightings and; engaging residents in energy efficient measures. In this section, two approaches to assess the energy performance, SAP and PHPP, and detailed modelling simulation approach using DesignBuilder are discussed.

7.1.3 Energy Performance Assessment using SAP and PHPP

Standard Assessment Procedure (SAP) and Passive House Planning Package (PHPP) were used by Plus Dane to predict energy performance. Since Plus Dane incorporated the principles behind Passivhaus Standard, the PHPP was used to evaluate the energy performance and to learn if Passivhaus requirements were met. The PHPP is a Microsoft

Excel-based calculation tool to certify Passivhaus buildings to meet the Passivhaus Standard (Cotterell & Dadeby, 2012).

The results of modelling the house in PHPP are shown in Figure 0:1. To meet the Passivhaus Standard, space heating demand should be under 15 kWh/m^2a and primary energy demand under 120 kWh/m^2a. PHPP estimates 102kWh/m^2a for primary energy demand meeting the Passivhaus Standard. However, the predicted space heating demand was 29 kWh/m^2a and could not meet the Passivhaus target.



Specific Demands with Reference to the Treated Floor Area

Treated Floor Area:	89.2	m^2		
	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	**29**	**kWh/(m^2a)**	**15 kWh/(m^2a)**	**No**
Pressurization Test Result:	**1.0**	**h^{-1}**	0.6 h^{-1}	**No**
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	**102**	**kWh/(m^2a)**	120 kWh/(m^2a)	**Yes**
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	71	kWh/(m^2a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m^2a)		
Heating Load:	13	W/m^2		
Frequency of Overheating:	0	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m^2a)	15 kWh/(m^2a)	
Cooling Load:	4	W/m^2		

Figure 0:1: PHPP results

The energy performance of the house was greatly enhanced with a 74% cut in CO_2 emissions; however, the house did not meet Passivhaus targets to be certified as Passivhaus. Although this is not the primary focus of this research, it is important to identify the discrepancies between actual and predicted energy performance and understand the underlying reasons for the discrepancies. There are considerable differences between PHPP results and real performance as shown in Table 0:1

Table 0:1: Comparison of monitored results with PHPP and SAP

Measurement method	Space Heating (kWh/m^{2}a)	Primary Energy Use (kWh/m^{2}a)
PHPP	29	102
SAP	16	85
Monitored	53	158

According to Mohammadpourkarbasi and Sharples (2015), who studied 2 Broxton House, the reasons for differences between real and predicted performance were referred to: "*using Manchester weather file for the weather estimations, together with unrealistic assumptions being made regarding, (i) internal heat gains, (ii) interior comfort temperatures, (iii) the efficiency of appliances, (iv) the use of shading devices, and (v) fabric heat loss*".

The discrepancies between the results of actual energy performance and predicted energy performance by PHPP does not mean that PHPP cannot predict accurate results. However, it can be concluded that using unrealistic assumptions gives unreliable results.

As mentioned, SAP was also used by Plus Dane to predict energy performance. There were large discrepancies between SAP predicted energy performance and real performance. Annual primary energy usage was predicted as 85 kWh/m^2 and space heating requirement as 16 kWh/m^2. SAP ratings assess energy performance through notional assumptions and an index calculated from a collection of different building components, which frequently leads to suggesting suboptimal solutions. Also, different building efficiency measures have different estimated life span; however, SAP ratings do not include this factor to achieve the most cost-effective measures over the whole lifecycle of buildings, and this is left out of SAP calculations (Kellya, et al., 2012). Considering the issue that SAP, as an independent calculation methodology, forms the backbone of government policy to estimate building performance and creation of Energy Performance Certification (EPC), CSH and many other schemes (Kellya, et al., 2012), it is essential to conduct further research to avoid the large discrepancies mentioned earlier.

7.1.4 Detailed modelling: A stand-alone Building Energy Simulation

DesignBuilder was chosen as the BPS tool for several reasons in this research. It is the most advanced graphical user interface for EnergyPlus, the reliable open-source energy simulation engine developed by the U.S. Department of Energy Building Technologies Office (EERE, 2015; Henninger & Witte, 2013); The capability of DesignBuilder for interoperability with BIM tools through gbXML and the potential of importing 2D DXF floor plan created in CAD model, enabled the comparison of both approaches with same energy simulation software; Due to DesignBuilder controllable options for occupancy schedule, the author was able to assign the same occupant schedule as documented in the monitored data. As this case study compared the accuracy of each approach based on their different data exchange format, occupancy inputs were considered as it was in a real situation.

There are several stages to evaluating energy performance in DesignBuilder: (i) the geometry of the house derived from the architectural drawing was imported to DesignBuilder using DXF format; (ii) The house was modelled by tracing over the imported drawing data through integrated 3D modeller within DesignBuilder; (iii) Building blocks were divided into individual zones based on their functions; (iv) Thermal characteristics of walls, floors, roofs and openings were set; (v) building systems including solar panel, gas boiler and MVHR, and appropriate activity were assigned to each building space.

Assumed input data in the model for parameters, which are closely related to occupants' behaviour regarding their interaction with energy efficient measures, were fine-tuned based on the monitored results. These parameters include lighting usage, occupancy density, consumption rate for domestic hot water and energy usage of equipment. These parameters are very subjective and depend on how occupants are interacting with energy efficiency measures. Therefore, it is crucial that the parameters are the same as indicated in the monitored data.

Figure 0:2: Model 2 Broxton house in DesignBuilder

DesignBuilder estimated 151.6 kWh/m^{2}a for primary energy consumption and 65.2 kWh/m^{2}a for space heating requirements. 2 Broxton Street was studied by Mohammadpourkarbasi and Sharples (2015) to evaluate the energy, carbon and cost performance for current and future UK climates. Their estimated results in DesignBuilder were 148.5 kWh/m^2.yr before calibration and 158.8 kWh/m^2.yr after calibration. Although the parameters in the model in this research were assigned the same values as by Mohammadpourkarbasi and Sharples (2015), this research estimated 151.6 kWh/m^{2}yr for primary energy consumption. The difference, 1.02%, is totally insignificant and could be the result of very small changes in assigned input data (Figure 0:3).

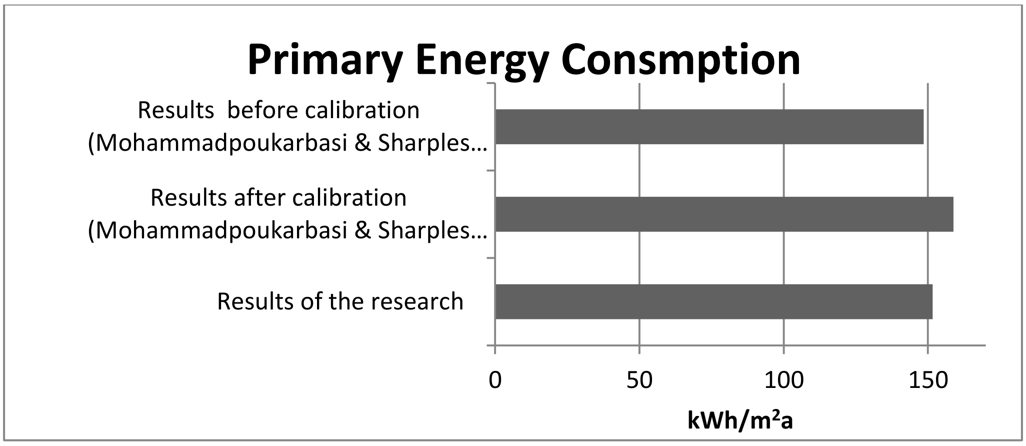


Figure 0:3: Comparison of estimated primary energy consumption by DesignBuilder

7.1.5 Evaluation the Effectiveness of the Existing Methods for Assessing and Simulating the Energy Performance of Buildings

Comparing the results of **energy performance assessment using SAP and PHPP** with monitored results demonstrated that the results are not accurate and reliable enough to make a proper decision at the early stages of the retrofit process. The estimation for 2 Broxton Street was different by 38% in PHPP and 47% in SAP calculations. Unrealistic and notional assumptions resulted in unreliable results.

The results from the **detailed modelling** simulation using DesignBuilder were very close to monitored results. However, as discussed in Section 2.1.9, the obtained data from BPS tools is frequently evaluative rather than proactive in the existing practices (Attia, et al., 2012; Kanters & Horvat, 2012). The **detailed modelling** simulation is not effective and is too time-consuming to adopt at the early stages of the retrofit process where the fundamental design decisions have the highest impact on the final energy performance (Osello, et al., 2011; Bazjanac, 2008a).

Furthermore, due to the time and resource limitations, the geometry of the building must be simplified that it is very subjective and depends on the person's knowledge, experiences, skills, understanding and the complexity of the building (Bazjanac, 2008a).

Providing the required information to create the thermal view of the building typically occurs after sufficient progress in the architectural and HVAC design. The lengthy process of capturing required information results based on questionable assumptions and documentations can generate unreliable simulation results at the early stage of the process (Bazjanac, 2008a). Hence, additional subjective decisions have been made to define the thermal view geometry regarding the details and accuracy of the geometry (Bazjanac, 2008a).

These are compelling reasons to not exploit BPS tools since, it is not just because the process is labour intensive, subjective and too costly, but also because the process takes a long time, and the results are irrelevant by the time they are delivered (Torcellini, et al., 2004; Bazjanac, 2008a).

A lack of interoperability has been claimed to be the reason for the limited use of BPS tools at the early design where design decisions have the highest impact on the final building performance (Venugopal, et al., 2012).

Therefore, an efficient information exchange can assist project partners to achieve streamlined workflows and smooth the use of BPS tool at the early design stage (Eastman, et al., 2011, p. 100; Bazjanac, 2004). This can help to avoid data repetition and redundancy between BIM and BPS tools (Cemesova, et al., 2015).

However, the digital information flow between BPS tools and BIM remains as a challenge (O'Brien, 2002). Due to the commercial nature of BPS tools and their exchange formats, the accessibility degree and interoperability with BIM are varied (Dimyadi, et al., 2008).

BIM Simulation Approach

Figure 0:1 shows the overview of the comparison of existing approaches to assess and simulate the energy performance and BIM simulation approaches. The BIM simulation approach includes the steps to create BIM, check the quality of model with SMC using IFC format, and analyse its energy performance using integrated BIM simulation approach. The interoperable BIM simulation approach using gbXML format is explained in sections 0, 0 and 0 respectively. The comparisons of all approaches are based on the primary energy consumption and CO_2 emissions. All other results for all approaches are avoided in this research since it is not the focus of this research and including all details could distract the reader from the main direction of the research.

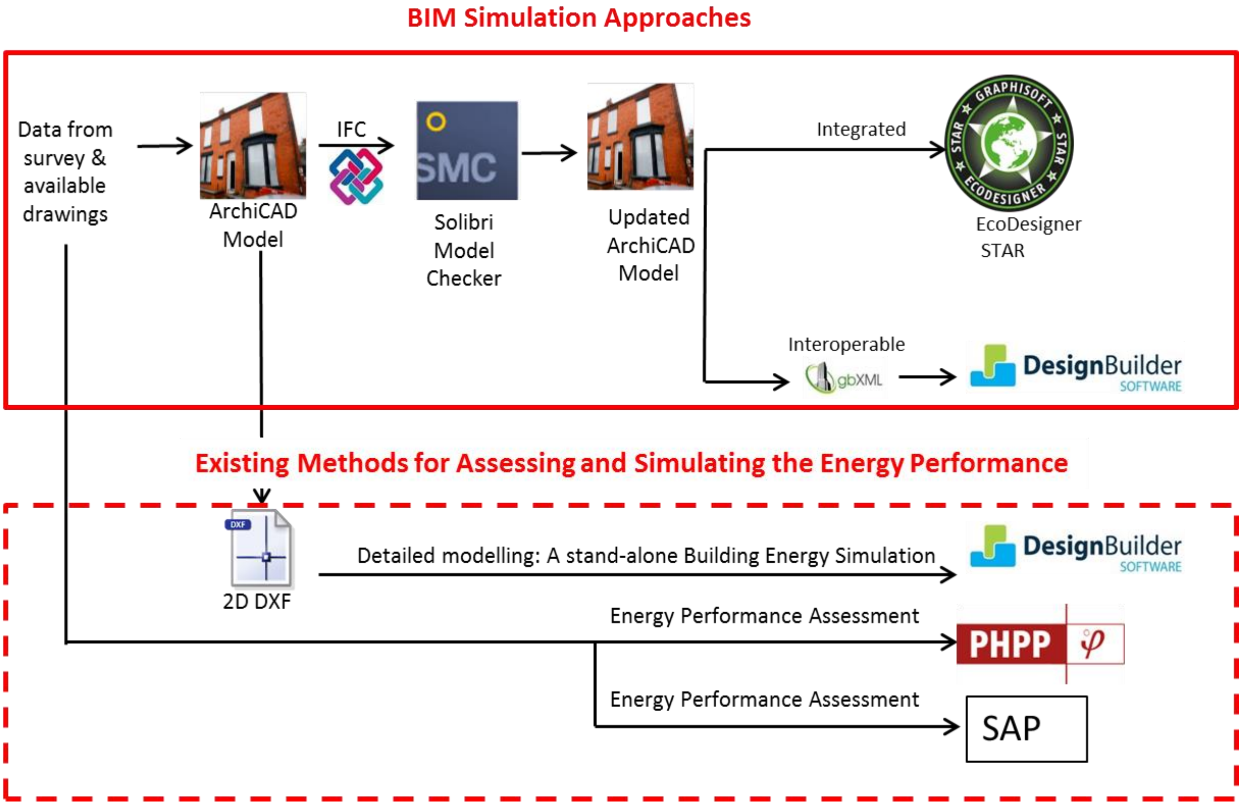


Figure 0:1: Comparison of existing approaches and BIM approaches

Two different BIM approaches, integrated and interoperable, for building energy performance are discussed in this section 0 and 0. Four different methods of data exchange and interoperability between BPS tools and BIM were reviewed in chapter 5 in detail. Prior to describing the proposed approach, the importance of interoperability and early adoption of BPS tools in the retrofit process is explained.

7.1.6 Steps to model the house in ArchiCAD

As explained in Chapter 6, before modelling a building it is critical to understand what 'model' refers to. According to Rothenberg (1989) *"Model in its broadest sense is the cost-effective use of something in place of something else for some cognitive purpose. It allows us to use something that is simpler, safer, or cheaper than reality and enables us to cope with the world in a simplified manner, avoiding the complexity, danger, and irreversibility of reality"*. Since a model is an abstraction for the intended aim, it is essential to identify required information for the given purpose which is energy analysis in this research.

As shown in Figure 0:2, data input requirements for modelling the house in ArchiCAD and running EcoDesigner STAR include:

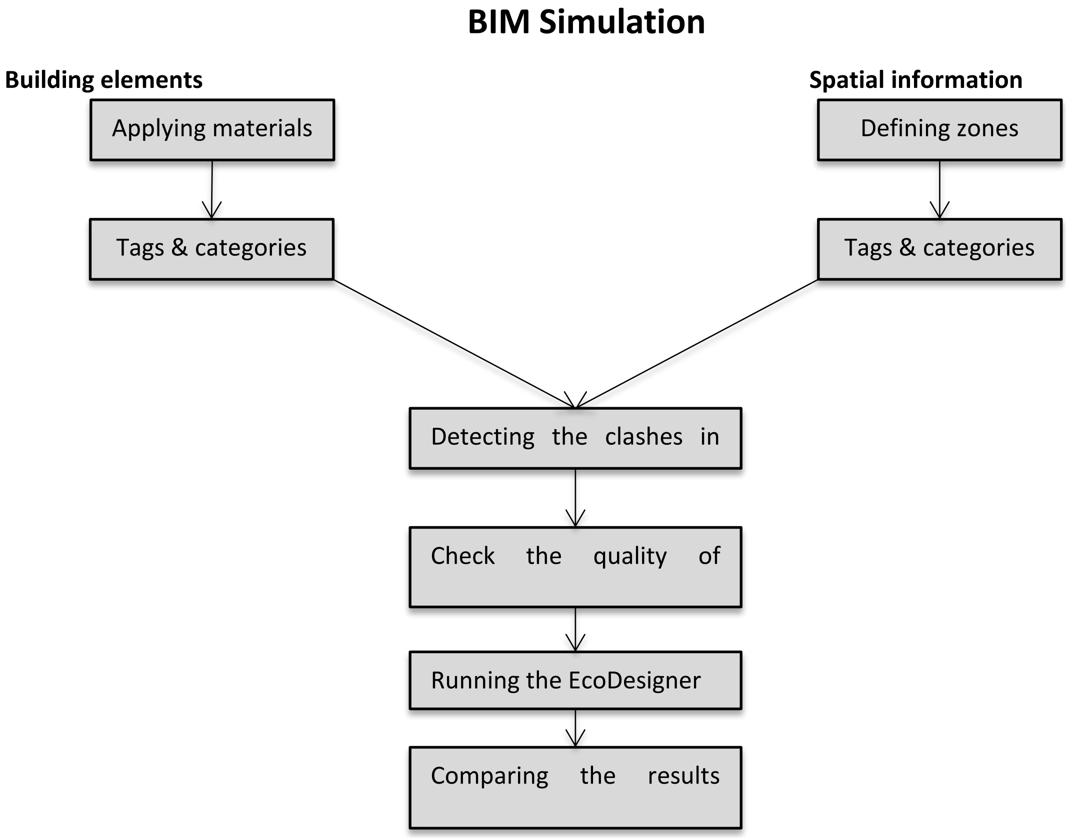


Figure 0:2: Proposed phases to model in ArchiCAD for energy evaluation

- Modelling the external and internal structure and openings; the virtual building model should comprise the openings, walls, roofs, slabs and partitions. Modelling detailed elements, such as door handles or electrical sockets, were avoided because it is not only time consuming, but also, it does not result in more accurate results as they are not required for the given purpose;
- Applying the materials for all elements including walls, roofs, slabs, partitions, windows and doors;
- Assigning category and IFC properties to the building elements: category classifications are assigned to building elements based on the OmniClass specification;
- Creating zones in all conditioned spaces of the building: space boundary property setting allows to fine-tune data based on post-occupancy data;
- Assigning category and IFC properties of zones: classifying spaces by function and assigning appropriate layer;
- Checking the quality of model in Solibri Model checker and modifying the ArchiCAD model;
- Assigning operation file, environmental settings, climate data and building systems in EcoDesigner STAR.

Figure 0:3: ArchiCAD model of 2 Broxton Street

7.1.7 Solibri Model Checker (SMC): Checking the quality of 2 Broxton House modelled in ArchiCAD

As explained in Chapter 6, after comparing FORNAX and Solibri Model Checker, two commercial applications, SMC was chosen. In 1999, a Finnish software developer launched SMC for Windows and Mac operating systems. SMC for Building Information Modelling is like the spell checker in Word (Corke, 2013). The automated quality assurance toolkit within SMC can validate the BIM files against the rulesets (Solibri, 2014; Corke, 2013). SMC was adopted for this research based on its capabilities and addressing the requirements of case studies in this research. The ArchiCAD model of the house was saved in “IFC 2x3 file” format and imported to SMC to check against a set of rules using neutral Industry Foundation Class

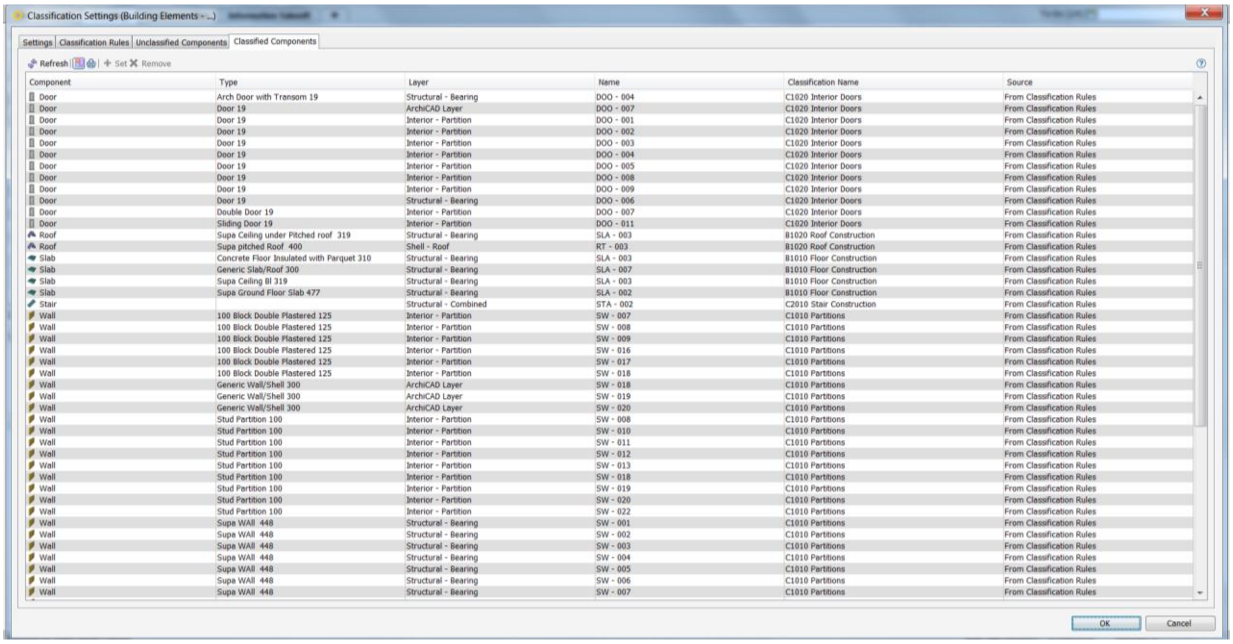
(IFC) format. The SMC software and its workflow, process of detecting the clashes, mistakes and missing information in the model are explained in this section. This approach is used to explore what level of information is needed at a specific phase and check how the potential problems may impact on the accuracy of energy simulation results.

7.1.7.1 Setting the Ruleset Manager

A ruleset contains information about the order of the rules and possible sub-rulesets, as well as parameter values used for the rules (Solibri, 2014). Rules are parametric, which means that their behavior can be controlled by setting the parametric values (Solibri, 2014). In this research the following rulesets were selected to check the quality of model for energy efficiency purposes: BIM Validation Architectural, General Space Check, Intersections between Architectural Components, and Pre-check for Energy Analysis.

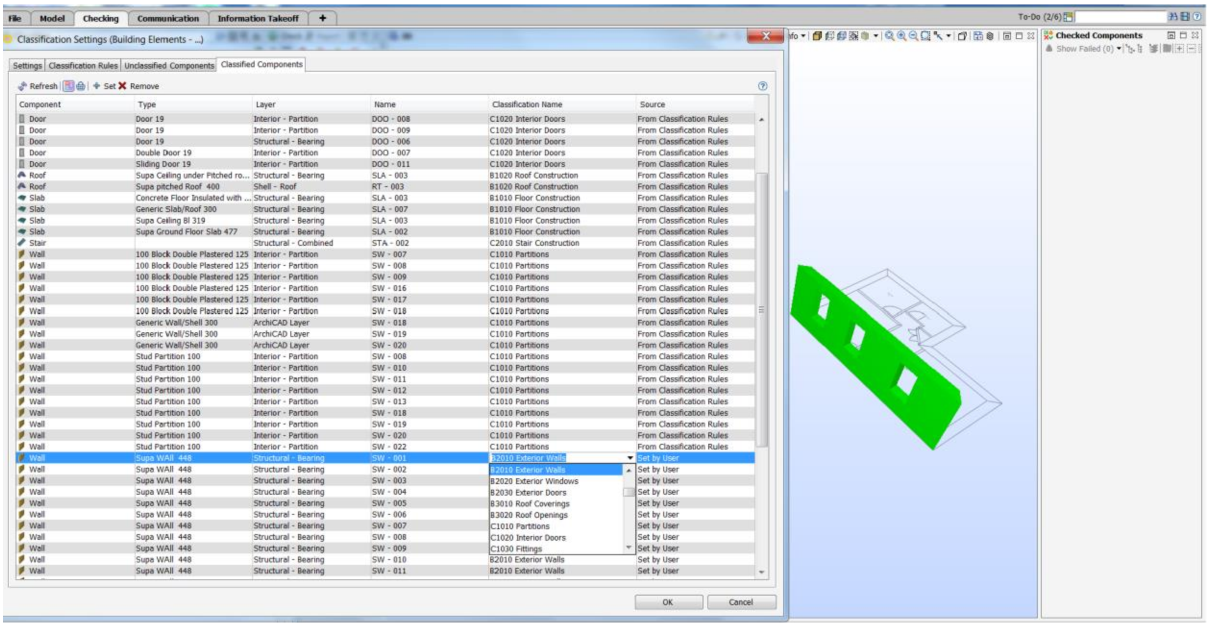
7.1.7.2 Classification

Classification of BIM information assists users to refine the data within the model for downstream uses (Corke, 2013). It is an effective approach to organize BIM information and it enhances accuracy and reliability of quantity take off, cost estimation and so forth. As shown in Figure 0:4, the components can be re-structured hierarchically based on any information in BIM (Corke, 2013). SMC is facilitated with tools for displaying data classification thematically. This capability assists users to obtain a better understanding of what information is in the BIM, and more importantly it checks for any discrepancies in the data (Corke, 2013; Solibri, 2014). As shown in Figure 0:5, SMC identified that eleven walls were classified incorrectly in the design model. This classification should set by the user to an appropriate classification to check the model against a set of rules. This step is essential prior to check the model as the model based on its classification will be checked against of rulesets.



Component	Type	Layer	Name	Classification Name	Source
Door	Arch Door with Transom 19	Structural - Bearing	DOO - 004	C1020 Interior Doors	From Classification Rules
Door	Door 19	ArchiCAD Layer	DOO - 007	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 001	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 002	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 003	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 004	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 005	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 008	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 009	C1020 Interior Doors	From Classification Rules
Door	Door 19	Structural - Bearing	DOO - 006	C1020 Interior Doors	From Classification Rules
Door	Double Door 19	Interior - Partition	DOO - 007	C1020 Interior Doors	From Classification Rules
Door	Sliding Door 19	Interior - Partition	DOO - 011	C1020 Interior Doors	From Classification Rules
Roof	Supa Ceiling under Pitched roof 319	Structural - Bearing	SLA - 003	B1020 Roof Construction	From Classification Rules
Roof	Supa pitched Roof 400	Shell - Roof	RT - 003	B1020 Roof Construction	From Classification Rules
Slab	Concrete Floor Insulated with Parquet 310	Structural - Bearing	SLA - 003	B1010 Floor Construction	From Classification Rules
Slab	Generic Slab/Roof 300	Structural - Bearing	SLA - 007	B1010 Floor Construction	From Classification Rules
Slab	Supa Ceiling Bl 319	Structural - Bearing	SLA - 003	B1010 Floor Construction	From Classification Rules
Slab	Supa Ground Floor Slab 477	Structural - Bearing	SLA - 002	B1010 Floor Construction	From Classification Rules
Stair		Structural - Combined	STA - 002	C2010 Stair Construction	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 007	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 008	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 009	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 016	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 017	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 018	C1010 Partitions	From Classification Rules
Wall	Generic Wall/Shell 300	ArchiCAD Layer	SW - 018	C1010 Partitions	From Classification Rules
Wall	Generic Wall/Shell 300	ArchiCAD Layer	SW - 019	C1010 Partitions	From Classification Rules
Wall	Generic Wall/Shell 300	ArchiCAD Layer	SW - 020	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 008	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 010	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 011	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 012	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 013	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 018	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 019	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 020	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 022	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 001	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 002	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 003	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 004	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 005	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 006	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 007	C1010 Partitions	From Classification Rules

Figure 0:4: Checking the components classification in SMC



Component	Type	Layer	Name	Classification Name	Source
Door	Door 19	Interior - Partition	DOO - 008	C1020 Interior Doors	From Classification Rules
Door	Door 19	Interior - Partition	DOO - 009	C1020 Interior Doors	From Classification Rules
Door	Door 19	Structural - Bearing	DOO - 006	C1020 Interior Doors	From Classification Rules
Door	Double Door 19	Interior - Partition	DOO - 007	C1020 Interior Doors	From Classification Rules
Door	Sliding Door 19	Interior - Partition	DOO - 011	C1020 Interior Doors	From Classification Rules
Roof	Supa Ceiling under Pitched ro...	Structural - Bearing	SLA - 003	B1020 Roof Construction	From Classification Rules
Roof	Supa pitched Roof 400	Shell - Roof	RT - 003	B1020 Roof Construction	From Classification Rules
Slab	Concrete Floor Insulated with ...	Structural - Bearing	SLA - 003	B1010 Floor Construction	From Classification Rules
Slab	Generic Slab/Roof 300	Structural - Bearing	SLA - 007	B1010 Floor Construction	From Classification Rules
Slab	Supa Ceiling Bl 319	Structural - Bearing	SLA - 003	B1010 Floor Construction	From Classification Rules
Slab	Supa Ground Floor Slab 477	Structural - Bearing	SLA - 002	B1010 Floor Construction	From Classification Rules
Stair		Structural - Combined	STA - 002	C2010 Stair Construction	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 007	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 008	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 009	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 016	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 017	C1010 Partitions	From Classification Rules
Wall	100 Block Double Plastered 125	Interior - Partition	SW - 018	C1010 Partitions	From Classification Rules
Wall	Generic Wall/Shell 300	ArchiCAD Layer	SW - 018	C1010 Partitions	From Classification Rules
Wall	Generic Wall/Shell 300	ArchiCAD Layer	SW - 019	C1010 Partitions	From Classification Rules
Wall	Generic Wall/Shell 300	ArchiCAD Layer	SW - 020	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 008	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 010	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 011	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 012	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 013	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 018	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 019	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 020	C1010 Partitions	From Classification Rules
Wall	Stud Partition 100	Interior - Partition	SW - 022	C1010 Partitions	From Classification Rules
Wall	Supa WAll 448	Structural - Bearing	SW - 001	B2010 Exterior Walls	Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 002		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 003		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 004		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 005		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 006		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 007		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 008		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 009		Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 010	B2010 Exterior Walls	Set by User
Wall	Supa WAll 448	Structural - Bearing	SW - 011	B2010 Exterior Walls	Set by User

B2010 Exterior Walls
B2020 Exterior Windows
B2030 Exterior Doors
B3010 Roof Coverings
B3020 Roof Openings
C1010 Partitions
C1020 Interior Doors
C1030 Fittings

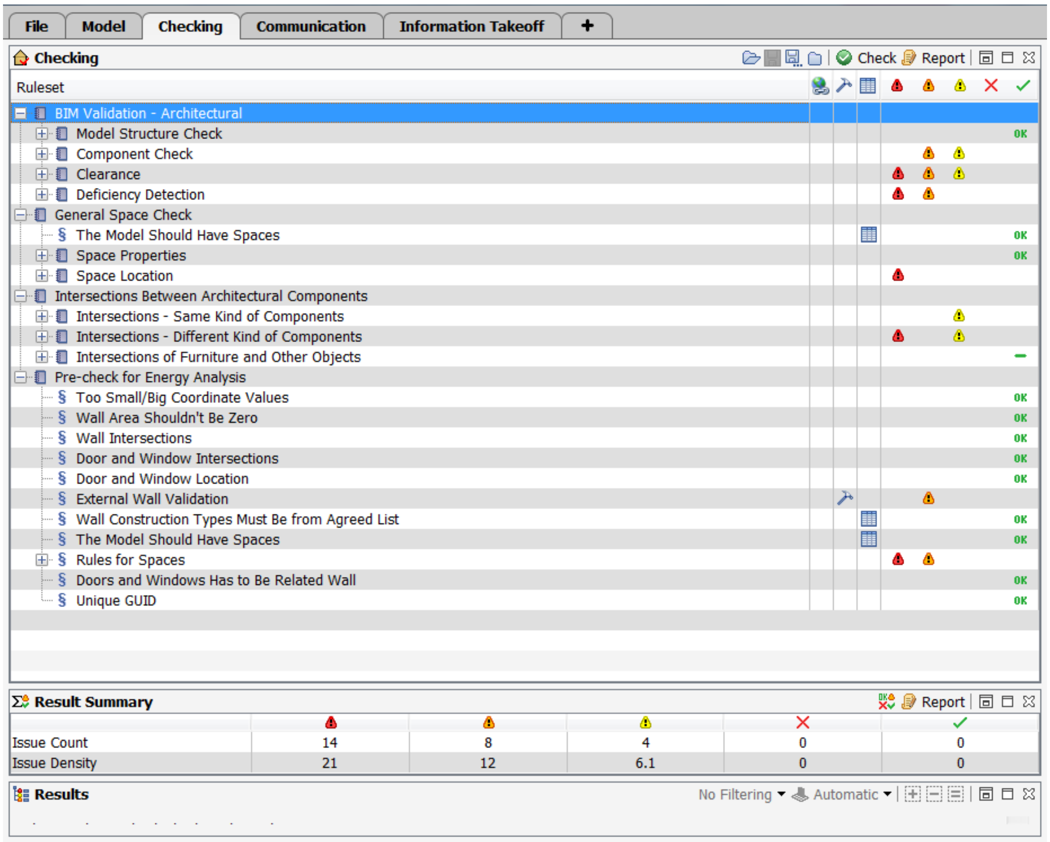
Figure 0:5: Modifying the components classification in SMC

7.1.7.3 Checking the model

Geometric and attribute data can be checked and validated in SMC. Its workflow is quite straightforward and by applying a set of rules to an IFC model, any critical, moderate and low severity issues can be assessed (Corke, 2013). In the Checking Layout, the summarized issues associated with specific rules are shown in Figure 0:6. It enabled the researcher to get an inclusive view of the model quality and provided the clashes with a more comprehensive view with the 3D interface.

7.1.7.4 Rulesets in Solibri Model Checker

In this research, the following four rulesets, BIM Validation Architectural, General Space Check, Intersections between Architectural Components, and Pre-check for Energy Analysis, were selected to check the model and report on any potential problems.



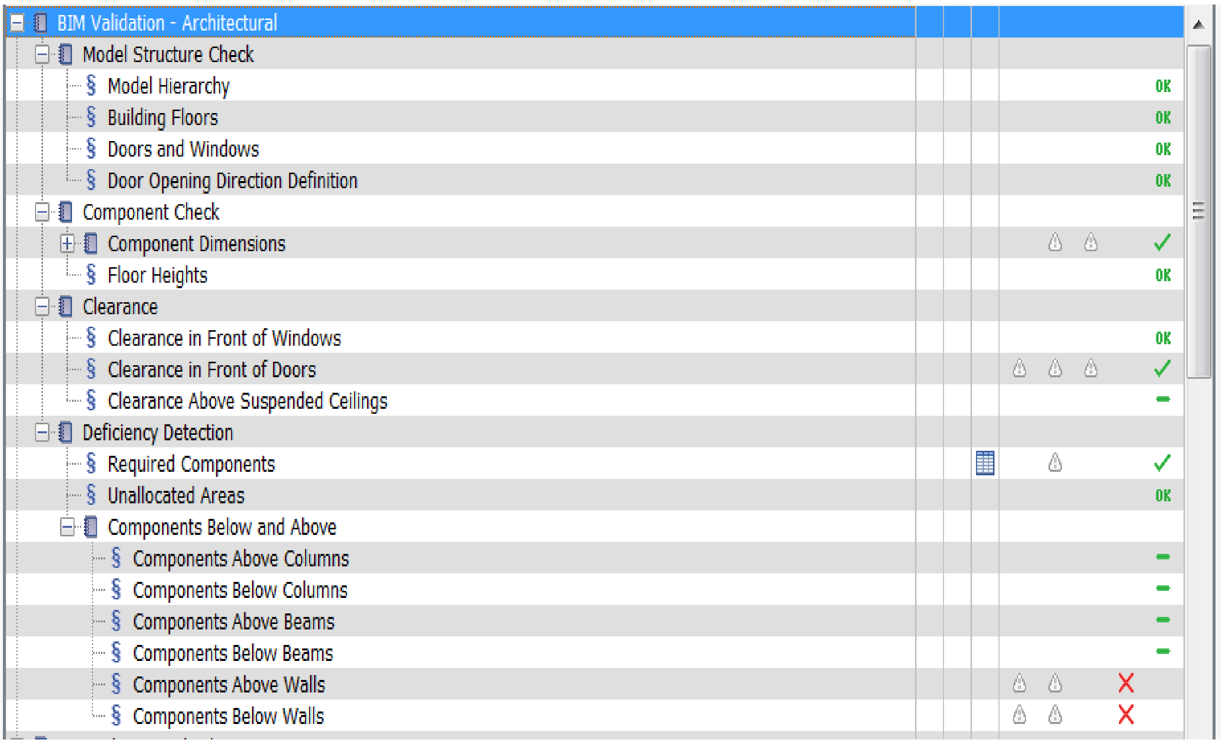
- BIM Validation - Architectural
  - Model Structure Check
  - Component Check
  - Clearance
  - Deficiency Detection
- General Space Check
  - The Model Should Have Spaces
  - Space Properties
  - Space Location
- Intersections Between Architectural Components
  - Intersections - Same Kind of Components
  - Intersections - Different Kind of Components
  - Intersections of Furniture and Other Objects
- Pre-check for Energy Analysis
  - Too Small/Big Coordinate Values
  - Wall Area Shouldn't Be Zero
  - Wall Intersections
  - Door and Window Intersections
  - Door and Window Location
  - External Wall Validation
  - Wall Construction Types Must Be from Agreed List
  - The Model Should Have Spaces
  - Rules for Spaces
  - Doors and Windows Has to Be Related Wall
  - Unique GUID

	⚠	⚠	⚠	✗	✓
Issue Count	14	8	4	0	0
Issue Density	21	12	6.1	0	0

Figure 0:6: Used rulesets to check the model in SMC

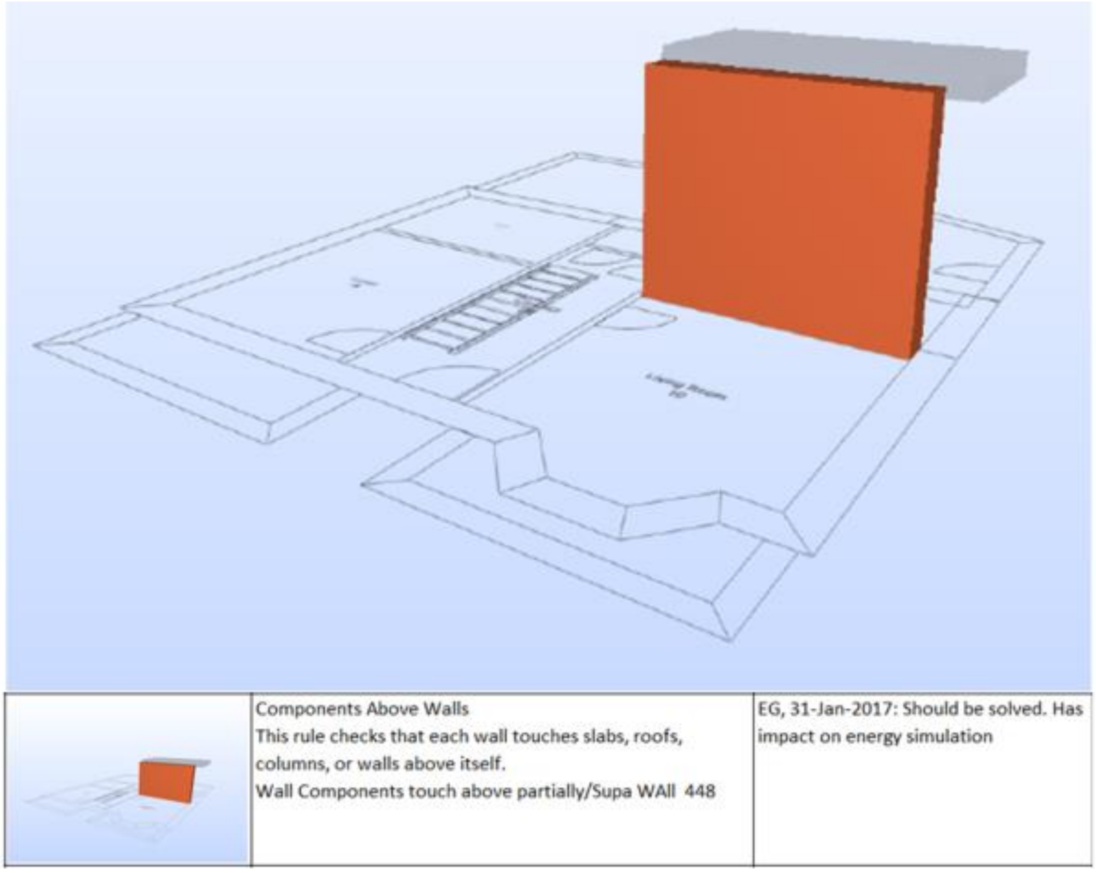
7.1.7.4.1 BIM Validation Architectural

This ruleset checks that the model follows the correct hierarchy and that components have reasonable dimensions and are in a correct way. This ruleset also checks the model structure, component, clearance and deficiency detection. For instance, doors and windows in the model are required to be related to the specific opening objects and to have defined minimum dimensions. Also, depending on the type of components, the clearance above or in front of the component can be checked. In the deficiency detection section, the missing components and their related information in the model can be checked. For example, the material layer thicknesses of components need to be verified. The type of component and the thickness of materials are essential to simulate the energy performance, and inaccurate or missing information associated with these issues might cause inaccurate or false outputs. After checking the model in BIM Validation Architecture, three critical severities, five moderate severities and two low severities were reported. These issues were solved in the ArchiCAD model before running EcoDesigner STAR.



- BIM Validation - Architectural
  - Model Structure Check
    - § Model Hierarchy OK
    - § Building Floors OK
    - § Doors and Windows OK
    - § Door Opening Direction Definition OK
  - Component Check
    - Component Dimensions ⚠ ⚠ ✓
    - § Floor Heights OK
  - Clearance
    - § Clearance in Front of Windows OK
    - § Clearance in Front of Doors ⚠ ⚠ ⚠ ✓
    - § Clearance Above Suspended Ceilings –
  - Deficiency Detection
    - § Required Components ▦ ⚠ ✓
    - § Unallocated Areas OK
    - Components Below and Above
      - § Components Above Columns –
      - § Components Below Columns –
      - § Components Above Beams –
      - § Components Below Beams –
      - § Components Above Walls ⚠ ⚠ ✗
      - § Components Below Walls ⚠ ⚠ ✗

Figure 0:7: Detecting Clashes in BIM Validation- Architectural

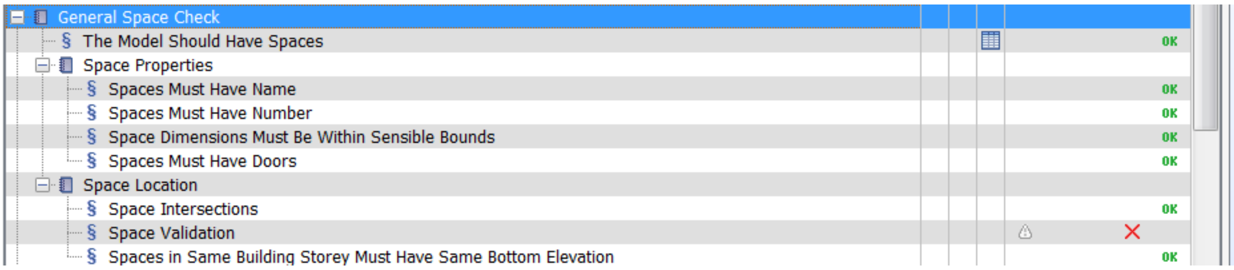


	Components Above Walls This rule checks that each wall touches slabs, roofs, columns, or walls above itself. Wall Components touch above partially/Supa WAll 448	EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

Figure 0:8: BIM Validation Architectural: Example of Deficiency Detection Check

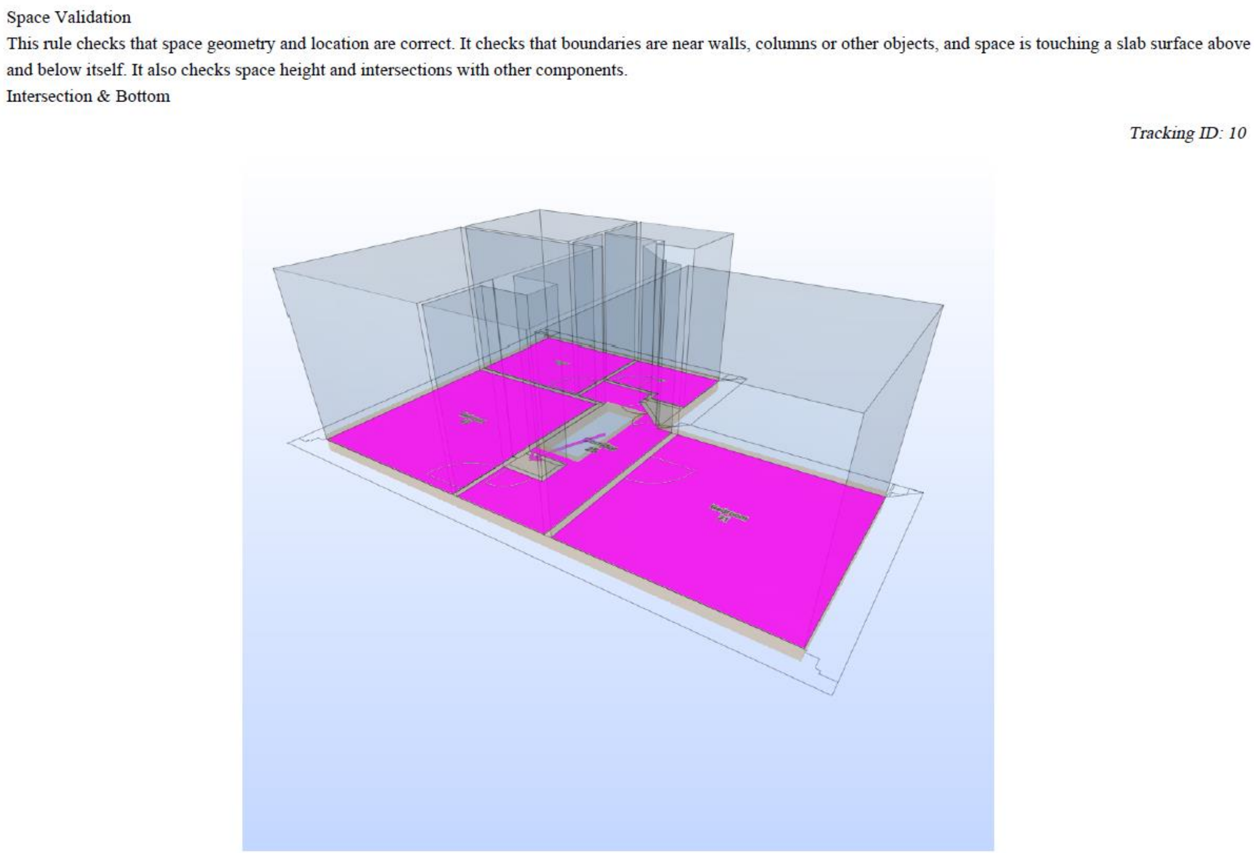
7.1.7.4.2 General Space Check

The properties of space can be checked for typical space related issues regarding how the space types and identification of individual spaces should be in the model and comply with the SMC settings (Solibri, 2014). To run the energy simulation, the space boundaries need to be defined. The ruleset check if the model has spaces, space properties and space validations. One critical severity is detected in space validation and as shown in Figure 0:9 and Figure 0:10, space boundaries are intersected with the slab surface.



- General Space Check
  - § The Model Should Have Spaces — OK
  - Space Properties
    - § Spaces Must Have Name — OK
    - § Spaces Must Have Number — OK
    - § Space Dimensions Must Be Within Sensible Bounds — OK
    - § Spaces Must Have Doors — OK
  - Space Location
    - § Space Intersections — OK
    - § Space Validation — ⚠ ✗
    - § Spaces in Same Building Storey Must Have Same Bottom Elevation — OK

Figure 0:9: Detecting Clashes in General Space Check



Space Validation

This rule checks that space geometry and location are correct. It checks that boundaries are near walls, columns or other objects, and space is touching a slab surface above and below itself. It also checks space height and intersections with other components.

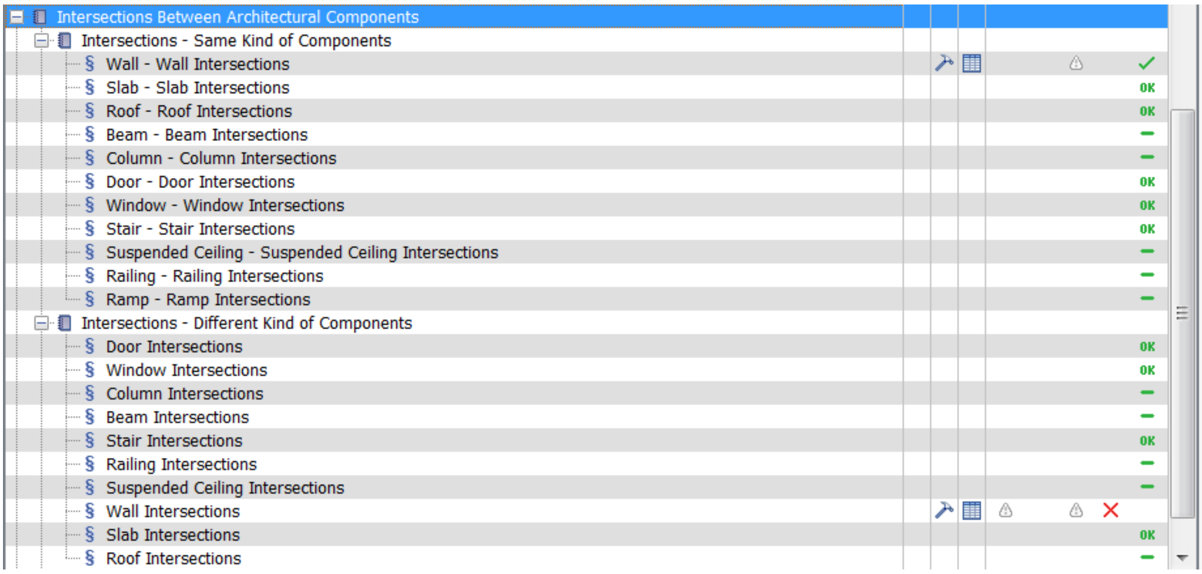
Intersection & Bottom

Tracking ID: 10

Figure 0:10: Example of clash detection in Space Validation

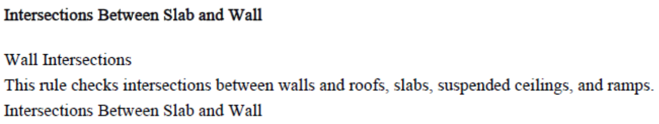
7.1.7.4.3 **Intersections between Architectural Components**

This ruleset checks all intersections of the same type and different types of components in the model, as shown in Figure 0:11. The geometry, location and the boundaries around components, such as slab and walls, can be checked. In addition, the boundaries of space can be checked to review how the components are connected and in contact with associated components. The untouched components that need to be intersected with other components may affect the energy performance of the building by creating unnecessary thermal bridges. One critical severity and one low severity were detected in this ruleset. As shown in Figure 0:12, there is an intersection between walls and slabs.



Intersections Between Architectural Components	
Intersections - Same Kind of Components	
§ Wall - Wall Intersections	✓
§ Slab - Slab Intersections	OK
§ Roof - Roof Intersections	OK
§ Beam - Beam Intersections	—
§ Column - Column Intersections	—
§ Door - Door Intersections	OK
§ Window - Window Intersections	OK
§ Stair - Stair Intersections	OK
§ Suspended Ceiling - Suspended Ceiling Intersections	—
§ Railing - Railing Intersections	—
§ Ramp - Ramp Intersections	—
Intersections - Different Kind of Components	
§ Door Intersections	OK
§ Window Intersections	OK
§ Column Intersections	—
§ Beam Intersections	—
§ Stair Intersections	OK
§ Railing Intersections	—
§ Suspended Ceiling Intersections	—
§ Wall Intersections	✗
§ Slab Intersections	OK
§ Roof Intersections	—

Figure 0:11: Detecting Clashes in Intersection between Architectural Components



Intersections Between Slab and Wall

Wall Intersections
This rule checks intersections between walls and roofs, slabs, suspended ceilings, and ramps.
Intersections Between Slab and Wall

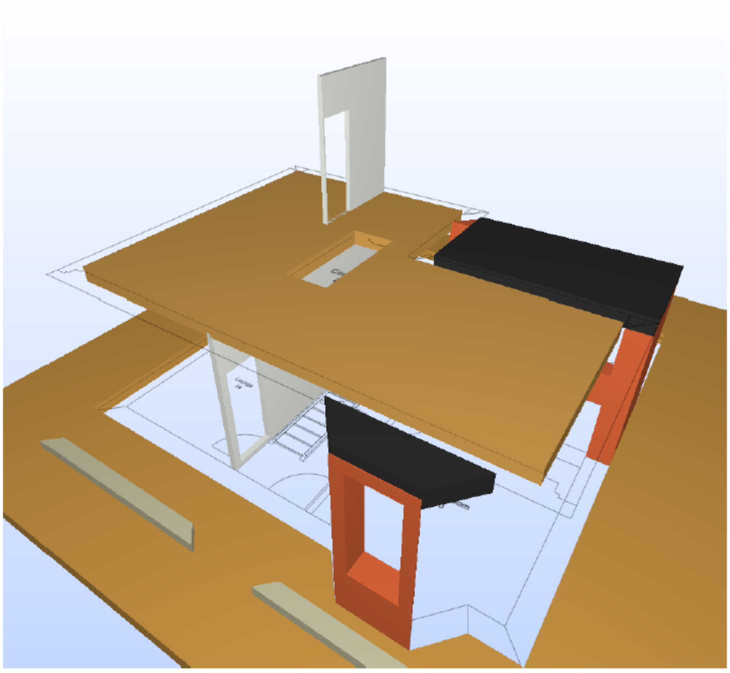
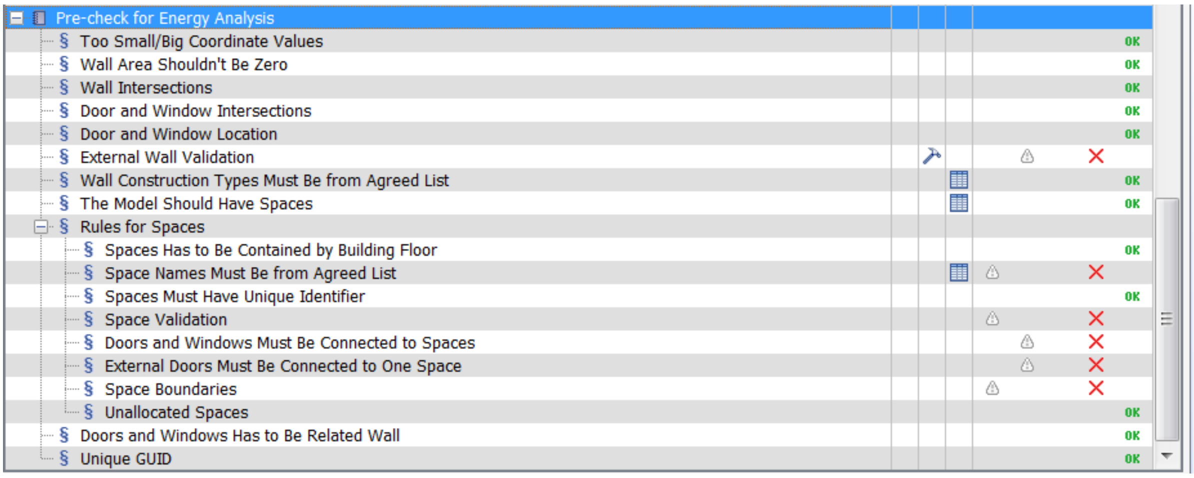


Figure 0:12: Intersection between slabs and walls

7.1.7.4.4 **Pre-check for Energy Analysis**

Different energy simulation software may have different requirements that need to be considered in the model. Depending on the energy analysis software, some rules can be skipped or added. Coordinate values, duplication or intersection of walls, windows and doors should be detected for clashes. External walls need to be defined in the model; also, doors and windows have to be related to a wall. Three critical severities and three moderate severities were detected in the ruleset shown in Figure 0:13. Space validation is detected as a critical severity as shown in Figure 0:14.



- Pre-check for Energy Analysis
  - § Too Small/Big Coordinate Values OK
  - § Wall Area Shouldn't Be Zero OK
  - § Wall Intersections OK
  - § Door and Window Intersections OK
  - § Door and Window Location OK
  - § External Wall Validation ⚠ ✗
  - § Wall Construction Types Must Be from Agreed List OK
  - § The Model Should Have Spaces OK
  - § Rules for Spaces
    - § Spaces Has to Be Contained by Building Floor OK
    - § Space Names Must Be from Agreed List ⚠ ✗
    - § Spaces Must Have Unique Identifier OK
    - § Space Validation ⚠ ✗
    - § Doors and Windows Must Be Connected to Spaces ⚠ ✗
    - § External Doors Must Be Connected to One Space ⚠ ✗
    - § Space Boundaries ⚠ ✗
    - § Unallocated Spaces OK
  - § Doors and Windows Has to Be Related Wall OK
  - § Unique GUID OK

Figure 0:13: Detecting Clashes in Pre-check Energy Analysis

Space Validation
This rule checks that space geometry and location are correct. It checks that boundaries are near walls, columns or other objects, and space is touching a slab surface above and below itself. It also checks space height and intersections with other components. Spaces intersecting each other, or inside each other are not accepted. SPACE INTERSECTION Category is important. In Energy analysis it is often important that space perimeters touch walls around themselves. BOUNDARY Category is important.

Tracking ID: 20

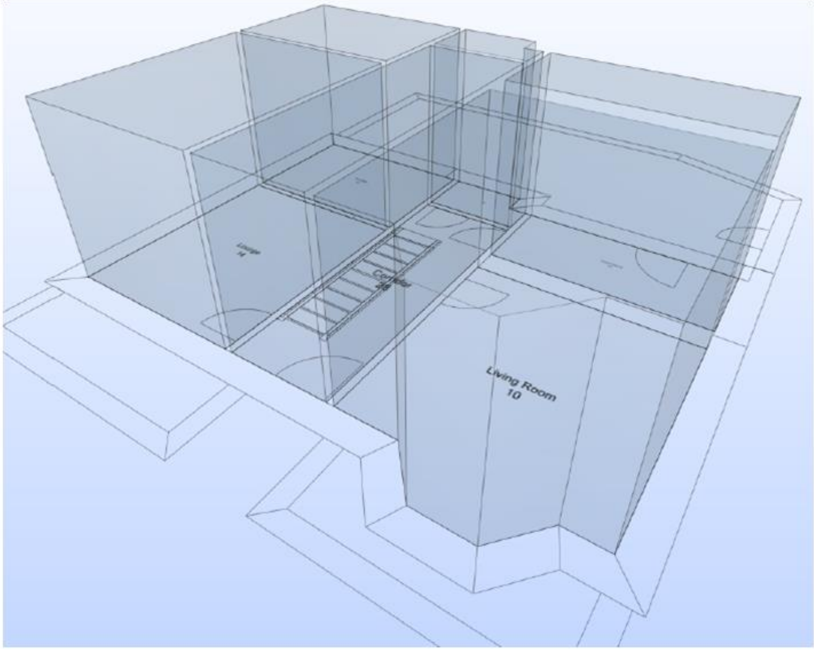


Figure 0:14: Detecting Clashes in Pre-check Energy Analysis: Space validation

The full report of detected clashes with 3D representation is documented in Appendix A.

The process of detecting the potential clashes, mistakes and missing information in the ArchiCAD model using SMC assisted in exploring what level of information is required at different phases and check how the potential problems may impact on the accuracy of energy simulation results. All potential clashes were reviewed and several modifications were applied to the ArchiCAD model. It is important to mention that the detected clashes, which do not impact on the energy simulation, were not modified and, as shown in Appendix A, they are assigned as accepted clashes. For example, the detected clashes in clearance in front of doors do not impact on energy simulation which is the intended purpose of this model and therefore it was not necessary to be modified. All spatial boundaries were checked through SMC and modified to be used for energy performance simulation as inconsistent and incorrect spatial boundaries result in false simulation results (Osello, et al., 2011).

Integrated BIM Simulation Approach: ArchiCAD EcoDesigner STAR

The BIM software has evolved over the last decades and semantic data have been integrated into the BIM packages for analysis such solar analysis, energy analysis and so forth (Østergård, et al., 2016). The Graphisoft EcoDesigner Star for ArchiCAD, Autodesk Green Building Studio for Revit (2015) have developed their proprietary BPS tools and integrated algorithms directly into the BIM software (Østergård, et al., 2016). EcoDesigner Star integrated in ArchiCAD 20 was selected for this research to reuse and share domain data in ArchiCAD (BIM tool) by BPS tools. A single building data model is used as the reference model for design and simulation. In this approach, BIM can be used to support efficient and effective design and construction processes and to inform decision making throughout the retrofit process, thereby improving, not just the energy efficiency of the existing housing stock, but also the effectiveness of the processes.

As the next step after modifying clashes and correcting the mistakes, which were not identified before checking the quality of the model with SMC using IFC format, additional data inputs were required to run the energy simulation. The operation file, environmental settings, climate data and building systems are required to run the EcoDesigner STAR. The inputs for building systems' specifications and parameters are as explained in sections 7.1.1.5, 7.1.1.6 and 7.1.1.7. The input of each parameter for operation files were set according to the monitored data, which was also used in DesignBuilder, since interaction of occupants with energy is subjective, and treating users as rational actors has given rise to the Energy Efficiency Gap (Lutzenhiser, 1992; Stern, 2006) and occupancy interaction cannot be predicted with energy simulation software.

7.1.8 Operation files

The function of the building was assigned to the model and the operation file was customised. Internal temperature and heat gain profiles were fine-tuned according to CIBSE and the monitored data. An operation file was assigned to all zones individually according to their function in the model. Comfort criteria for each zone were based on CIBSE Guide A (2006). However, since it is not applicable in EcoDesigner STAR to put comfort criteria in winter different from comfort criteria in summer, the whole range was considered. For example, CIBSE suggested assigning 22-23^{0}C for the living room in winter and 23-25^{0}C in summer; however, 22-25 ^{0}C was assigned to the Eco Designer STAR model. The assigned temperature was fine-tuned by measured internal temperature over two years of monitoring data.

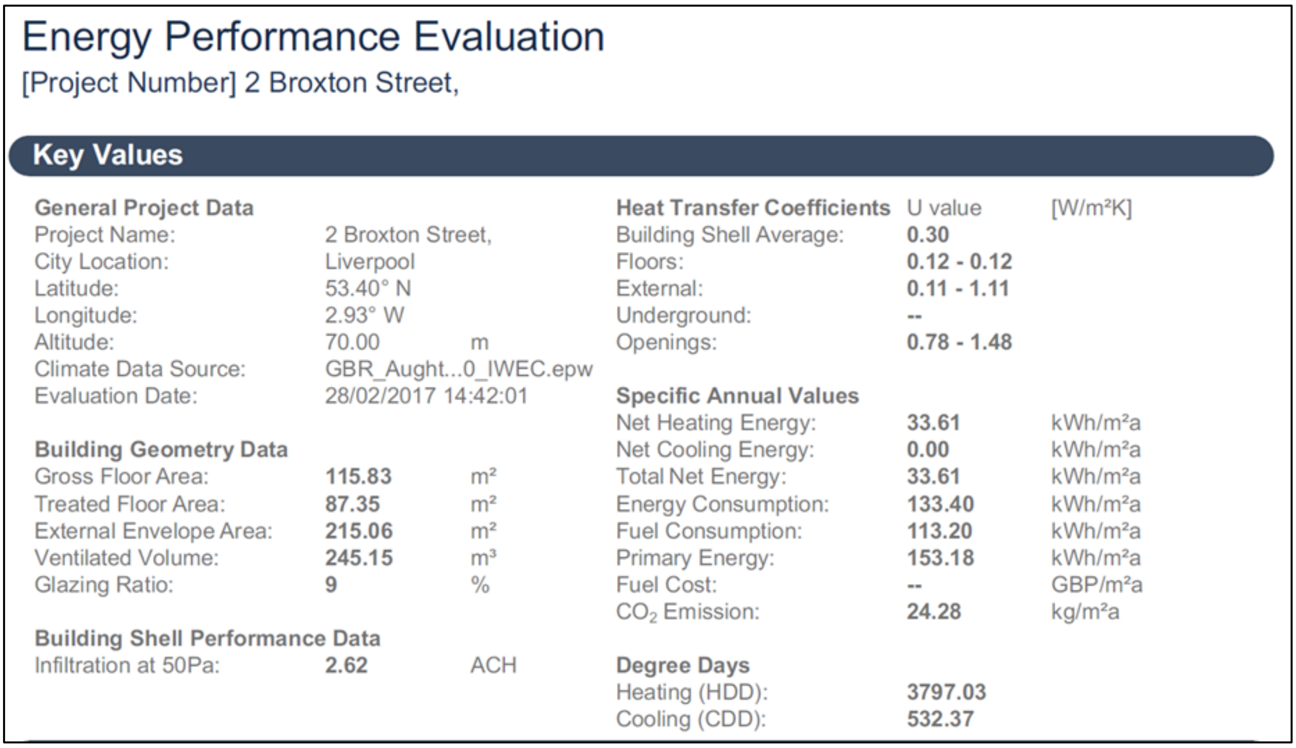
7.1.9 Environmental Settings

Project location was assigned based on a latitude 53.4° N and longitude 2.9°E. Climate data were uploaded from EnergyPlus Energy Simulation Software website (EERE, 2016). Climate data shows air temperature, relative humidity, solar radiation and wind speed for the project location which is used for the energy simulation.

7.1.10 Building Systems

Building systems information is essential for the energy calculation. All building systems for heating, hot water generation and ventilation, including solar thermal panel, condensing boiler and MHRV, were assigned to each zone. EcoDesigner STAR estimated 153.18 kWh/m^{2}a for primary energy consumption, and 24.28 kg/m^{2}a for CO_2 emissions. The key value results of EcoDesigner STAR are shown in Table 0:1.

Table 0:1: Key Values results evaluated by EcoDesigner STAR



Energy Performance Evaluation

[Project Number] 2 Broxton Street,

Key Values

General Project Data		
Project Name:	2 Broxton Street,	
City Location:	Liverpool	
Latitude:	53.40° N	
Longitude:	2.93° W	
Altitude:	70.00	m
Climate Data Source:	GBR_Aught...0_IWEC.epw	
Evaluation Date:	28/02/2017 14:42:01	
Building Geometry Data		
Gross Floor Area:	**115.83**	m²
Treated Floor Area:	**87.35**	m²
External Envelope Area:	**215.06**	m²
Ventilated Volume:	**245.15**	m³
Glazing Ratio:	**9**	%
Building Shell Performance Data		
Infiltration at 50Pa:	**2.62**	ACH

Heat Transfer Coefficients	U value	[W/m²K]
Building Shell Average:	**0.30**	
Floors:	**0.12 - 0.12**	
External:	**0.11 - 1.11**	
Underground:	**--**	
Openings:	**0.78 - 1.48**	
Specific Annual Values		
Net Heating Energy:	**33.61**	kWh/m²a
Net Cooling Energy:	**0.00**	kWh/m²a
Total Net Energy:	**33.61**	kWh/m²a
Energy Consumption:	**133.40**	kWh/m²a
Fuel Consumption:	**113.20**	kWh/m²a
Primary Energy:	**153.18**	kWh/m²a
Fuel Cost:	**--**	GBP/m²a
CO_2 Emission:	**24.28**	kg/m²a
Degree Days		
Heating (HDD):	**3797.03**	
Cooling (CDD):	**532.37**	

Although an integrated BIM simulation approach provides effortless interoperability, this type of integrated framework needs more intelligent guidance and basically depends on vendors to integrate performance simulation into their BIM environment (Batueva & Mahdavi, 2015).

Table 0:2: Comparison of all simulations and assessments with monitored results

	Primary Energy Use kWh/m^{2}a	CO_2 Emissions kg/m2/yr
DesignBuilder	151	23
EcoDesigner STAR	153.8	24.28
Monitored Results (Average)	157.7	24
PHPP	102	20
SAP	85	-

Interoperable BIM: Green Building XML (gbXML)

gbXML was developed to facilitate transmission of the information between BIM and BPS tools to improve the interoperability between them (gbXML, 2014; Moon, et al., 2011). It is one of the most widely supported data formats and many software vendors, such as Graphisoft, Bentley and Autodesk, support the format for interoperability with BIM (Sokolov & Crosby, 2011; Nasyrov, et al., 2015).

To compare the interoperable BIM simulation approach with the existing simulation approach using DesignBuilder, gbXML can be used as data exchange format. After checking the quality of the model in SMC, the updated ArchiCAD model was exported in gbXML format and visualized with the graphical interface of BPS tools compatible with gbXML format. The ArchiCAD model was exported in gbXML in two different approaches since ArchiCAD 20 has native gbXML export option, but ArchiCAD 19 requires pulg-in to export in gbXML format.

7.1.11 The native gbXML export in ArchiCAD 20

The BIM, in this research the ArchiCAD model, as a shared model provides the ability to store data and avert repetition. ArchiCAD 20 has the native gbXML export option to support interoperability with external BPS tools. The ArchiCAD model was exported from ArchiCAD 20 to the energy simulation software, DesignBuilder. The required data input to be transferred from BIM to BPS tools were recognized as: geometry, material specifications, building systems and technical equipment, site condition and building operation data (Maile, et al., 2007; Bazjanac, 2009). The researcher tested the applicability of the gbXML to run the energy simulation in DesignBuilder. The required stages to run the energy simulation software based on the necessary input data are explained to evaluate the applicability of gbXML to exchange data.

7.1.11.1 Geometry

Transferring the geometry from BIM to simulation tools has been improved and it is an active area of research (Hitchcock & Wong, 2011). Generally, the conversion process of the geometry includes some pre-processing and post-processing since the geometry model in gbXML is about spatial connections to a zone or the building exterior rather than a collection of surfaces. Some raw data from BIM tools is required to be prepared or deleted depending if they are relevant or irrelevant for simulation. Although the algorithms and process for conversion of geometry from BIM tools to BPS tools have been improved by several software vendors, the quality of spatial models still is faced with some problems (Hitchcock & Wong, 2011). Problems can derive over the post-processing, such as inconsistencies in the thermal model as a result of the automatic simplification of walls (Cemesova, et al., 2013). As the shape of the case study was not complex, the geometry was exported successfully;

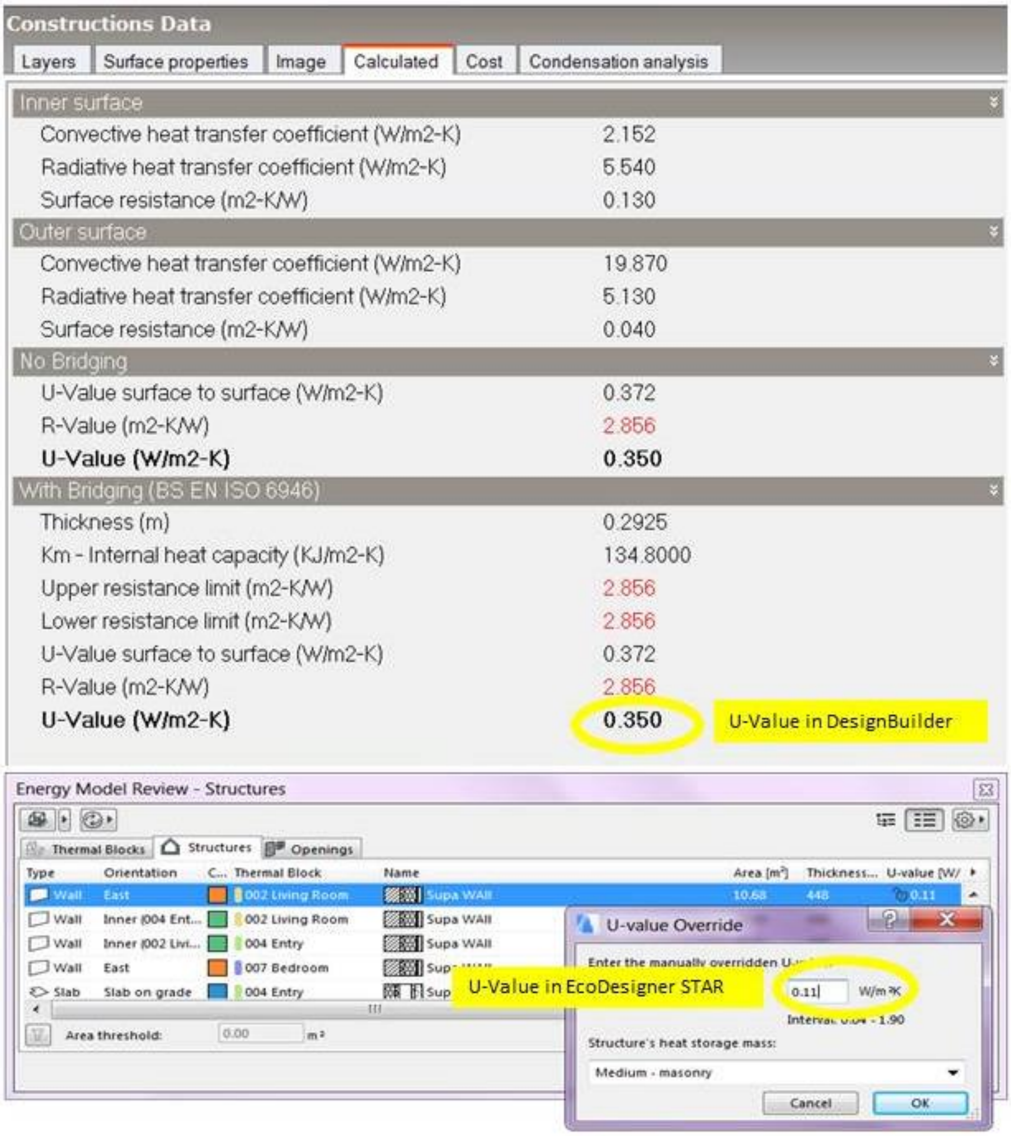
however, it can be problematic for complex geometries and its reliability and usefulness need to be checked (Maile, et al., 2013).

To run the energy simulation, it is important that building elements are aligned with space objects and have the correct dimension to enclose the space. Since space boundaries are the most essential objects for BPS tools, spatial duplications or overlapping with other elements are not accepted (Maile, et al., 2013). Moreover, additional data in the model should be stripped away in gbXML, since they are not enhancing the results and make the simulation process unnecessarily slower. For the 2 Broxton Street case study, as it was modelled to simulate the energy performance, there was no need to delete any elements. However, it could be a case as 3D digital model usually are generated for virtual and architectural purposes and typically do not meet the required quality for BPS tools (Maile, et al., 2013). As shown in Figure 0:1, the geometry was transferred correctly into DesignBuilder.

Figure 0:1: Exported gbXML file into DesignBuilder through native option of gbXML in ArchiCAD 20

7.1.11.2 Material properties

Most BPS tools supporting gbXML format currently use default construction and material properties. Corresponding BIM or BPS tools typically do not yet provide the means to import or export mechanism to enter construction and material properties (Hitchcock & Wong, 2011; Nasyrov, et al., 2015). The exported gbXML from ArchiCAD to DesignBuilder tested by the researcher showed that material properties are not included in the exported gbXML file.



Inner surface	
Convective heat transfer coefficient (W/m2-K)	2.152
Radiative heat transfer coefficient (W/m2-K)	5.540
Surface resistance (m2-K/W)	0.130
Outer surface	
Convective heat transfer coefficient (W/m2-K)	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130
Surface resistance (m2-K/W)	0.040
No Bridging	
U-Value surface to surface (W/m2-K)	0.372
R-Value (m2-K/W)	2.856
U-Value (W/m2-K)	**0.350**
With Bridging (BS EN ISO 6946)	
Thickness (m)	0.2925
Km - Internal heat capacity (KJ/m2-K)	134.8000
Upper resistance limit (m2-K/W)	2.856
Lower resistance limit (m2-K/W)	2.856
U-Value surface to surface (W/m2-K)	0.372
R-Value (m2-K/W)	2.856
U-Value (W/m2-K)	**0.350**

Type	Orientation	C...	Thermal Block	Name	Area [m²]	Thickness...	U-value [W/
Wall	East	🟧	002 Living Room	Supa WAll	10.68	448	0.11
Wall	Inner (004 Ent...	🟩	002 Living Room	Supa WAll			
Wall	Inner (002 Livi...	🟩	004 Entry	Supa WAll			
Wall	East	🟧	007 Bedroom	Sup			
Slab	Slab on grade	🟦	004 Entry	Sup			

Area threshold: 0.00 m²

U-value Override

Enter the manually overridden U-

0.11 W/m²K

Interval - 1.90

Structure's heat storage mass:

Medium - masonry

Figure 0:2: Comparing the U-Value of exported file in DesignBuilder (top) with EcoDesigner STAR (below)

The lack of export functions for material data from Graphisoft ArchiCAD 20 to the gbXML format is a barrier to utilising the full potential of interoperability between them. A lack of automated import functions for material and construction properties, and entering the properties manually to BPS user interface, is a time-consuming and redundant task (Nasyrov, et al., 2015).

7.1.11.3 Building systems

"There is a gap in the transformation of the IFC file to the input data for EnergyPlus simulation engine, which is difficult to overcome because of the complexity of building systems." (Nasyrov, et al., 2015). Wealthy simulation options provided in EnergyPlus simulation engine require domain expertise for input specifications. This transformation cannot currently be addressed in automated processes. Hitchcock and Wong (2011) recommended a rudimentary solution to use the available EnergyPlus template for building systems.

7.1.11.4 Weather and climate data

The weather condition and climate data are derived from external data sources and building model does not include any actual information over it. To export gbXML file to DesignBuilder, opening a new file is required and location should be chosen from external data source prior to importing the gbXML file. Although the inability of DesignBuilder to read the weather data from a BIM tool, it is not a time-consuming process to do it in energy simulation software.

7.1.11.5 Building operation information

The operation information and internal loads can be selected in ArchiCAD 20 and they were fine-tuned based on the monitored data. Although the EcoDesigner STAR, native internal simulation plugin in ArchiCAD, can read the operation conditions of the model, gbXML does not include any detail of the operation information after export from ArchiCAD. The details of the operation information must be entered manually to DesignBuilder.

Although many BIM and BPS tools are supporting the gbXML format, which can be considered as an advantage of this format, there are also several unresolved issues and tasks on the interoperability of BIM and BPS tools (Moon, et al., 2011; Osello, et al., 2011), as discussed in section 0. Using default structure and material properties and being ineffective to transfer these properties to external energy simulation software are the main barriers to get the full potentials of this open format (Nasyrov, et al., 2015).

7.1.12 The plug-in to export gbXML in ArchiCAD 19: Cadimage

ArchiCAD 19 does not include a native gbXML export function. However, Cadimage developed a free plug-in to enable ArchiCAD file to be exported as gbXML for ArchiCAD 16 and later versions (Cadimage, 2015). The comparison of exporting ArchiCAD 19 through Cadimage plug-in and ArchiCAD 20 with native gbXML export option demonstrates several discrepancies between the native and plug-in option to export gbXML file to DesignBuilder. Although the geometry was exported correctly through native gbXML in ArchiCAD 20, the geometry transferred by a plug-in option in ArchiCAD 19, in this case Cadimage, was not successful. Three major problems occurred in the conversion process, as shown in Figure 0:3, and it requires a process of fixing partially converted geometry manually. This issue was explored by Osello, et al (2011) as well.

As mentioned earlier, although the algorithms and process for conversion of BIM tools have been enhanced, quality of spatial models needs to be improved. In September 2016, gbXML validator became available online. It allows software vendors to check the quality of gbXML files created by their software tools (gbXML, 2016).

The result summary of gbXML vendor certification validator for the gbXML file of 2 Broxton Street exported from ArchiCAD 20 is shown in Table 0:1.

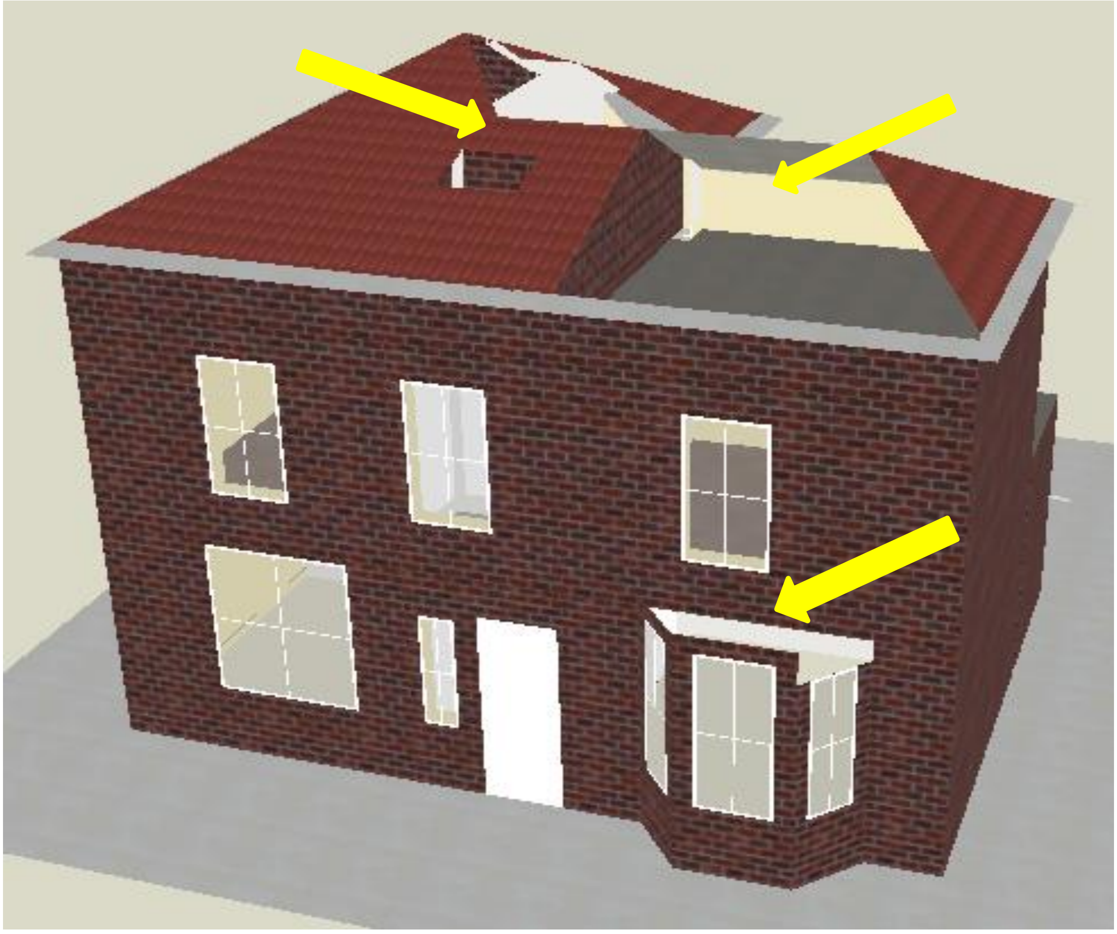
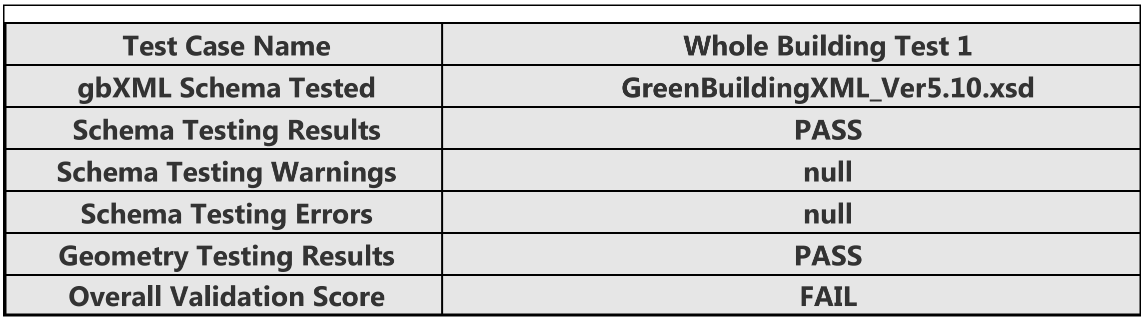


Figure 0:3: Exported gbXML file into DesignBuilder through Cadimage from ArchiCAD 19: displacements and absence of original elements

Table 0:1: gbXML vendor certification validator



Test Case Name	**Whole Building Test 1**
gbXML Schema Tested	**GreenBuildingXML_Ver5.10.xsd**
Schema Testing Results	**PASS**
Schema Testing Warnings	**null**
Schema Testing Errors	**null**
Geometry Testing Results	**PASS**
Overall Validation Score	**FAIL**

The **geometry testing results** of the case study shows pass and **overall validation score** shows fail as it was tested by the researcher, since the geometry transformed correctly but the material properties required manual modifications.

Exchanging building data can improve the process by saving time and reducing errors (Cemesova, et al., 2013). It offers an opportunity to analyse different model views of a building by different domains (Cemesova, et al., 2013). Transforming an architectural view to a thermal view is necessary since software tools represent a model in various ways and concepts require to be mapped from one to another to avoid data repetition and redundancy (Wilkins & Kiviniemi, 2008). Although interoperability can facilitate the early integration of building performance simulation through re-using of domain data model, use of BIM tool for simulation requires an understanding of its limitations and often requires manual checking and fixing the converted geometry (Osello, et al., 2011; Moon, et al., 2011).

Conclusion

In this chapter, existing assessment (SAP and PHPP) and simulation approaches (stand-alone DesignBuilder), and BIM simulation approaches, integrated BIM tools and interoperable BIM, were evaluated and tested through a case study. To evaluate the accuracy and efficiency of all the mentioned approaches, their results were compared with the results of monitored house over a two-year period.

The **energy performance assessments** are not accurate enough to rely on it in the decision-making process. The PHPP results were out by 38% in comparison with the monitored results. This research does not claim that PHPP cannot estimate accurate results, but it could be concluded that using unrealistic assumptions gives unreliable results. The SAP calculation was off by 47%, which is a very critical issue since SAP, as an independent calculation methodology, forms the backbone of government policy to estimate building performance. SAP rating omits the life cycle assessments and it is mainly based on the notional assumptions and an index calculated from a collection of different building components that frequently leads to suboptimal solutions (Kellya, et al., 2012). Comparing **energy performance assessment, SAP and PHPP,** with monitored results shows that the **assessment** which is based on the unrealistic and notional assumptions is not accurate and reliable enough to make a proper decision at the early stages of the retrofit process.

The **detailed modelling** approach estimated 151.6 kWh/m^{2}a for primary energy consumption in DesignBuilder that is very close to the average monitored results over a two-year period with 157.7 kWh/m^{2}a. However, the **detailed modelling** approach was a very time-consuming process, since collecting a considerable amount of data and putting architectural information into the BPS tools in the early design stage to run energy simulation is a very lengthy process and requires more time than usually is available at the early stage of decision-making process (Ryu & Park, 2016). Hence, the results are irrelevant by the time they are delivered and arbitrary decisions and assumption might have been made (Osello, et al., 2011). Also, due to the time and resource limitations, the geometry of the building should be simplified to define the thermal geometry. Usually, an energy specialist defines the thermal view of the building based on the 2D drawings created by the architect, and the simplification of the geometry depends on his/her knowledge, skills and understanding of the geometry and it is very subjective and not reliable (Bazjanac, 2008a). The **detailed modelling** is very time-consuming, labour intensive, costly, arbitrary and typically adopted at the late stage where fundamental design decisions have been already made. Even accurate energy performance simulation after a sufficient progress has the lowest and limited impacts on the final building performance (Hygh, et al., 2012; Mondrup, 2014).

Interoperability between BIM and BPS tools has enabled designers to improve their design options by learning the impact of their design on energy simulation performance in a real time. The potential of storing data centrally in BIM tools provide the opportunity to extract data from this container for various purposes to avoid the redundancy and repetition. BPS tools integration in BIM tools at the early design stage can assist involved bodies to choose the optimal strategies leading informed decision (Mondrup, 2014; Shaviv, et al., 1996).

Two BIM simulation approaches, the integrated BIM simulation approach, EcoDesigner using the native ArchiCAD 20 file, and interoperable BIM approach, using the gbXML format to transfer the data from BIM tool to PBS tool, were studied in this research through a case study.

Prior to simulating the energy performance, the created model in ArchiCAD 20 was checked in Solibri Model Checker (SMC) to validate the BIM files against the rulesets using neutral IFC format. The success of data exchange depends highly on the quality of shared information and in the initial stages of process it has a significant role in making proper decisions (Nicolaou & McKnight, 2006; Mukhopadhyay, et al., 1995; Hartonoa, et al., 2010; Ding, et al., 2006). In this context quality refers to accuracy, accessibility and usefulness of the shared information (Li, et al., 2006). Four rulesets were selected to check the quality of model for energy efficiency purposes, including BIM Validation Architectural, General Space Check, Intersections between Architectural Components, and Pre-check for Energy Analysis. Since "A model is an abstraction of reality for the given purpose" (Rothenberg, 1989) and the shared model must provide the necessary information for intended aim, it is important to explore the potential problems and missing information that may impact on the accuracy of energy simulation results. Five critical issues, five moderate issues and four low severity issues reported by SMC were solved in the ArchiCAD model before running EcoDesigner STAR.

EcoDesigner STAR estimated 153.18 kWh/m^{2}a for primary energy consumption which is close to the monitored data with 157.7 kWh/m^{2}a. The excellent and extreme accuracy of both **detailed modelling** approach and integrated BIM approach are to some extent associated with the reason that the user behaviour (interactions with energy) was based on the monitored data. This shows that if the inputs for an existing building are correct, the simulation results will also be correct.

The integrated BIM simulation approach provides effortless interoperability, but this type of integrated framework needs more intelligent guidance and, basically, it depends on vendors to integrate performance simulation into the BIM environment (Batueva & Mahdavi, 2015).

The interoperable BIM using gbXML format re-used of data from ArchiCAD to simulate in DesignBuilder. The exported geometry through ArchiCAD 20 with native gbXML export option was correct based on the test done using the online gbXML vendor certification validator. However, the geometry transferred by a plug-in option in ArchiCAD 19, in this case Cadimage, required manual checking and fixing three parts of the converted roof geometry.

In both ArchiCAD 20 and ArchiCAD 19, all other data including material properties, building systems, site condition and building operation information are required to be assigned in DesignBuilder. This is one of the main barriers to reaching the full potential of this open interoperability standard. Exchanging and reusing the geometry data saved time and reduced errors by transforming the architectural view from ArchiCAD 20 to the thermal view in DesignBuilder, and data repetition and redundancy were avoided. However, interoperable BIM simulation approach requires an understanding of its limitations and often also manual checking and fixing the converted geometry and possibly missing attributes (Osello, et al., 2011; Moon, et al., 2011).

The major contribution of this chapter is in providing the base to evaluate the benefits, barriers and limitations of the existing assessment and simulation approaches, and BIM simulation approaches, and also providing a practical example of how BIM can be integrated in the energy performance simulation. The potential benefits and barriers of BIM as Building Information Modelling in energy simulation was discussed in this chapter.

The next chapter provides a framework to evaluate the potentials and limitations of BIM implementation in the early stage of energy efficient domestic retrofit process, where BIM refers to Building Information Management. Furthermore, the current shortcomings, good practices and future research topics will be discussed.

Chapter Eight

Discussion

8 Discussion

Introduction

To the best knowledge of the author, this thesis was the first research to implement BIM in the small-scale retrofit process in the residential sector in the UK. However, in the meanwhile, two other projects commenced implementing BIM in the domestic retrofit process. The implication of BIM implementation in these two projects, their expected and actual results will be discussed in this section. The study of these two projects not only explores how these projects have benefitted from BIM implementation in small-scale retrofit projects but also explores if BIM implementation has faced challenges which are identified by the author in this research.

The first project considered adopted BIM and Computer Numerical Control (CNC) technology to speed up the retrofit process and minimise the construction time to reduce the disruption for elderly people in London.

In the second project, the implication of BIM to improve the energy efficiency, reduce energy cost, and expedite the delivery process will be discussed. The author was involved in this research to check the quality of shared model prior to being used for energy, time and cost analysis. Although this is an ongoing research and the results are not yet verified, the research funding granted by the Technology Strategy Board can be seen as a validation of the identified research gap.

Sustainable retrofit of housing for the elderly in historic district in London with Building Information Modelling (BIM) and Computer Numerical Control (CNC)

More than a quarter of the population in the selected historic district in London with terraced house typology built from 1830-1900 are older than 60 years. Over 150,000 terraced homes were built in the Victorian period, especially in the 1890s decade, and the majority of them still exist. In this project, several aspects were required to be considered to fit elderly people characteristics, including better distribution of spaces for installing technological machinery for elderly and disabled people, bigger and more comfortable bathrooms, wider corridors and doors. From a sustainability perspective, the priority was given to preserve the current old masonry walls and timber-framed structure. The main reason for implementing BIM in this project was to minimise disruption for disabled aged people while reducing energy consumption, costs and construction time in comparison with the traditional retrofit process (Iturralde, 2012).

BIM and Computer Numerical Control (CNC) were implemented to improve the existing practices of the retrofit process. Advanced CNC fabrication (Bock, 2008) and advanced three dimensional data collection (Naticchia, et al., 2010; Bosche & Haas, 2008; Sakamoto, et al., 2011) assisted to minimise construction time and occupants disruption as they lived in home within the retrofit process. The workflow was divided into five main tasks as follows (Iturralde, 2012):

- *"Demolition of the internal partition and dismantling of all Mechanical, Electrical and Plumbing (MEP) services;*
- *Reparation of timber joist, wherever it was needed;*
- *Placement of a properly levelled floor, meaning that it will correct the common differential settlement of the structure;*
- *Installation of new MEP and erection of new distribution, according to the inhabitant's needs and respecting local laws;*
- *An improvement of insulation of the entire perimeter closings, that is floors, external walls and ceilings;*
- *Finishing.*

The main motivation to implement BIM and CNC technology was the general ineffectiveness of existing practices in the traditional retrofit process, such as a lack of collaboration and communication between architect and construction workers. The architect was not able to guarantee the requirements of the project to be delivered. The traditional process frequently leads to the repetition of some works, considerable delay, increased costs by almost 20% (Iturralde, 2012). The previous retrofit project in the same location had collateral effects, including several cracks in the neighbours' walls, collapsing ceilings partially due to the poor condition of some structural elements; and noise complaints from neighbours. Therefore, BIM and CNC technology were implemented to improve the traditional process.

To implement BIM and CNC technologies in the retrofit process, detailed and accurate measurements should be considered to avoid problems in assembling fabricated elements. Capturing data from an over 100 year old building, inner wooden joist and load-bearing walls required a proper data capturing technique. Advanced surveying techniques were employed (Bosche & Haas, 2008; BCIS, 2012) to measure twisted beams and joists as a result of torsion and tension force. Although the set-up of the project took three weeks to implement BIM, compared to the traditional process time of five days, it minimised the construction time and occupants' disturbance. Also, accurate virtual presentation of building not only provided involved bodies with opportunities to discuss issues, such as installing ventilation pipes with neighbours, but also prevented damages to stair cases through fabricating elements in accordance with stair case size and in general avoiding collateral effects.

BIM implementation in this case reduced the disruption of occupants, shortened construction time, provided as-built BIM for future maintenance and retrofitting, but could not minimise the costs, which was partially due to the lack of a systematised way to exchange data between software programs and the high price of 3D data collection at the time when the project was done (2011). The quantity of material used was difficult to evaluate, but it was estimated to be the same as the traditional approach (Iturralde, 2012).

The work load would be reduced with advances in automation. To achieve the full potential of BIM several improvements, such as a more systematised and simpler approaches for 3D data collection, should be considered to get access to the reliable and accurate geometry prior to fabricating the elements. Furthermore, regarding software programs, an effective data sharing approach between software programs is required.

Building Information Modelling [BIM] for energy efficiency in housing refurbishments

The Northern Ireland Housing Executive (NIHE), one of the largest social landlords in Europe, owns around 9,000 homes with solid wall construction (NIHE, 2016). The Technology Strategy Board (TSB) funded a research project, S-IMPLER, in August 2013 to investigate the opportunities to reduce the CO_2 emissions of those solid wall houses (BRE, 2015). S-IMPLER (Solid Wall Innovative Insulation and Monitoring Processes using Lean Energy Efficient Retrofit) was a collaborative project with NIHE, BRE, Carillion Energy Services, Leeds Beckett University, the University of Huddersfield and other key partners (Comlay & Tzortzopoulos, 2015; S-IMPLER, 2015). This three year project aimed to minimise disruption, reduce energy cost by 60%, deliver faster by 10%, and improve the energy performance without impacting on safety and quality (BRE, 2015). The funding decision for the S-IMPLER project by TSB in August 2013 can also be seen as a validation of the identified real world problem (research gap) identified by the author in October 2012.

8.1.1 How has BIM been implemented in S-IMPLER Project to reduce the CO_2 by improving the retrofitting solid wall home?

The University of Huddersfield, as one of the key partners in the project, was responsible for developing a BIM Retrofit Protocol through using ‘what if’ scenarios to evaluate the possible retrofit options. BIM was implemented to build a 3D modelling and evaluation energy performance, time and cost of different alternatives (Comlay & Tzortzopoulos, 2015). A Design Science Research (DSR) method was adopted in this research since it was aimed to address the identified real world issue through testing innovative solutions with an iterative and evaluative process (Comlay & Tzortzopoulos, 2015). The innovative solution or artefact in the research is implementing BIM for the retrofit process of solid wall homes.

"The S-IMPLER research aims to improve U-values, maximise heat retention, reduce heat loss, improve air tightness, deliver a ventilation strategy and assist householders with their energy consumption through increased awareness of controls and the interactions between use and energy demand. The programme will be delivered using BIM, lean and collaborative work flows and explore innovative technological solutions and supply mechanisms, establishing experience and expertise within the construction delivery team" (Comlay & Tzortzopoulos, 2015).

To evaluate the impact of BIM implementation, six houses, as a sample population, were chosen to enable the team to test the proposed solutions. The test cycle had been analysed, modified and adjusted to implement analysis findings (Comlay & Tzortzopoulos, 2015).

The expected BIM outputs of the ongoing project and research include improved collaboration and communication; enhanced productivity; reduced coordination issues; reduced cost; improved the energy efficiency; and developed a BIM Object Library concept to increase interoperability (Comlay & Tzortzopoulos, 2015). The benefits of 4D BIM in the projects include improved communication with occupants and involved bodies in the construction site, minimised occupants' disruption and enhanced site safety with better scheduling and planning construction tasks. 5D BIM improves the decision making process through cost analysis of alternatives of the test cycle. Energy performance analysis will assess the energy performance of alternatives. The results of energy performance simulation based on the 3D BIM will be compared with monitored results (post-occupancy data collection) after completion of the project in refinement cycles.

Learning points from the projects

Although both projects were benefitting from BIM implementation in the domestic retrofit process, several challenges were faced to achieve the full potential of exploiting BIM.

In the first project, the set-up stage of the project and using BIM and CNC technologies took considerably more time, by 76%, in comparison with the traditional process. Improving automated 3D data collection and expediting post-processing of 3D data collection could speed up the set-up phase and overcome one of the main challenges to implementing BIM. Furthermore, improving the interoperability between BIM and CNC technology not only could improve the quality and accuracy and shared data but also, it could speed up the process of fabricating the elements.

The S-IMPLER project is an on-going project and the challenges to implementing BIM have not yet been published.

Chapter Nine

Conclusion

9 Conclusion

Research significance

The significance of this research arises from the fact that this is the first study investigating the implementation of BIM in energy efficient domestic retrofit in practice in the UK. Although in the last few years other studies have been conducted to use BIM to retrofit existing buildings, many of these studies are theoretical and conceptual (Ilter & Ergen, 2015). In this research, the BIM implementation in energy efficient domestic retrofit, provide a potential for actual analysis of BIM simulation approaches that can be adopted for the retrofit process. The experimental project allows to the opportunity to evaluate energy performance through BIM simulation approaches and assess the accuracy and reliability of the outputs compared with results of two-year monitoring the house. Furthermore, this research illustrates, through the experimental study, why existing assessment and simulation approaches are not effective and efficient in achieving climate change targets and why it is necessary to enhance the existing practices. However, this research is considered as a starting point, where an initial analysis of the project has commenced and future research areas can be suggested.

Research main findings

In this section, the main findings with regard to the research question and sub-questions are summarised and highlighted.

- **What are the barriers in the residential sector with respect to the energy efficiency?**

The answer to this question was provided within two chapters in this research, the literature review within Chapter 2, and a series of interviews in Chapter 5. The barriers to improving the energy efficiency based on the interviews and literature are listed in Table 0:1.

Table 0:1: Barriers to improving the energy-efficient retrofit process

Barriers	Description
Social	• **Unwillingness to adopt energy efficient measures** (Crosbie & Baker, 2010; Interviewee A, 2013; Pelenur & Cruickshank, 2011); • **Uncertainty about the payback period** (Pelenur & Cruickshank, 2011); • **Uncertainties over the quality of retrofit measures** (78% of participants); • **The lack of occupants' knowledge** (Crosbie & Baker, 2010; Interviewee I, 2013; Interviewee E, 2014; Interviewee B, 2013; Interviewee F, 2013); • **Rebound effects and energy efficiency gap** (Pelenur & Cruickshank, 2011; Lutzenhiser, 1992; Jaffe & Stavins, 1994; Stern, 2006); • **Lack of appropriate communication and collaboration approaches amongst occupants, designers and contractors** (Crosbie & Baker, 2010; Ma, et al., 2012).
Financial	• **Upfront cost of energy efficiency measures** (Webber, et al., 2015; Pelenur & Cruickshank, 2011); • **A very long payback period** (Pelenur & Cruickshank, 2011; Interviewee D, 2014; Interviewee H, 2014); • **Ineffective initiatives and programs with limited funds** (Mallaband, et al., 2011; Interviewee A, 2013); • **Lack of transparent approach to calculate the cost-effectiveness of energy efficiency measures** (Pelenur & Cruickshank, 2011; Interviewee E, 2014; Interviewee B, 2013).
Building regulations	• **SAP calculations are based on notional assumptions and the results are not reliable and accurate** (Kellya, et al., 2012; Interviewee C, 2014; Interviewee I, 2013; Interviewee F, 2013); • **Lifecycle cost is not taken into consideration in SAP calculations** (Kellya, et al., 2012; Interviewee F, 2013).
Technical	• **Late adoption of BPS tools** (all interviewees) • **Lack of transparent approach to estimate the U-Value** (Ham & Golparvar-Fard, 2015) and 78% of interviewees; • **Lack of clear qualitative and quantitative practical knowledge and evidence for input data in BPS tools** (Interviewee B, 2013; Interviewee I, 2013; Interviewee C, 2014); • **Applying the same approach to different projects regardless of their unique characteristics, age and construction types** (Interviewee I, 2013) • **The obtained data from BPS tools is frequently evaluative rather than proactive in the existing practices** (Attia, et al., 2012; Kanters & Horvat, 2012).
Education	• **The knowledge and skill gaps among suppliers, surveyors and installers** (Mashford, et al., 2015); • **Insufficient level of knowledge to implement the state-of-the-art approaches** (Lowe & Oreszczyn, 2008);

- **How are BIM applications comprehended and used in the construction industry to improve the efficiency of existing practices in new buildings?**

The answer to this question was provided within Chapter 3. The construction industry has benefitted from BIM considerably to improve the existing practices in medium to large scale projects during last decades (Eastman, et al., 2011; Jalae & Jrade, 2015; Iturralde, 2012). BIM's potential in the construction industry are shown in Table 0:1. The potentials of BIM are classified in to four main categories as follows:

- Enhancing the quality control of design and construction process (Eastman, et al., 2011, pp. 331-333; Browne & Menzel, 2012; Konstantinoua & Knaacka, 2011; Azhar, et al., 2008);
- Promoting the process of planning and controlling the budget of a project (Eastman, et al., 2011, p. 156; Iturralde, 2012; Eadie, et al., 2013);
- Enhancing sustainability and energy efficiency (Browne & Menzel, 2012; Eastman, et al., 2011, pp. 23, 156);
- Improving time management (Eastman, et al., 2011, pp. 156-162; Migilinskasa, et al., 2013; Jalae & Jrade, 2015).

However, there are some challenges to shifting existing practices in the construction industry. Shifting to BIM adoption has been confronted with social barriers to change the existing practices (Rezgui & Miles, 2011; Eastman, et al., 2011, pp. 258-261). Involved bodies are still facing with undefined ownership of data, legal and contractual implication of BIM (Ashcraft, 2008; Eastman, et al., 2011, p. 27). Also, fragmentation of the construction industry has influenced in the heterogeneous adoption of IT in the fragmented construction sector (Tang, et al., 2010; Laakso & Kiviniemi, 2012) where 93.3% of enterprises have less than 10 employees in the UK (Eurostat, 2017).

- **What are the deficiencies in the current practices to improve the efficiency of energy efficient retrofit process?**

The answer to this question was provided within Chapter 7. The energy performance simulations in the current practices were demonstrated in Section 7.3. The current practices of energy performance assessment and simulation were assessed through a real-world case study. The efficiency and accuracy of them were evaluated through comparing their results with monitored results over a two-year period.

To determine the accuracy of energy performance assessment methods, SAP and PHPP, were compared with monitored results. The SAP results were off by 46.10%. The large discrepancies between the predicted results and monitored results are due to this reason that SAP calculations are based on the notional assumption regardless of unique characteristics of buildings. It is very important to conduct further research to prevent large discrepancies as SAP is used to create EPC and CSH (Kellya, et al., 2012). The PHPP results were off by 35.23%. Although this research does not claim that PHPP estimates lead to inaccurate results, it could be concluded that using unrealistic assumptions lead to unreliable results.

A stand-alone building energy simulation, DesignBuilder, was used to evaluate the accuracy and efficiency of the detailed modelling approach. Although the results of the detailed modelling approach was very close to monitored results, with a difference of 3.86%, it is costly and very time-consuming, and the results are usually delivered at the late stage where evaluating energy performance has limited impacts on the final energy efficiency of the building (Torcellini, et al., 2004; Bazjanac, 2008a; Ryu & Park, 2016). Also, simplification of the geometry to create energy model is required to save time and resources. However, simplification of the geometry by energy specialist is not only very subjective and unreliable since it is based on energy specialists' understanding, knowledge and skills to define the thermal view (Osello, et al., 2011), but also the results are often not reproducible (Bazjanac, 2008b). Figure 0:1 compares the results of the current practices with monitored results. Despite the potential of evaluating building performance, the obtained data from BPS tools in existing practices is frequently evaluative rather than proactive (Attia, et al., 2012; Kanters & Horvat, 2012).

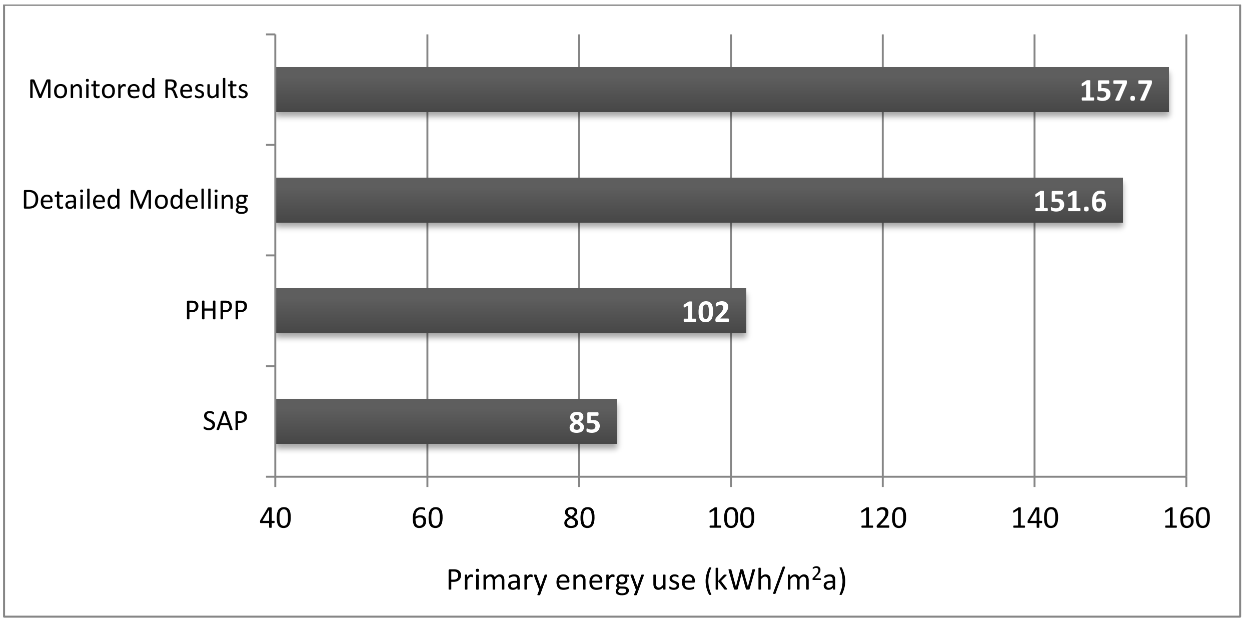


Figure 0:1: The comparison of existing energy performance assessment and stand-alone simulation approache with actual performance

- **What are the BIM's potentials and challenges to improve the efficiency of energy performance simulation?**

The answer to this question was provided within Chapters 4 and 5, from a series of interviews and reviewing existing literature. The potential benefits of BIM in the retrofit process are numerous, as shown in Table 0:2.

Table 0:2: BIM’s potentials to improve the efficiency of retrofit process

Potentials	**Description**
Sustainability	• **Improving decision making process** (Volk, et al., 2014; Østergård, et al., 2016) and the majority of interviewees; • **Improving final energy performance** (Cho, et al., 2010) and the majority of interviewees; • **Enhancing retrofit planning** (Mill, et al., 2013; Volk, et al., 2014); • **Improving assessment and monitoring** (Eastman, et al., 2011; Becerik-Gerber, et al., 2012); • **Improving space management** (Eastman, et al., 2011); • **Improving maintenance of warranty and service information** (Becerik-Gerber, et al., 2012; Singh, et al., 2011); • **Enhancing quality control** (Boukamp & Akinci, 2007; Akinci, et al., 2006); • **Improving collaboration and communication** (Interviewee G, 2014; Volk, et al., 2014; Interviewee H, 2014)**;** • **Improving documentation and more accurate visualisations** (Volk, et al., 2014; Interviewee D, 2014; Interviewee H, 2014); • **Assisting sustainability ratings and certifications** (U.S. Green Building Council, 2013; Khaddaj & Srour, 2016); • **Supporting sustainable design** (Jalae & Jrade, 2015)**.**
Time	• **Reducing construction time on site** (Volk, et al., 2014; Interviewee F, 2013)**;** • **Speeding up energy performance simulation** (Interviewee H, 2014; Interviewee E, 2014)**;** • **Expediting the retrofit process** (Interviewee E, 2014; Interviewee B, 2013).
Cost	• **Improving cost management** (Volk, et al., 2014; Interviewee H, 2014)**;** • **Minimised costs** (Volk, et al., 2014)**.**
Social	• **Assuring clients about the quality of retrofit measures** (Interviewee A, 2013; Interviewee E, 2014; Interviewee D, 2014); • **Minimising disruption for residents** (Interviewee A, 2013; Interviewee F, 2013)**.**

All interviewees and Volk, et al. (2014) believe that BIM implementation offers numerous opportunities to improve existing buildings. However, there are also some challenges to implementing it in the retrofit process as there are no pre-existing models of buildings (Volk, et al., 2014). The model creation in existing buildings is a reverse engineering process and information availability, required functionality and data quality are varied depending on the data collection methods and building age and type (Hajian & Becerik-Gerber, 2010; Klein, et al., 2012; Volk, et al., 2014). The challenges to implementing BIM in the retrofit process are summarised in Table 0:3.

Table 0:3: Challenges to implementing BIM to improve the efficiency of retrofit process

Challenges	Description

	• **Dealing with inaccurate and uncertain captured data** (Penttilä, et al., 2007) and the majority of interviewees;
	• **Lack of transparent approach to estimate the thermal performance of building fabric**;
	• **Lack of interoperability between BPS tools and BIM** (Venugopal, et al., 2012; Interviewee F, 2013; Interviewee H, 2014);
	• **Lack of BPS tools to provide well-timed feedback** (Kanters, et al., 2014; Attia, et al., 2012);
	• **Less than 8% of BPS tools have the potential for early integration** (IBPSA-USA, 2014; Batueva & Mahdavi, 2015);
	  • **Common misconception to implement BIM only in new buildings** (Interviewee H, 2014) **and complex mega projects** (NBS, 2016) and the majority of interviewees;
	  • **Lack of clients demands in private sectors** (Interviewee F, 2013)
	  • **Lack of clients' knowledge about BIM benefits and its socio-economic potentials** (Interviewee F, 2013)

- **How can interoperability improve the efficiency of the energy efficient retrofit process at the early stage?**

As discussed, scarce use of BPS tools in the early design stage is claimed as one of the main barriers to improving the energy efficient retrofit process (Venugopal, et al., 2012). Open interoperability not only provides opportunities to integrate BPS tools at the early design stage (Østergård, et al., 2016), but can also overcome the barriers associated with a fragmented construction industry (Eastman, et al., 2011; Bazjanac, 2004). By improving interoperability at the early design stage and adopting BIM, challenges identified in Chapters 3 and 4 could be addressed, such as uncertainty about the quality of retrofit measure and time-consuming iterative modelling. The common interoperability standard formats, including COBie, gbXML and IFC, which are used in the AEC industry, were studied in Chapter 6 to select an appropriate data exchange format for the research. COBie cannot be used for this research since it does not include any geometrical or architectural data which are essential to evaluate energy performance. IFC, the international standard for OpenBIM, was chosen for the automated rule checking to ensure the quality of BIM prior to be used for energy simulation, since it is a globally accepted format and well-suited for the purpose (Malsane, et al., 2015; GSA, 2015). For interoperability between BIM and BPS tools one of the most widely adopted formats, gbXML, was selected for BIM simulation approaches. Also, the existing research supports the finding that gbXML enables project participants to transfer data directly from BIM to BPS tools, such as Ecotect, EnergyPlus and DesignBuilder (Sokolov & Crosby, 2011; GSA, 2015; gbXML, 2014).

However, to the best of the author’s knowledge, and based on the results of interviews, the application of gbXML is not a common practice for transmitting data between BIM and BPS tools. Therefore, the capability of this data exchange format was studied through a real world case to explore its effectiveness and possible challenges in using it. The results were discussed in Section 7.6.

- **What is the importance of the quality of shared information in BIM to achieve reliable energy performance simulation analysis?**

Instead of the common misconception of integrated BIM being one model, where various disciplines are working with the same data (Kiviniemi, 2005), the shared parts of the individual domain models must provide the required data for intended aims. However, the designers often do not know what exactly is required. Therefore, it is essential to check the quality of models before they can be used for any additional task, such as energy performance analysis, as the success of interoperability highly depends on the quality of shared models (Li, et al., 2006; Nicolaou & McKnight, 2006). ‘Automated compliance checking’ and ‘model checking for data quality’, two rule-based model checking processes were studied in Chapter 6. In this study, automated compliance checking was not used, since the author did not intend to check the model for meeting the legislation requirements. As the quality of the architectural design model was aimed to be checked for energy analysis, model checking for data quality was chosen. Improving the quality of interoperability and BIM files enhances the consistency with the information requirements and makes the entire design process more transparent and effective (Kulusjärvi, 2012; Ciribini, et al., 2016; Malsane, et al., 2015). It is important to emphasise that quality checking aims to ensure whether BIM is based on the specific requirements for the given purpose, and not for checking the design quality, which is impossible to check as many of its aspects are non-quantifiable (Kulusjärvi, 2012). Two commercial ‘model checking for data quality’ applications, FORNAX and Solibri Model Checker (SMC), were reviewed to choose which one fitted to the research based on their potentials and capabilities. Classification of rule-checking into four general classes of rules by Solihin and Eastman (2015) assisted the researcher in identifying the involved complexity level of each class of rules to select the appropriate application to address the requirement of this research. SMC was selected as it can check the correctness of required attributes as well as attribute and derived values. As described in Section 7.4.2, four rulesets were assigned in SMC to check the quality of the model in a case study before transferring the data to BPS tools. After checking the quality, the required level of information and potential problem were identified. The detected clashes and errors were reviewed and modified in BIM to be used for BIM simulation approaches.

- **In the current situation, to what extent does BIM provide an effective method to pave the way to improve the energy performance simulation in the energy efficient domestic retrofit process in practice?**

To answer the question, the author evaluated two different BIM approaches, integrated and interoperable, through a real word case study in Chapter 7 (Figure 0:2).

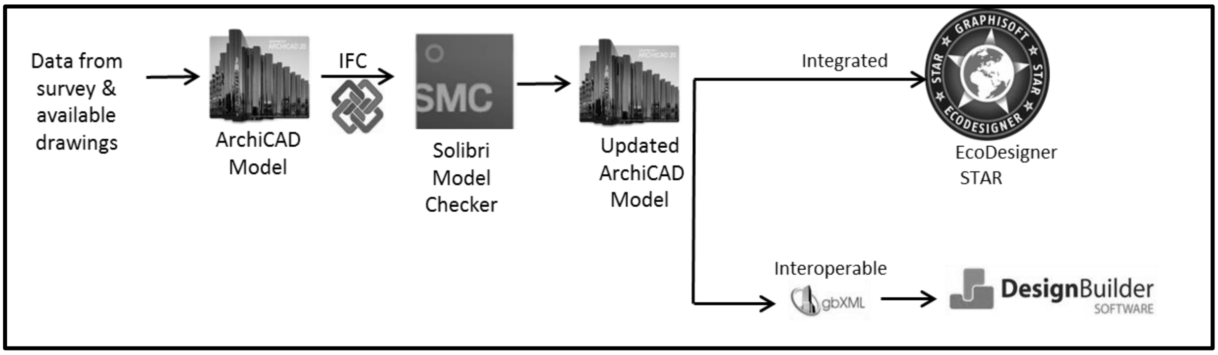


Figure 0:2: BIM simulation approaches

After modelling the case study in ArchiCAD, the quality was checked in SMC, detected clashes and errors were corrected in the model, and the model was used for both BIM simulation approaches. To evaluate the accuracy of BIM simulation approaches, the results were compared with results of monitored data. Therefore, the occupancy inputs were considered as it was in a real situation.

Graphisoft EcoDesigner Star for ArchiCAD was used to evaluate the accuracy and efficiency of integrated BIM simulation approach. The required information to run the EcoDesigner Star includes operation file, environmental settings, climate data and building systems. Building systems were assigned based on the building system's specifications and parameters which are as explained in Section 7.2. EcoDesigner STAR estimated 153.18 kWh/m^{2}a for primary energy consumption with a 1.43% difference with monitored results. Integrated BIM simulation approach provided effortless interoperability and improved the effectiveness of the process. However, it requires intelligent guidance and depends on the vendors to integrate performance simulation into BIM environment (Batueva & Mahdavi, 2015). The simulation illustrated the simulation results will be correct if the inputs for an existing buildings are correct.

To assess the accuracy and efficiency of interoperable BIM approach, the gbXML format was used for transferred data from BIM to DesignBuilder. To assess the use of gbXML, the author evaluated two different approaches, 1) transferring from ArchiCAD 20 with the native gbXML export option and 2) from ArchiCAD 19, which is the required plug-in option, in this case, Cadimage. gbXML should be able to transfer required data including geometry, material specifications, building systems and technical equipment, site condition and building operation data. Transferring geometry from ArchiCAD 20 to DesignBuilder was successful; however, the properties of construction and materials were not transferred from BIM to DesignBuilder, except the geometry. Although transferring the geometry correctly to a thermal view in DesignBuilder avoided repetition of data creation, saved time and reduced errors, putting all other required data manually to the simulation model was a time-consuming and redundant task which should be improved to get the full potential of this data exchange format.

Transforming the architectural view from ArchiCAD 19 with the free gbXML export option, Cadimage, was not successful. Three major problems occurred in the conversion process.

To validate the gbXML export results, the author used gbXML validator which became available in September 2016. As it was tested, the overall validation score for gbXML export showed fail and for geometry in ArchiCAD 20 showed pass and the geometry in ArchiCAD 19 showed fail. The results indicate that interoperability through gbXML can facilitate the early integration of BPS tools in the early design stage, but it requires an understanding of its limitations and often manual checking and fixing the converted geometry and adding missing attribute values and material properties.

The limitations of this research

Although an individual case study may help by providing more detailed information to evaluate the usability of different simulation approaches, the detailed results cannot be generalised due to the specific location, age, type of house, and its occupancy pattern. However, the results answer sufficiently to the research questions and indicate clearly the potential of BIM in small-scale retrofit projects.

The nature of experimental research and simulations are bound by a series of limitations. The occupancy pattern for both BIM simulation approaches and a detailed model approach was assumed based on the monitored data due to the subjective nature of users' interaction with energy. It was necessary to assign the same occupancy pattern to be able to evaluate and measure the efficiency of data exchange format. The inability to include occupancy patterns is one of the probable reasons for the inaccurate results in SAP.

Furthermore, the interoperable BIM simulation was done through gbXML data exchange format between ArchiCAD and DesignBuilder. To evaluate conclusively the effectiveness of gbXML, it should be tested in other BIM authoring and BPS tools as well. However, the results indicate that there are potential shortcomings in transferring all the required data content from BIM to the BPS software using gbXML.

Future research direction

Based on this research, further studies could be carried out, such as:

SAP as an independent calculation methodology forms the backbone of government policy to estimate building performance in the UK and creating EPC, CSH and many other policy schemes. However, lifecycle cost of alternatives is not considered and the calculations are based on notional assumptions. For example, in 2 Broxton Street, the SAP calculation was in error by almost 50%. So, further research regarding the accuracy and reliability of SAP calculations should be considered.

Further research to improve the accuracy of SAP calculations and more definitive EPC at the point of sale with a database set up at the Land Registry for open sourcing should be considered to speed the creation process of as built BIM.

gbXML format supports interoperability between many BIM and BPS tools, however, there are several unsolved issues such as exporting complex geometry, structure and material properties. Using default material and structure properties and being ineffective to transfer these data are the main challenges to getting the full potentials of this open format and more research should be conducted to improve the reliability and usefulness of this format.

More research should be carried put to improve the automation of capture data and automated post-processing 3D data collection.

References

Abanda, F., Vidalakis, C., Oti, A. & Tah, J., 2015. A critical analysis of Building Information Modelling systems used in construction projects. *Advances in Engineering Software,* Volume 90, p. 183–201.

Abrahames, W. & Steg, L., 2009. How do socio-demographic and psychological factors relate to households' direct and indirect energy use and savings? *Journal of Economic Psychology,* Volume 30, pp. 711-720.

AEPCA, 2004. *A Best Practice Guide to Measurement and Verification of Energy Savings,* South Melbourne, Australia: Australian Energy Performance Contracting Association.

Agisoft, 2015. *Agisoft PhotoScan.* [Online] Available at: http://www.agisoft.com/ [Accessed November 2016].

Ahmed, V., Opoku, A. & Aziz, Z., 2016. *Research methodology in the built environment: A selection of case studies.* Abingdon: Routledge.

Akbarnezhad, A., Ong, K., Chandra, L. & Lin, Z., 2012. *Economic and environmental assessment of deconstruction strategies using Building Information Modelling.* West Lafayette, Proceedings of Construction Research Congress: Construction Challenges in a Flat World.

Akcamete, A., Akinci, B. & Garrett Jr, J., 2010. *Potential utilization of building models for planning maintenance activities.* Nottingham, Britain, Proceedings of the International Conference on Computing in Civil and Building Engineering (ICCCBE).

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C. & Park, K., 2006. A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Automation in Construction,* 15(2), pp. 124-138.

Alajmi, A., 2012. Energy audit of an educational building in a hot summer climate. *Energy and Buildings,* Volume 47, p. 122–130.

Albatici, R. & Tonelli, A., 2010. Infrared thermovision technique for the assessment of thermal transmittance value of opaque building elements on site. *Energy and Buildings,* 42(11), pp. 2177-2183.

Amaratunga, R., Baldry, D., Sarshar, M. & Newton, D., 2002. Qualitative and quantitative research in the built environment: application of “mixed” research approach. *Work Study (renamed International Journal of Productivity and Performance Management),* 51(1), pp. 17-31.

Anton, J. J. & Biglaiser, G., 2013. Quality, upgrades and equilibrium in a dynamic monopoly market. *Economic Theory,* Volume 148, p. 1179–1212.

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,* Volume 20.

Ascione, F., Rossi, F. & Vanoli, G., 2011. Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios. *Energy and Buildings,* Volume 43, p. 1925–1936.

Ashcraft, H., 2008. Building information modeling: a framework for collaboration. Construction Lawyer 28.. *Construction Lawyer,* Volume 28.

ASHRAE, 2011. *ASHRAE Handbook – HVAC Applications.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Attia, S., 2012. *A Tool for Design Decision Making - Zero Energy Residental Buildings in Hot Humid Climates.* Louvain: Presses universitaires de Louvain.

Attia, S., Gratia, E., Herde, A. D. & Hensen, J. L. M., 2012. Simulation-based decision support tool for early stages of zero-energy building design. *Energy and Buildings,* Volume 49, pp. 2-15.

Attia, S., Hensen, J., Bertran, L. & De Herde, A., 2011. Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs'. *Journal of Building Performance Simulation.*

Auld, G. W., Diker, A., Bock, A., Boushey, C. J., Bruhn, C. M., Cluskey, M., Edlefsen, M., Goldberg, D. L., Misner, S. L., Olson, B. H., Reicks, M., Wang, C. & Zaghloul, S., 2007. Development of a decision tree to determine appropriateness of NVivo in analysing qualitative data sets. *Journal of Nutrition Education and Behavior,* 39 (1), p. 37–47.

Autodesk, 2015. *Autodesk 2016.* [Online] Available at: http://www.autodesk.co.uk/ [Accessed Dec 2015].

Autodesk, 2017. *About Green Building Studio and Energy Analysis.* [Online] Available at: https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2016/ENU/Revit-Analyze/files/GUID-7948A714-1B97-4176-A942-D99A8ECA4786-htm.html [Accessed 25 January 2017].

Azhar, S., Hein, M. & Sketo, B., 2008. Building Information Modeling (BIM): Benefits, Risks and Challenges. In: Associate Schools of Construction Conference 2008. Auburn University, Alabama, US.

Babbie, E., 1983. *The Practice of Social Research.* 3rd ed. Belmont California: Wadsworth.

Baeli, M., 2013. *Residential retrofit: 20 case studies.* London: RIBA Publishing.

Banks, N., 2008. *Implementation of energy performance certificates in the domestic sector,* Oxford: UKERC.

Barker, T., Ekins, P. & Foxon, T., 2007. The macro-economic rebound effect and the UK economy. *Energy Policy,* Volume 35, pp. 4935-4946.

Batueva, E. & Mahdavi, A., 2015. Assessment of a computational design environment with embedded simulation capability. In: A. Mahdavi, B. Martens & R. Scherer, eds. *eWork and eBusiness in Architecture, Engineering and Construction.* Proceedings of the 10th European Conference on Product and Process Modelling, ECPPM 2014, pp. 197-202.

Bazjanac, V., 2004. Building energy performance simulation as part of interoperable software environments. *Building and Environment,* 39(8), p. 879–883.

Bazjanac, V., 2004a. Virtual Building Environments - Applying Information Modeling to Buildings. In: A. Dikbas & R. Scherer, eds. *eWork and eBusiness in architecture, engineering and construction.* Istanbul: Taylor & Francis, p. 41–48.

Bazjanac, V., 2008a. IFC BIM-Based Methodology for Semi-Automated Building Energy Performance Simulation. *Lawrence Berkeley National Laboratory.*

Bazjanac, V., 2008b. *Response to the OGC Request for Technology (RFT) in Support of the AECOO Testbed,* Berkeley, CA.: Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory.

Bazjanac, V., 2009. *Implementation of semi-automated energy performance simulation: building geometry.,* California: Lawrence Berkeley National Laboratory, University of California.

Bazjanac, V. & Kiviniemi, A., 2007. *Reduction, simplification, translation and interpretation in the exchange of model data.* Maribor, Proceedings of the 24th CIBW78 conference: Bringing ICT knowledge to workUniversity of Maribor.

BCIS, 2012. *BCIS Alterations and Refurbishment Price Book.* 17th ed. London: Building Cost Information Service.

Beach, T., Kasim, T., Li, H., Nisbet, N. & Rezgu, Y., 2013. *Towards Automated Compliance Checking in the Construction Industry.* Prague, Czech Republic, DEXA 24th International Conference.

Beaven, M., 2011. *Building Information Modelling (BIM) - Arup.* [Online] Available at: http://www.arup.com/services/building_modelling [Accessed Oct 2016].

Becerik-Gerber, B., Jazizadeh, F., Li, N. & Calis, G., 2012. Application areas and data requirements for BIM-enabled facilities management. *Construction Engineering and Management,* 138(13), pp. 431-442.

Benedettoa, A., Tostib, F., Ciampolia, L. & D'Amicoa, F., 2017. An overview of ground-penetrating radar signal processing techniques for road inspections. *Signal Processing,* Volume 132, p. 201–209.

Berlo, L., 2015. *Collaborative Design and engineering with IFC in the Netherlands,* Manchestre: The Chartered Institute of Architectural Technologists (CIAT). BIM Show Live: Manchester.

Bew, M. & Richards, M., 2008. *BIM maturity model.* London: Royal Institute of British Architects (RIBA).

Bhatla, A., Choe, S., Fierro, O. & Leite, F., 2012. Evaluation of accuracy of as-built 3D modeling from photos taken by handheld. *Automation in Construction,* Volume 28, p. 116–127.

Biernacki, P. & Waldorf, D., 1981. Snowball sampling; problems and techniques of chain referral sampling. *Sociological Methods & Research,* 10(2), pp. 141-163.

Björk, B.-C., 1987. *RATAS A Proposed Finnish Building Product Model, Studies in Environmental Research No. T6,* Otaneimi, Finland: Helsinki University of Technology.

Björk, B.-C. & Penttilä, H., 1989. A scenario for the development and implementation of a building product model standard. *Advances in Engineering Software (1978),* 11(4), pp. 176-187.

Bock, T., 2008. *Digital design and robotic production of 3 D shaped precast components.* Vilnius, Lithuania, Proceedings of the 25th ISAARC.

Borrego, M., Douglas, E. P. & Amelink, C. T., 2009. Qualitative, quantitative methods in Engineering education. *Journal of Engineering Education,* pp. 53-66.

Bosche, F. & Haas, C., 2008. *Automated 3D data collec-tion (A3DDC) for 3D building information modeling.* Vilnius, Lithuania, Proceedings of the 25th ISAARC.

Boukamp, F. & Akinci, B., 2007. Automated processing of construction specifications to support inspection and quality control. *Automation in Construction,* 17(1), pp. 90-106.

Bouzakis, K. D., Pantermalis, D., Mirisidis, I., Grigoriadou, M., Varitis, E., Sakellaridou, A., Bouzaki, A., Efstathiou, K., Theodoridou, S., Papacharisi, A. & Diamanti, E., 2016. 3D-laser scanning of the Parthenon west frieze blocks and their digital assembly based on extracted characteristic geometrical details. *Journal of Archaeological Science,* Volume Reports 6, pp. 94-108.

Boyd, D. & Weaver, P., 1994. *Improving the management and operations of refurbishment projects.* Loughbrough, Proceedings of the lOth. ARCOM Annual Conference, Loughbrough University of Technology.

BRE, 2011. *RdSAP 2009 version 9.90, Appendix S: Reduced Data SAP for existing dwelling,* London: Building Research Establishment.

BRE, 2015. *The S-IMPLER way to insulate solid wall homes.* [Online] Available at: https://www.bre.co.uk/page.jsp?id=3236 [Accessed 20 January 2017].

Browne, D. & Menzel, K., 2012. Validation of simulation results using sensor data to improve. *eWork and eBusiness in Architecture, Engineering and Construction.*

Bryman, A., 2001. *Social Research Methods.* New York: Oxford University Press.

bSI, 2012. *Open BIM Focus.* [Online] Available at: http://www.buildingsmart.org.uk/openbim-focus-issue-1 [Accessed NOV 2015].

bSI, 2015. *Summary of IFC Releases.* [Online] Available at: http://www.buildingsmart-tech.org/specifications/ifc-releases/summary [Accessed June 2016].

Building Act, 1984. *Building Act 1984.* [Online] Available at: http://www.legislation.gov.uk/ukpga/1984/55 [Accessed Feb 2016].

Building.co.uk, 2003. *Buildings.* [Online] Available at: http://www.building.co.uk/buildings/architectural-reviews/housing/ [Accessed June 2016].

buildingSMART, 2011. *Industry Foundation Classes (IFC) data model. buildingSMART International.* [Online] Available at: http://www.buildingsmart.org/standards/standards-process/ [Accessed NOV 2015].

buildingSMART, 2013. *Industry Foundation Classes (IFC).* [Online] Available at: http://buildingsmart.org/ifc/ [Accessed December 2016].

Burgess, F., 2001. *A general Introduction to the design of questionnaire for survey research: Guide to the design of questionnaire.* Leeds: University of Leeds.

Cadimage, 2015. *Cadimage gbXML:.* [Online] Available at: http://www.cadimage.com/support/knowledgebase/gbxml/cadimage-gbxml-product-overview-1124# [Accessed 19 November 2016].

Carbon Trust, 2012. *Building fabric: Energy saving techniques to improve the efficiency of building structures,* London: The Carbon Trust.

Cemesova, A., Hopfe, C. J. & Mcleodc, R. S., 2015. PassivBIM: Enhancing interoperability between BIM and low energy design software. *Automation in Construction,* Volume 57, p. 17–32.

Cemesova, A., Hopfe, C. J. & Rezgui, Y., 2013. *An approach to facilitating data exchange between BIM environments and a low energy design tool.* Chambery, France., Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association.

Ceredigion County Council, 2010. *A brief history of building control.* [Online] Available at: https://www.ceredigion.gov.uk/index.cfm?articleid=16167 [Accessed Feb 2016].

Chaves, F., Tzortzopoulos, P., Formoso, C. & Biotto, C., 2016. *Building information modelling to cut disruption in housing retrofit.* Proceedings of the Institution of Civil Engineers - Engineering Sustainability.

Chow, D. & Levermore, G., 2010. The effects of future climate change on heating and cooling demands in office buildings in the UK. *Building Services Engineering Research & Technology,* Volume 31, pp. 307-323.

Cho, Y., Alaskar, S. & Bode, T., 2010. *BIM-integrated sustainable material and renewable energy simulation.* Banff Alberta, Canada, Proceedings of CRC2010, pp. 288-297.

CIBSE, (. 7. e. :. ,. p.-4., 2006. *CIBSE Guide A: Environmental Design.* 7th ed. London: The Charted Institute of Building Services Engineers (CIBSE).

CIOB, 2014. *The BIM journey... Destination retrofit sector,* Bracknell: The Chartered Institute of Building (CIOB).

Ciria, 2004. *Construction Industry Research and Information Association, Good Practice Guidance for Refurbishing Occupied Buildings.* Ciria, London, UK: Ciria Guide C621.

Ciribini, A., Mastrolembo Ventura, S. & Paneroni, M., 2016. Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project. *Automation in Construction.*

Citherlet, S., 2001. *Towards the holistic assessment of building performance based on an integrated simulation approach,* Lausanne: Architecture Department, Swiss Federal Institute of Technology.

Clarke, J. A., Johnstone, C. M., Kelly, N. J., Strachan, P. A. & Tuohy, P., 2008. The role of built environment energy efficiency in a sustainable UK energy economy. *Energy Policy,* Volume 36, p. 4605–4609.

Coffey, A., Holbrook, B. & Atkinson, P., 1996. *Qualitative Data Analysis technologies and represntations, Sociological Research Online.* [Online] Available at: http://www.socresonline.org.uk/1/1/4.html [Accessed August 2016].

Collinson, P., 2014. *The energy efficiency 'savings' that are just hot air. The Guardian.* [Online] Available at: http://www.theguardian.com/money/2014/jan/18/energy-efficiency-savings-less-than-advertised-green-deal [Accessed Feb 2016].

Comlay, J. & Tzortzopoulos, P., 2015. *Building Information Modelling [BIM] for energy efficiency in housing refurbishments.* Guimaraes, Portugal, EUROELECS 2015 - Latin American and European Conference on Sustainable Buildings and Communities, 21s.

Corke, G., 2013. Solibri Model Checker V8. *AEC MAGAZINE*, 15 Feb, pp. 16-17.

Cotterell, J. & Dadeby, A., 2012. *Passivhaus handbook : a practical guide to constructing and refurbishing buildings for ultra-low-energy performance.* Cambridge: Green Books.

Creswell, J. W., 2013. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches.* 4th ed. London: SAGE Publications Ltd.

Crompton, T., 2010. *Common Cause: The Case for Working with Our Cultural Values. ,* London: UK.

Crosbie, T. & Baker, K., 2010. Energy-efficiency interventions in housing: learning from the inhabitants. Building Research & Information. Volume 38.

CSE, 2011. *Analysis of hard-to-treat housing in England,* Bristol: Centre for Sustainability Energy (CSE).

Dall'O', G., Sarto, L. & Panza, A., 2013. Infrared screening of residential buildings for energy audit purposes: results of a field test. *Energies,* 6(8), p. 3859–3878.

Das, T. H., 1983. Qualitative Research in Organizational Behaviour. *Journal of Management Studies,* 20(3), pp. 301-314.

Dave, B., Boddy, S. & Koskela, L., 2013. *Challenges and opportunities in implementing Lean and BIM on an infrastructure project.* Fortaleza, Brazil, 21st Annual Conference of the International Group for Lean construction (IGLC 21).

DECC, 2009. *Warmer homes, greener homes: a strategy for household energy management.* [Online] Available at: https://www.gov.uk/government/organisations/department-of-energy-climate-change [Accessed Dec 2015].

DECC, 2010. *The Green Deal: A summary of the Government's proposals.* [Online] Available at:https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47978/1010-green-deal-summary-proposals.pdf [Accessed Feb 2016].

DECC, 2011a. *Green Deal: energy saving for your home.* [Online]
Available at: https://www.gov.uk/green-deal-energy-saving-measures/overview
[Accessed Feb 2016].

DECC, 2011. *Department of Energy and Climate Change. The carbon plan: delivering our low carbon future,* London: The Stationery Office.

DECC, 2012a. *Warm Homes, Greener Homes - A strategy for household energy management,* London: Crown.

DECC, 2012. *Department of Energy and Climate Change, Warmer homes, greener homes: a strategy for household energy management. Stationery Office, London..* [Online] Available at:http://www.housinglin.org.uk/_library/Resources/Housing/OtherOrganisation/warm_homes_greener_homes.pdf [Accessed 2013].

DECC, 2015a. *Energy consumption in the UK (2015). Chapter 1: Overall energy consumption in the UK since 1970.* [Online] Available at:
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/449102/ECUK_Chapter_1_-_Overall_factsheet.pdf [Accessed July 2015].

Department for Communities and Local Government, 2011. *Appendix 6: energy performance of buildings.* [Online] Available at: https://www.gov.uk/government/publications/2010-to-2015-government-policy-energy-efficiency-in-buildings/2010-to-2015-government-policy-energy-efficiency-in-buildings#appendix-6-energy-performance-of-buildings [Accessed Feb 2016].

Dickinson, J., Pardasani, A., Ahamed, S. & Kruithof, S., 2009. *A survey of automation technology for realising as-built models of services.* Espoo, Finland, CIB IDS 2009 - Improving Construction and Use through Integrated Design Solutions, p. 365–381.

Dimyadi, J., Spearpoint, M. & Amor, R., 2008. Sharing Building Information using the IFC Data Model for FDS Fire Simulation. *Fire Safety Science,* Volume 9, p. 1329–1340.

Ding, L., Drogemuller, R., Rosenman, M., Marchant, D. & Gero, j., 2006. Automating code checking for building designs- DesignCheck. *CRC for Construction Innovation. Clients Driving Innovation: Moving Ideas into Practice,* pp. 1-16.

Donmoyer, R., 2008. Quantitative Research. In: L. M. Given, ed. *The SAGE Encyclopedia of Qualitative Research Methods.* London: SAGE Publications, Inc.

Doukas, H., Nychtis, C. & Psarras, J., 2009. Assessing energy-saving measures in buildings through an intelligent decision support model. *Building and Environment,* 42(2), p. 290–298.

Drago, J., 2010. *Survey Lasers - The Advantages and Disadvantages of Laser Scanning.* [Online] Available at: http://ezinearticles.com/?Survey-Lasers---The-Advantages-and-Disadvantages-of-Laser-Scanning&id=4303829 [Accessed 23 October 2016].

Eadie, R, Browne, M, Odeyinka, H,McKeown, C. & McNiff, S., 2013. BIM implementation throughout the UK construction project lifecycle, *Automation in Construction,* Volume 36.

East, B. & Carrasquillo-mangual, M., 2013. *The COBie guide: a commentary to the NBIMs-us COBie standardand,* buildingSMART alliance- NIBS (National Institute of Building Science).

Easterby-Smith, M., Thorpe, R. & and Lowe, A., 1991. *Management Research: An Introduction.* London: SAGE Publications.

Eastman, C., 1975. The Use of Computers Instead of Drawings. *AIA Journal 63(3),* p. 46–50.

Eastman, C., Lee, J., Jeong, Y. & Lee, J., 2009. Automatic rule-based checking of building designs. *Automation in Construction,* 18(8), p. 1011–1033.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K., 2011. *BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers, and Contractors.* Canada: John Wiley & Sons. Inc.

EERE, 2015. *EnergyPlus Energy Simulation Software, U.S. Department of Energy, Energy Efficiency & Renewable Energy.* [Online] Available at: http://apps1.eere.energy.gov/buildings/energyplus/?utm_source=EnergyPlus&utm_medium=redirect&utm_campaign=EnergyPlus%2Bredirect%2B1 [Accessed 20 January 2017].

EERE, 2016. *EnergyPlus Energy Simulation Software, weather data.* [Online] Available at: http://apps1.eere.energy.gov/buildings/energyplus/ [Accessed 10 June 2016].

El-omari, S. & Moselhi, O., 2008. Integrating 3D laser scanning and photogrammetry for progress measurement of construction work. *Automation in Construction Journal,* 18(1), pp. 1-9.

Energy Efficiency Partnership for Homes, 2008. *A Landlord's Guide to Energy Performance Certificates.* [Online] Available at: http://www.smartlets.org.uk/files/A%20Landlord's%20Guide%20to%20Energy%20Performance%20Certificates.pdf [Accessed Feb 2016].

Energy Saving Trust, 2006. *Hidden Value Guide: The magazine for energy efficient homes.* [Online] Available at: http://www.adbredenltd.co.uk/HiddenValue.pdf [Accessed Feb 2016].

Enkovaara, E., Salmi, M. & Sarja, A., 1988. *RATAS Project — Computer Aided Design for Construction.* Helsinki: Building Book Ltd.

EPBD, 2011. *Implementing the energy performance of buildings directive EPBD.* [Online] Available at: http://www.epbdca.org/Medias/Downloads/CA_Book_Implementing_the_EPBD_Featuring_Country_Reports_2010.pdf [Accessed Feb 2016].

Eurostat, 2017. *Structural business statistics overview.* [Online] Available at: http://ec.europa.eu/eurostat/web/structural-business-statistics/data/database [Accessed 10 May 2017].

Fabbri, S., Sauro, F., Santagata, T., Rossi, G. & DeWaele, J., 2017. High-resolution 3-D mapping using terrestrial laser scanning as a tool for geomorphological and speleogenetical studies in caves: An example from the Lessini mountains (North Italy). *Geomorphology,* Volume 280, p. 16–29.

Faiers, A., Cook, M. & Neame, C., 2007. Towards a contemporary approach for understanding consumer behaviour in the context of domestic energy use. *Energy Policy,* 35(34), pp. 4381-4390.

FARO, 2016. *FARO Focus.* [Online] Available at: http://www.faro.com/products/3d-surveying/laser-scanner-faro-focus-3d/overview [Accessed 13 December 2016].

Fenves, S. J., 1996. Tabular Decision Logic for Structural Design. *Structural Division,* 92(6), pp. 473-490.

Fiatech Regulatory Streamlining Committee, 2012. *AutoCodes Project: Phase 1, Proof-of Concept Final Report.* [Online] Available at: http://www.fiatech.org/images/stories/techprojects/project_deliverables/Updated_project_deliverables/AutoCodesPOCFINALREPORT.pdf [Accessed June 2016].

Fischer, M., 2006. Formalizing Construction Knowledge for Concurrent Performance-Based Design. In: S. I.F.C., ed. *Intelligent Computing in Engineering and Architecture, 13th EG-ICE Workshop 2006.* Ascona, Switzerland: Springer-Verlag Berlin Heidelberg, pp. 186-205.

Fitzgerald, B. & Howcroft, D., 1998. Towards dissolution of the IS research debate: from polarization to polarity. *Journal of Information Technology,* Volume 13, pp. 313- 326.

Flowers, S., Hippel, E., Jong, J. & Sinozic, T., 2010. *Measuring user innovation in the UK: The importance of product creation by users,* NESTA.

Fokaides, P. & Kalogirou, S., 2011. Application of infrared thermography for the determination of the overall heat transfer coefficient (U-value) in building envelopes. *Applied Energy,* 88(12), pp. 4358-4365.

Forbes, L. H. & Ahmed, S. M., 2011. *Modern Construction Lean Project Delivery and Integrated Practices.* New York: CRC Press, Taylor and Francis Group.

Fritz, R. & McNeil, A., 2015. *Radiance.* [Online] Available at: http://www.radiance-online.org/ [Accessed 30 December 2016].

Frohlich, C. & Mettenleiter, M., 2004. TERRESTRIAL LASER SCANNING –NEW PERSPECTIVES IN 3D SURVEYING. *International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences,* Volume XXXVI-8/W2, p. 7–13.

Galvin, R., 2015. How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge?. *Journal of Building Engineering,* Volume 1, pp. 2-12.

gbXML, 2013. *GREEN BUILDING XML SCHEMA.* [Online] Available at: http://gbxml.org/ [Accessed June 2016].

gbXML, 2014. *gbXML Open Green Building XML Schema: a Building Information Modeling Solution for Our Green World.* [Online] Available at: http://gbxml.org/ [Accessed June 2016].

gbXML, 2016. *gbXML Vendor Certification Validator.* [Online] Available at: http://gbxml.org/validator/Pages/TestPage.aspx [Accessed 05 May 2017].

GEA, 2012. *Global energy assessment – toward a sustainable future,* Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria: Cambridge University Press.

Geomagic, 2014. *3D Systems Announces Geomagic 2014.* [Online] Available at: http://www.geomagic.com/en/community/press-releases/3d-systems-announces-geomagic-2014/ [Accessed 13 December 2016].

Gibbs, G. R., 2002. *Qualitative Data Analysis: Explorations with Nvivo.* Phiadelphia: Open University Press.

Gielingh, w., 2008. An assessment of the current state of product data technologies. *Computer-Aided Design,* Volume 40, p. 750–759.

Gladwin, M., 2011. *Retrofit for the Future Project, Final Report, PassivHaus Retrofit: Refurb and regenerate,* Liverpool: Plus Dane Group.

Golparvar-Fard, M., Bohn, J., Teizer, J., Savarese, S. & Peña-Mora, F., 2011. Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques. *Automation in Construction,* 20 (8).

Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. & Lee, S., 2009. Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of Computing in Civil Engineering,* 23(6), p. 391–404.

Götz, K., Karóczkai, A. & Kovács, D. A., 2016. *Import/Export File Formats in ARCHICAD.* [Online] Available at: https://helpcenter.graphisoft.com/technotes/setup/software-technologies/file-formats-in-archicad/#Model3D_Formats [Accessed 22 May 2017].

GOV.UK, 2013. *Approved Document F: ventilation (2010 edition incorporating 2010 and 2013 amendments),* London: Department for Communities and Local Government.

GOV.UK, 2014. *Standard assessment procedure.* [Online] Available at: https://www.gov.uk/guidance/standard-assessment-procedure [Accessed Feb 2016].

Graphisoft, 2015. *EcoDesigner Star.* [Online] Available at: http://www.graphisoft.com/archicad/ecodesigner_star/ [Accessed 23 November 2016].

Graphisoft, 2016. *Interoperability with Green Software.* [Online] Available at: https://helpcenter.graphisoft.com/guides/archicad-20/archicad-20-reference-guide/energy evaluation/energy performance evaluation/interoperability with green software/ [Accessed 22 January 2017].

Gray, M., Gray, J., Teo, M., Chi, S. & Cheung, F., 2013. *Building Information Modeling: an international survey.* Brisbane, World Building Congress.

Groat, L., 2002. Qualitative Research. In: L. N. Groat & D. Wang, eds. *Architectural Research Methods.* New York: John Wiley, pp. 173-203.

GSA, 2015. *GSA BIM Guide 05 - Energy Performance: Version 2.1,* Washington, The National 3D-4D BIM Program.

Guba, E. & Lincoln, Y. S., 1994. Competing paradigms in qualitative research. In: N. K. Denzin & Y. S. Lincoln, eds. *Handbook of Qualitative Research.* Thousand Oaks, California: Sage, pp. 105-117.

Haapio, A. & Viitaniemi, P., 2008. A critical review of building environmental assessment tools. *Environmental Impact Assessment Review,* Volume 28, p. 469–482.

Haines, V. & Mitchell, V., 2014. A persona-based approach to domestic energy retrofit. *Building Research & Information,* 42(4), pp. 462-476.

Hajian, H. & Becerik-Gerber, B., 2010. *Scan to BIM: factors affecting operational and computational errors and productivity loss.* Bratislava, Slovakia, Proceedings of the 27th International Symposium on Automation and Robotics in Construction (ISARC).

Ham, Y. & Golparvar-Fard, M., 2015. Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in Construction,* Volume 49, p. 214–224.

Hartonoa, E., Li, X., Nab, K.-S. & Simpsonc, J. T., 2010. The role of the quality of shared information in interorganizational systems use. *International Journal of Information Management,* Volume 30, p. 399–407.

Harty, C., Throssell, D., Jeffrey, H. & Stagg, M., 2010. *Implementing building information modelling: a case study of the Barts and the London hospitals Building information models (BIMs).* Nottingham, Proceedings of the International Conference on Computing in Civil and Building Engineering, ICCCBE, p. 6.

Harvey, F., 2013. *Green deal 'unlikely to deliver promises', say experts. The Guardian.* [Online] Available at: http://www.theguardian.com/environment/2013/jan/27/green-deal-unlikely-deliver-promises [Accessed Feb 2016].

Henninger, R. & Witte, M., 2013. *EnergyPlus Testing with HVAC Equipment Performance Tests CE300 to CE545 from ANSI/ASHRAE Standard 140-2011, EnergyPlus Version 8.0.0.008,* Washington, Energy Efficiency and Renewable Energy.

Hitchcock, R. J. & Wong, J., 2011. *Transforming IFC architectural views BIMS for energy simulation.* Sydney, Proceedings of Building Simulation 2011:12th Conference of International Building Performance Simulation Association.

Hjelseth, E., 2011. *Capturing Normative Constraints by Use Of The Semantic Mark-Up RASE Methodology.* Sophia Antipolis, France, CIBW78 2011 28th International Conference-Applications of IT in the AEC Industry.

Hjelseth, E. & Nisbet, N., 2010. *Overview of concepts for model checking.* Cairo, CIB-W078.

Horna, J., 1994. *The Study of Leisure: An Introduction.* Oxford University Press, Canada.

Hu, Z., Zhang, J. & Deng, Z., 2008. Construction Process Simulation and Safety Analysis Based on Building Information Model and 4D Technology. *Tsinghua Science and Technology,* 13(S1), p. 266–272.

Hygh, J. S., DeCarolis J. F., Hill, D. B. & Ranjithan, S. R., 2012. Multivariate regression as an energy assessment tool in early building design. *Building and Environment,* Volume 57, p. 165–175.

IBC., 2011. *Environmental Scan of BIM Tools and Standards.* Canadian Construction Association.

IBPSA-USA, 2014. *Best Directory_ Building Energy Software Tools.* [Online] Available at: http://www.buildingenergysoftwaretools.com/ [Accessed November 2016].

IEA, 2011. *Energy in Buildings and communities programme (EBC).* [Online] Available at: http://www.iea-ebc.org/ [Accessed 2015].

IEA, 2015. *Energy efficiency market report 2015: Market Trends and Medium-Term Prospects,* Paris: International Energy Agency (IEA).

ifcwiki, 2015. *Basic information of IFC.* [Online] Available at: http://www.ifcwiki.org/index.php?title=Basic_Informations [Accessed June 2016].

Ilter, D. & Ergen, E., 2015. BIM for building refurbishment and maintenance: current status and research directions. *Structural Survey,* 33(3), pp. 228-256.

Innovate UK, 2014. *Retrofit for the future guide,* London: Contains public sector information licensed under the Open Government Licence v3.0.

Integrated Environmental Solutions Ltd., 2015. *IESVE.* [Online] Available at: https://www.iesve.com/ [Accessed 30 December 2016].

Interviewee A, 2013. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (7 October 2013).

Interviewee B, 2013. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (3 October 2013).

Interviewee C, 2014. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (7 April 2014).

Interviewee D, 2014. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (4 March 2014).

Interviewee E, 2014. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (14 March 2014).

Interviewee F, 2013. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (12 August 2013).

Interviewee G, 2014. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (5 June 2014).

Interviewee H, 2014. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (19 March 2014).

Interviewee I, 2013. *Exploiting BIM in Energy Efficient Refurbishment* [Interview] (26 April 2013).

ISO Standard, 2008. *ISO 22263: 2008-01: Organization of Information About Construction Works — Framework for Management of Project Information,* International Standard.

ISO Standard, I. 2.-1., 2010. Building Information Modeling — Information Delivery Manual — Part 1: Methodology and Format, 2010.

ISO, 2010. *ISO 29481-1:2010(E): building information modeling — information delivery manual. (part 1: methodology and format).*

Iturralde, K., 2012. Refurbishing homes for elderly using CAD-BIM-CNC technology. *Gerontechnology, International journal of the fundamental aspects of technology to serve the aging society,* 11(2).

Jaffe, A. & Stavins, R., 1994. The energy-efficiency gap what does it mean?. *Energy Policy,* Volume 22, pp. 804-810.

Jaggs, M. & Palmer, J., 2000. Energy performance indoor environmental quality retrofit- a European diagnosis and decision making method for building refurbishment. *Energy and Buildings,* Volume 31, pp. 97-101.

Jalae, F. & Jrade, A., 2015. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society,* Volume 18, pp. 95-107.

James, D., Eckermann, J., Belblidia, F. & Sienz, J., 2015. *Point cloud data from Photogrammetry techniques to generate 3D Geometry.* Swansea, Proceedings of the 23rd UK Conference of the Association for Computational Mechanics in Engineering, Swansea University.

Janda, K., 2011. Buildings don’t use energy: people do. *Architectural Science Review ,* Volume 54, pp. 15-22.

Jeffrey, H., 2012. *AEEBC Salford Nov. 2012,* Skanska UK at the University of Salford: Association of European Experts in Building and Construction.

Jevons, W. S., 1906. *The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines.* 3rd ed. New York: A.M. Kelley.

Jones, A., 2013. Investigating deep retrofits for Toronto’s financial district office towers. *Journal of Sustainable Real Estate,* 5(1), pp. 206-238.

Kanters, J. & Horvat, M., 2012. The Design Process known as IDP: A Discussion. *Energy Procedia,* Volume 30, pp. 1153-1162.

Kanters, J., Horvat, M. & Dubois, M.-C., 2014. Tools and methods used by architects for solar design. *Energy and Buildings,* 68(Part C), pp. 721-731.

Katz, M. L. & Shapiro, C., 1998. Antitrust in software markets. In: J. A. Eisenach & T. M. Lenard, eds. *Competition, Innovation and the Microsoft Monopoly: Antitrust in the Digital Marketplace.* Washigton: The Progress & Freedom Foundation, pp. 29-81.

Kavulya, G., Jazizadeh, F. & Becerik-Gerber, B., 2011. *Effects of Color, Distance, And Incident angle on Quality of 3D point clouds.* Miami, Florida, United States, Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering.

Kellya, S., Crawford-Browna, D. & Pollittb, M., 2012. Building performance evaluation and certification in the UK: Is SAP fit for purpose?. *Renewable and Sustainable Energy Reviews,* 16(9), pp. 6861-6878.

Kennerley, B., 2013. *What is BIM?.* [Online] Available at: http://www.wsp-pb.com/en/Who-we-are/In-the-media/News/2013/What-is-BIM/ [Accessed 1 December 2016].

Khaddaj, M. & Srour, I., 2016. Using BIM to Retrofit Existing Buildings. *Procedia Engineering 145 (2016) 1526 – 1533,* Volume 145, pp. 1526-1533.

Khemlani, L., 2004. *The IFC Building model: a look under the hood, AEC Bytes.* [Online] Available at: http://home.fa.utl.pt/~franc/2007/mapoio/projdig/Ifcmodel.pdf [Accessed June 2016].

Khemlani, K., 2005. *CORENET e-PlanCheck: Singapore's Automated Code Checking System.* [Online] Available at: http://www.novacitynets.com/pdf/aecbytes_20052610.pdf [Accessed May 2016].

Khemlani, L., 2007. *Top criteria for BIM solutions, October issue.* [Online] Available at: http://www.aecbytes.com [Accessed 12 June 2015].

Khemlani, L., 2009. *Solibri ModelChecker, AECbytes.* [Online] Available at: http://www.aecbytes.com/archive-articles/categories/review.html [Accessed May 2016].

Kimmance, A. G., 2002. *An Integrated Product and Process Information Modelling System for On-Site Construction,* Loughborough: Loughborough University, A Doctoral Thesis.

Kim, M-K., Wang, Q., Park, J. W., Cheng, J. C. P., Sohn, H. & Chang, C-C., 2016. Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM. *Automation in Construction,* Volume 72, p. 102–114.

Kiviniemi, A., 2005. *Requirements management interface to building product models.* VTT Technical Research centre of Finland, JULKAISIJA- UTGIVARE- Publisher.

Kiviniemi, A., 2010. *Intervista a Arto Kiviniemi.* [Online] Available at: http://www.ingenio-web.it/immagini/CKEditor/Intervista%20a%20Arto%20Kiviniemi.pdf [Accessed NOV 2014].

Klein, L., Li, N. & Becerik-Gerber, B., 2012. Image-based verification of as-built documentation of operational buildings. *Automation in Construction,* Volume 21, p. 161–171.

Koehn, E. & Towers, S., 1982. Current aspects of construction rehabilitation. *Construction Divison, Proceedings of the American Society of Engineers, ASCE,* Volume 108, pp. 330-340..

Kolokotsa, D., Diakaki, C., Grigoroudis, E., Stavrakakis, G. & Kalaitzakis, K., 2009. Decision support methodologies on the energy efficiency and energy management in buildings. *Advances in Building Energy Research,* 3(1), pp. 121-146.

Konstantinoua, T. & Knaacka, U., 2011. Refurbishment of residential buildings: a design approach to energy-efficiency upgrades. *Procedia Engineering,* Volume 21.

Kreith, F. & Goswami, D., 2008. *Energy Management and Conservation Handbook,* Boca Raton, Florida, USA: CRC Press, Taylor & Francis Group.

Krygiel, E., Nies, B. & Mcdowell, S., 2008. *Green BIM: Successful Sustainable Design with Building Information Modeling.* Minnesota: Wiley Pub.

Kulusjärvi, H., 2012. *Common BIM Requirements 2012 – Series 6 Quality Assurance,* Helsinki: buildingSMART Finland.

Kumar, S., 2008. *Interoperability between Building Information Modeling (BIM) and energy analysis programs,* California: University of southern California, MSc thesis.

Kunz, J. & Fischer, M., 2007. *CIFE Research Questions and Methods: How CIFE Does Academic Research for Industrial Sponsors,* Stanford: Stanford university publications.

Laakso, M. & Kiviniemi, A., 2012. The IFC standard -A review of history, development, and standardization. *Journal of Information Technology in construction (ITcon),* Volume 17, pp. 134-159.

Laefer, D. F. & Truong-Hong, L., 2017. Toward automatic generation of 3D steel structures for building information modelling. *Automation in Construction,* Volume 74, pp. 66-77.

Lagüela, S., Díaz-Vilariño, L., Armesto, J. & Arias, P., 2014. Non-destructive approach for the generation and thermal characterization of an as-built BIM. *Construction and Building Materials,* 51(31), pp. 55-61.

Larrosa Marshall and Associates, 2010. *Details of floor plans and elevations,* Liverpool: Plus Dane Group.

Latham, M., 1994. *Constructing the team. Final Report of the Government's Industry Review of Procurement and Contractual Arrangements in the UK,* London: HMSO.

LEB, 2010. *Passiv Haus Retrofit: refurb and regenerate,* London: Low Energy Building Database.

Legislation.gov.uk., 2008. *Climate Change Act 2008: Part 1 Carbon target and budgeting,* Norwich: The Stationery Office Limited.

Lewis, J. & Smith, L., 2014. *Breaking Barriers: An industry review of the barriers to Whole House Energy Efficiency Retrofit and the creation of an industry action plan Summary Report,* The Energy Efficiency Partnership for Buildings.

Lie, Å., 2008. *Use of dRofus in the HITOS project,* Project report.

Li, S., Ragu-Nathan, B., Ragu-Nathan, T. S. & Rao, S. S., 2006. The impact of supply chain management practices on competitive advantage and organizational performance. *Omega,* 34(2), p. 107–124.

Locke, L. F., Silverman, S. J. & Spirduso, W. W., 1998. *Reading and Understanding Research.* Thousand Oaks: California: SAGE Publications.

Lowe, R. & Oreszczyn, T., 2008. Regulatory standards and barriers to improved performance for housing. *Energy Policy,* Volume 36, pp. 4475-4481.

Lutzenhiser, L., 1992. A cultural model of household energy consumption. *Energy,* Volume 17, pp. 47-60.

Madding, R., 2008. Finding R-values of stud frame constructed houses with IR thermography. *InfraMation 9,* Volume 9, pp. 261-277.

Madlener, R. & Alcott, B., 2009. Energy rebound and economic growth: A review of the main issues and research needs. *Energy,* Volume 34, pp. 370-376.

Maile, T., Fischer, M. & Bazjanac, V., 2007. *Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective,* Stanford: Center for integrated facility engineering - Stanford University. CIFE Working Paper WP107.

Maile, T., O'Donnell, J., Bazjanac, V. & Rose, C., 2013. *BIM-geometry modeling guidelines for building energy performance simulation.* Chambéry, France., Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association.

Mallaband, B., V., H. & V, l. M., 2011. *Barriers to domestic retrofit – learning from past home improvement experiences,* Loughborough: Loughborough Design School, Loughborough University.

Malsane, S., Matthews, J., Lockley, S., Love, P. E.D. & Greenwood, D., 2015. Development of an object model for automated compliance checking. *Automation in Construction,* Volume 49, p. 51–58.

Marchand, R., Koh, S. & Morris, J., 2015. Delivering energy efficiency and carbon reduction schemes in England: Lessons from Green Deal Pioneer Places. *Energy Policy,* Volume 84, pp. 96-106.

Markley, J., Stutzman, J. & Harris, E., 2008. *Hybridization of photogrammetry and laser scanning technology for as-built 3D CAD models.* Big Sky, Montana, United States, IEEE Aerospace Conference.

Mashford, K., Steeland, A., Mallett, G., Smith, L. & Simpson, B., 2015. *Improving the use of energy in buildings: Homeowners Advice Facility,* Milton Keynes: National Energy Foundation.

May, T., 2011. *Social research: Issues, Methods and Research.* 4th ed. Berkshire: Open University Press: McGraw.

Ma, Z., Cooper, P., Daly, D. & Ledo, L., 2012. Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings,* Volume 55, p. 889–902.

McGraw Hill, 2009. *The business value of BIM: Getting Building Information Modeling to the Bottom Line,* SmartMarket Report.

McKenzie, R. B. & Shughart II, W. F., 1998. *Independent Institute.* [Online] Available at: http://www.independent.org/publications/tir/article.asp?a=322 [Accessed June 2016].

Migilinskasa, D., Popovb, V., Juoceviciusc, V. & Leonas, U., 2013. The Benefits, Obstacles and Problems of Practical Bim Implementation. *Procedia Engineering,* Volume 57.

Mikhail, E., Bethel, J. & McGlone, J., 2001. *Introduction to Modern Photogrammetry.* New York: John Wiley and Sons.

Mills, E. & Rosenfeld, A., 1996. Consumer Non-Energy Benefits as a Motivation for Making Energy-Efficiency Improvements. *Energy,* 21(7-8), pp. 707-720.

Mill, T., Alt, A. & Liias, R., 2013. Combined 3D building surveying techniques — terrestrial laser scanning (TLS) and total station surveying for BIM data management purposes. *CIVIL ENGINEERING AND MANAGEMENT,* Issue 19.

Mohammadpourkarbasi, H. & Sharples, S., 2015. *The Eco-Refurbishment of a 19th Century Terraced House (Energy, Carbon and Cost Performance for Current and Future UK Climates),* Liverpool: University of Liverpool, Faculty of Humanities and Social Sciences.

Mondrup, T. F., 2014. *Methods for implementing Building Information Modeling and Building Performance Simulation approaches,* Kongens Lyngby: Department of Civil Engineering, Technical University of Denmark.

Moon, H. J., Choi, M. S., Kim, S. K. & Ryu, S. H., 2011. *Case Studies for the Evaluation of Interoperability between a BIM Based Architectural Model and Building Performance Analysis Programms.* Sydney, Proceedings Building Simulation 2011: 12th Conference of International Building Performance Simulation Association.

Morgan, D. L., 2004. Snowball Sampling. In: M. S. Lewis-Beck, A. Bryman & T. F. Liao, eds. *The SAGE Encyclopedia of Social Science Research Methods.* London: SAGE Publications, Inc, pp. 815-816.

Morita, T., Robinson, JR., Alcamo, J., Nakicenovic, N. & Riahi, K., 2001. Greenhouse gas emission mitigation scenarios and implications. In: *Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel Climate change.* Cambridge: Cambridge University Press.

Mukhopadhyay, T., Kekre, S. & Kalathur, S., 1995. Business value of information technology: A study of electronic data interchange. *MIS Quarterly,* 19(2), p. 137–156.

Nasyrov, V., Stratbücker, S., Ritter, F., Borrmann, A., Hua, S. & Lindauer, M., 2015. Building information models as input for building energy performance simulation – the current state of industrial implementations. In: B. Martens, A. Mahdavi & R. Scherer, eds. *eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2014.* London: Taylor & Francis Group, pp. 479-488.

Naticchia, B., Giretti, A., Carbonari, A. & Vaccarini, A., 2010. *A real-time and non intrusive structural health monitoring system for buildings.* Bratislava, Slovakia, Proceedings of the 27th ISAARC.

National Renewable Energy Laboratory, 2015. *OpenStudio.* [Online] Available at: https://www.openstudio.net [Accessed 30 December 2016].

Nawari, N., 2012a. BIM-Model Checking in Building Design. *Structures Congress,* pp. 941-952.

Nawari, N., 2012b. *The challenge of computerizing building codes in BIM environment.* Clearwater Beach, Florida, Asce International Conference on Computing in Civil Engineering.

NBIMS-US™, 2007. *National BIM Standard - United States™ Version 2,* Washington: National Institute of Building Sciences buildingSMART alliance™.

NBS, 2015. *National BIM Report 2015,* Newcastle: RIBA Enterprises Ltd.

NBS, 2016. *Top 10 BIM myths debunked,* Newcastle upon Tyne: RIBA Enterprises Ltd.

NBS, 2017. *National BIM Report 2017,* Newcastle upon Tyne: RIBA Enterprises Ltd.

Negendahl, K., 2015. Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction,* Volume 54, p. 39–53.

Newman, I. & Benz, C. R., 1998. *Qualitative-quantitative research methodology: Exploring the interactive continuum.* Carbondale and Edwardsville: Southern Illinois University Press.

Nicolaou, A. I. & McKnight, D. H., 2006. Perceived information quality in data exchanges: Effects on risk, trust, and intention to use. *Information Systems Research,* 17(4), p. 332–351.

NIHE, 2016. *Home Energy Conservation Authority, 20th Progress Report 2016,* Belfast: Northern Ireland Housing Executive.

novaCITYNETS, 2002. *Implementing IFC-Automatic code checking (e-plancheck) Pte.* [Online] Available at: http://www.novacitynets.com/ [Accessed May 2016].

NVivo, 2014. *NVivo 10 for windows: Getting started.* [Online] Available at: http://www.qsrinternational.com/default.aspx [Accessed August 2016].

O’Brien, W. L., 2002. *Preliminary Investigation of the Use of Sankey Diagrams to Enhance Building Performance Simulation-Supported Design.* San Diego, USA, Proceedings of the Symposium on Simulation for Architecture and Urban Design, SimAUD.

Omar, T. & Nehdi, M. L., 2016. Data acquisition technologies for construction progress tracking. *Automation in Construction,* Volume 70, pp. 143-155.

Open BIM Focus, 2012. *Issue 1: BIM and the OPEN BIM Network,* OPEN BIM Network.

Osello, A., Cangialosi, G., Dalmasso, D., Antonio Di Paolo, M. L., Piumatti, P. & Vozzola, M, 2011. *Architecture Data and Energy Efficiency Simulations: BIM and Interoperability Standards.* Sydney, 12th Conference of International Building Performance Simulation Association.

Østergård, T., Jensen, R. L. & Maagaard, S. E., 2016. Building simulations supporting decision making in early design – A review. *Renewable and Sustainable Energy Reviews,* Volume 61, p. 187–201.

Oxera, 2006. *Policies for energy efficiency in the UK household sector ,* Oxford: Oxera Consulting Limited.

Palmer, J. & Cooper, I., 2012. *United Kingdom housing energy fact file.* [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/201167/uk_housing_fact_file_2012.pdf [Accessed Dec 2015].

Patton, M., 2002. *Qualitative evaluation and research methods.* 3rd ed. Newbury Park, California: SAGE.

Pelenur, M., 2013. Retrofitting the domestic built environment: investigating household perspectives towards energy efficiency technologies and behaviour. *Department of Engineering, University of Cambridge, Queens' College.*

Pelenur, M. & Cruickshank, H., 2011. *The social barriers towards adopting energy efficiency measures and behaviours in the home: a Manchester and Cardiff case study,* Cambridge: Centre for Sustainable Development, Department of Engineering University of Cambridge.

Pelenur, M. & Cruickshank, H., 2013. Investigating the link between well-being and energy use; an explorative case study between passive and active domestic energy management systems. *Building and Environment,* Volume 65, pp. 26-43.

Peltomäki, A., 2009. *ICT for a Low Carbon Economy: Smart Buildings,* Brussels: Findings by the High-Level Advisory Group and the REEB Consortium On the Building and Construction sector, EU Commission.

Penttilä, H., Rajala, M. & Freese, S., 2007. Building Information modelling of modern historic buildings. *eCAADe,* Volume 25, pp. 607-613.

Petersen, S., 2011. *Simulation-based support for integrated design of new lowenergy office buildings,* Kongens Lyngby: Department of Civil Engineering, Technical University of Denmark.

Photofly, 2011. *Autodesk, Autodesk Labs Utilities Project Photofly.* [Online] Available at: http://autodesk.blogs.com/between_the_lines/2011/05/project-photofly-v2-released-for-download.html [Accessed November 2016].

Photosynth, 2011. *Microsoft, Photosynth - Capture your world in 3D.* [Online] Available at: https://photosynth.net/ [Accessed November 2016].

Planing Portal, 2007. *Energy Performance Certificate.* [Online] Available at: http://www.planningportal.gov.uk/buildingregulations/greenerbuildings/epc [Accessed Feb 2016].

Planing Portal, 2011. *Approved Document L - Conservation of fuel and power.* [Online] Available at: http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/approved [Accessed Feb 2016].

Polit, D. & Beck, C., 2003. *Nursing research: Principles and methods.* 7th ed. Philadelphia: Lippincott Williams & Wilkins.

Pout, C., 2001. *CO2 Emission Figures for Policy Analysis,* Watford: BRE.

Rahmat, I. B., 1997. *The Planning and Control Process of Refurbishment Projects.* London: A Thesis Submitted to the Faculty of the Built Environment University College London for the Degree of Doctor of Philosophy.

Redman, L. & Mory, A., 1933. *The Romance of Research.* Baltimore: Williams & Wilkins.

Reed, R., Bilos, A., Wilkinson, S. & Schulte, K., 2009. International comparison of sustainable rating tools. *Journal of Sustainable Real Estate,* Volume 1, pp. 1-22.

Reinhart, C., 2015. *DAYSIM Advanced Daylight Simulation Software.* [Online] Available at: http://daysim.ning.com/ [Accessed 30 November 2016].

Remenyi, D., Williams, B., Money, A. & Swartz, E., 1998. *Doing Research in Business sand Management.* London: Sage.

Remondino, F. & El-hakim, S., 2006. Image-based 3D modelling: a review. *The Photogrammetric Record,* 21(115), p. 269–291.

Rezgui, Y. & Miles, J., 2011. *Harvesting and managing knowledge in construction: from theoretical foundations to business applications.* Abingdon: Routledge.

Rickaby, P. & Willoughby, J., 2014. *An introduction to low carbon domestic refurbishment.* 2nd ed. London: RIBA Publishing.

Ridley, I., Clarke, A., Bere, J., Altamirano, H., Lewis, S., Durdev, M. & Farr, A., 2013. The monitored performance of the first new London dwelling certified to the Passive House standard. *Energy and Buildings,* Volume 63, pp. 67-78.

Rose, C. & Bazjanac, V., 2015. An algorithm to generate space boundaries for building energy simulation. *Engineering with Computers,* 31(2), p. 271–280.

Rossman, G. B. & Wilson, B. L., 1994. Numbers and words revisited: Being “shamelessly eclectic”. *International Journal of Methodology,* 9(5), p. 315–327.

Rothenberg, J., 1989. *The nature of Modelling,* California: The RAND Corporation.

Ryu, H. S. & Park, K. S., 2016. A Study on the LEED Energy Simulation Process Using BIM. *Sustainability,* Volume 8.

Sakamoto, S., Kano, N., Igarashi, T., Kishimoto, H., Fuji, H., Osawa, Y., Minami, K. & Ishida, K., 2011. *Laser marking system based on 3D CAD model.* Seoul, South Korea, Pro-ceedings of the 28th ISAARC.

Sarantakos, S., 1998. *Social Research.* 2nd ed. London: Macmillan.

Sefaira, 2015. *Sefaira.* [Online] Available at: http://sefaira.com/
[Accessed 30 December 2016].

Shaviv, E., Yezioro, A., Capeluto, I. G., Peleg, U. J. & Kalay, Y. E., 1996. Simulations and knowledge-based computer-aided architectural design (CAAD) systems for passive and low energy architecture. *Energy and Buildings,* Volume 23, pp. 257-269.

Shipworth, M., Firth, S.K., Gentry, M.I., Wright, A.J., Shipworth, D.T. & Lomas, K.J., 2010. Central heating thermostat settings and timing: building demographics. *Building Research & Information,* Volume 38, pp. 50-69.

Shorrock, L. D., Henderson, J. & Utley, J. I., 2005. *Reducing carbon emissions from the UK housing stock,* Watford: BRE Bookshop.

Silverman, D., 1998. Qualitative research: meanings or practices?. *Information System Journal,* 8(3), pp. 3-20.

S-IMPLER, 2015. *Solid Wall Innovative Insulation and Monitoring Processes using Lean Energy Efficient Retrofit.* [Online] Available at: http://www.s-impler.com [Accessed 21 Feb 2017].

Singh, V., Gu, N. & Wang, X., 2011. A theoretical framework of a BIM-based multidisciplinary collaboration platform. *Automation in Construction,* 20(2), pp. 134-144.

SMC, 2009. *Solibri: automated code checking for accessibility.* [Online] Available at: http://www.solibri.com/category/press-releases/ [Accessed May 2016].

Smith, R., 2011. *surveying and assessing dwellings for low carbon retrofit,* London: Institute for Sustainability.

Smyth, R., 2004. NVivo (Software). In: M. S. Lewis-Beck, A. Bryman & T. F. Liao, eds. *The SAGE Encyclopedia of Social Science Research Methods.* London: SAGE Publications, Inc, pp. 563-565.

Sokolov, I. & Crosby, J., 2011. *Utilizing gbXML with AECOsim Building Designer and speedikon,* Bentley.

Solibri, 2014. *Solibri Model Checker v9.5, Getting started with Solibri Model Checker,* Solibri Oy.

Solihin, W. & Eastman, C., 2015. Classification of rules for automated BIM rule checking development. *Automation in Construction,* Volume 53, p. 69–82.

Solihin, W. & Shaikh, N., 2005. *Improving application resiliency the face of imperfect information.* Manchester, 2nd International Workshop on nD Modelling Road map: A Vision for nD-Enabled Construction.

Solihin, W., Shaikh, N., Rong, X. & Poh, L., 2004. *Beyond interoperability of building models: a case for code compliance checking.* Pittsburgh, BP-CADWorkshop, Carnegie Melon University.

Stafford, A., Gorse, C. & Shao, L., 2012. *The Retrofit Challenge: Delivering Low Carbon Buildings,* Birmingham: The Centre for Low Carbon Future.

Standards Australia, 2000. *Australian/New Zealand Standard: Energy Audits (AS/NZS 3598:2000).* New Zealand: Standards Australia International Ltd and Standards.

Steg, L., 2008. Promoting Household Energy Conservation. *Energy Policy,* 36(12), pp. 4449-4453.

Stern, N., 2006. Stern Review: The Economics of Climate Change. *HM Treasury.*

Strauss, A. L., 1987. *Qualitative Analysis for Social Scientist.* Cambridge: Cambridge University Press.

Strauss, A. L. & Corbin, J., 1998. *Basics of qualitative research: techniques and procedures for developing grounded theory.* Thousand Oaks(California): Sage Publications.

Succar, B., 2009. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction,* 18(3), pp. 357-375.

Suermann, P., 2009. Evaluating industry perception of building information modelling (BIM) impact on construction. *International Journal of IT in construction 14,* pp. 574-594.

Sunikka-Blank, M., Chen, J., Britnell, L. & Dantsiou, D., 2012. *Improving energy efficiency of social housing areas: a case study of a retrofit achieving an 'A' energy performance rating in the UK.* London, UK: Routledge.

T.R.C.C., 2008. *Your Home in a Changing Climate: Retrofitting Existing Homes for Climate Change Impacts : Report for Policy Makers,* London: Greater London Authority.

Tang, L.C.M., Yuyang, Z., Austinc, S.; Darlingtond, M., Culleyd, S., 2010. Codification vs personalisation: A study of the information evaluation practice between aerospace and construction industries. *International Journal of Information Management,* 30(4), p. 315–325.

Tan, X., Hammad, A. & Fazio, P., 2010. Automated Code Compliance Checking for Building Envelope Design. *Computing in Civil Engineering,* 24(2), pp. 203-211.

Teddlie, C. & Tashakkori, A., 2009. *Foundations of Mixed Methods Research.* Thousand Oaks, California: Sage Publications.

Tobias, L. & Vavaroutsos, G., 2009. *Retrofitting Office Buildings to Be Green and Energy-Efficient: Optimizing Building Performance, Tenant Satisfaction, and Financial Return.* Washington, DC: Urban Land Institute (ULI).

Torcellini, P.A., Deru, M., Griffith, B., Long, N., Pless, S., Judkoff, R. & Crawley, D.B., 2004. *Lessons Learned from Field Evaluation of Six High-Performance Buildings,* Washington DC: National Renewable Energy Laboratory, American Council for an Energy-Efficient Economy.

Torgal, F.P., Mistretta, M., Kaklauskas, A., Granqvist, C.G. & Cabeza, L.F, 2014. *Nearly Zero Energy Building Refurbishment: A Multidisciplinary Approach.* London: Springer-Verlag.

Trist, E. & Bamforth, K. W., 1951. Some social and psychological consequences of the long-wall method of coal-getting. *Human Relations,* Volume 4, pp. 3-38.

TSB, 2013. *Retrofit Revealed, The Retrofit for the Future projects – data analysis report,* Swindon: Technology Strategy Board.

U.S. Department of Energy, 2015. *Energy efficiency and renewable energy, EnergyPlus.* [Online] Available at: https://www.energyplus.net/ [Accessed 30 November 2016].

U.S. Green Building Council, 2013. *LEED for Existing Buildings: Operations & Maintenance,* Washington: Green Building Certification Institute, Inc.

United Nations, 2013. *Official Languages.* [Online] Available at: http://www.un.org/en/sections/about-un/official-languages/ [Accessed June 2016].

Vainio, T., 2011. *Building renovation: a new industry?.* Amsterdam, the Netherlands, Proceedings of Management and Innovation for a Sustainable Built Environment, MISBE 2011.

Venugopal, M., Eastman, C. M., Sacks, R. & Teizer, J., 2012. Semantics of model views for information exchanges using the industry foundation class schema. *Advanced Engineering Informatics,* Volume 26, p. 411–428.

Volk, R., Stengel, L. & Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction,* Volume 38, p. 109–127.

Wang, Q., Kim, M.-K., Chenga, J. C. P. & Sohn, H., 2016. Automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning. *Automation in Construction,* Volume 68, p. 170–182.

Webber, P., Gouldson, A. & Kerr, N., 2015. The Impacts Of Household Retrofit And Domestic Energy Efficiency Schemes: A Large Scale, Ex Post Evaluation. *Energy Policy,* Volume 84, pp. 35-43.

Weygant, R. S., 2011. *BIM Content Development: Standards, Strategies, and Best Practices.* 1st ed. Chichester: John Wiley and Sons Ltd.

Whiteman, W. & Irwig, H., 1988. Disturbance scheduling technique for managing renovation work. *Construction Engineering and Management,* 114(2), pp. 191-213.

Whyte, J., 2000. *Virtual reality applications in the house-building industry,* Loughborough: Loughborough University Institutional Repository, A Doctoral Thesis.

Wilkins, C. & Kiviniemi, A., 2008. Engineering-Centric BIM. *ASHRAE Journal,* 50(12), p. 44–48.

Wilson, C. & Dowlatabadi, H., 2007. Models of decision making and residential energy use. *Annual Review of Environment and Resources,* Volume 32, p. 169–203.

Yin, K., 1994. *Case Study Research: Design and Methods.* Newbury Park, CA: Sage Publications.

Zhang, S., Teizer, J., Lee, J.K., Eastman, C. & Venugopal, M., 2013. Building information modeling (BIM) and safety: automatic safety checking of Construction models and schedules. *Automation in Construction,* Volume 29, pp. 183-195.

Zou, Y., 2017. *BIM and Knowledge Based Risk Management System,* Liverpool: University of Liverpool, A Doctoral Thesis.

Appendices

Appendix A: Interview Questions

Exploiting BIM in Energy Efficient Domestic Retrofit: Evaluation of Benefits and Barriers

Elaheh Gholami, School of Architecture, University of Liverpool

Introduction

The interview has been developed as a part of a PhD research project that aims to evaluate, through discussion with experts, barriers, opportunities and practical challenges in the retrofit process. The findings will be used to develop a framework to enable informed decisions to be made at the early stage of a retrofitting scheme through exploiting BIM.

The objectives of this interview are to:

- Explore the methodologies adopted during the various stages of refurbishment.
- Identify current trends related to refurbishment and evaluate the challenges and enablers through gathering information from experts.
- Understand project team involvement (architect, client, contractor and stakeholders) and the applicability of BIM to improve energy efficiency through refurbishment.

Section 1: Background information:

1. What is your professional background and how many years have you been working in your field?

2. What type of projects (residential refurbishment or research, etc.) are you typically involved in?

Section 2: Current trends in refurbishment regarding the energy efficiency and BIM implementation

1. Regarding your experience, what are the **driving factors** for refurbishment? (For instance legal minimum energy efficiency standard for homes from 2018, extension, energy consumption, increasing demand, etc.)

2. What are the **challenges** you are faced with in energy efficient refurbishment?

3. Do you think that the use of BIM could help solve any of the challenges you have identified above and how might BIM help?

4. From your perspective and experience, what is the general level of refurbishment in the housing sector (extensions, upgrading, energy, interior re-planning, etc.)?
5. How do you consider energy efficiency measures during the various stages of refurbishment? How could BIM be practically exploited to improve the energy efficiency?

6. How do you undertake building surveys and assessments in order to improve the energy efficiency of retrofit measures (i.e. capturing data, materials, compositions and physical properties)?

7. Do you have concerns about captured data that might result in ineffective project management? Do you have any methodologies or tools to solve any of the challenges you have identified?

8. Do you think that exploiting BIM could help solve some of these issues?

9. What tools and/or frameworks do you use during refurbishment processes? What are the reasons for your selection (user experience, easy to use, client demand, visualisation, etc.)?

10. What are the tasks in which you use them (energy simulation, cost estimation, payback analysis etc.)?

11. What trends have you identified in the residential refurbishment sector and what is your opinion on those (i.e. energy improvements, refurbishment, BIM)?
12. Do you have any suggestion to improve the energy efficiency of the residential sector?

13. Regarding your experience, can you identify or propose any methodologies, tools, and framework useful for the refurbishment of the residential sector?

Section 3:

Please provide any other information, which might be useful to this project. (For example:

case study, tool, suggestion, contact, reference, etc.

Appendices

Appendix B: Report of SMC for 2 Broxton Street

Presentation	
Model Name	Project 2 Broxton Street Version: 9.5
Checker	Elaheh Gholami
Organization	Liverpool University
Time	17/07/17 16:49
31 January2017	Time: 2017-01-30 14:20:30 Application: ArchiCAD-64 IFC: IFC2X3

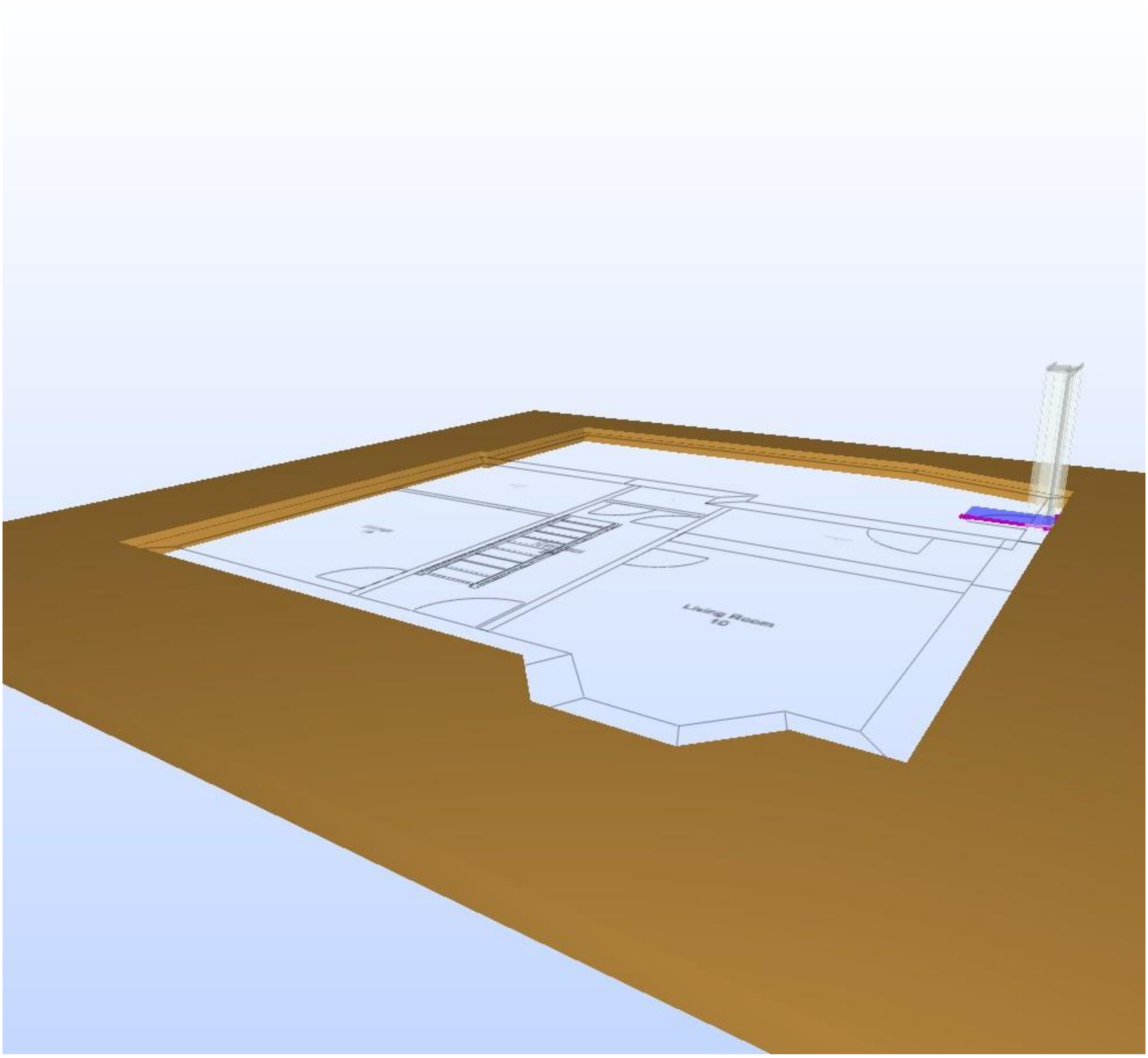
Slab too close to Door component

Clearance in Front of Doors

This rule checks there is enough clearance on both sides of doors.

Slab too close to Door component

Tracking ID: 28



EG, 31-Jan-2017: No impact on energy analysis

Ground Floor

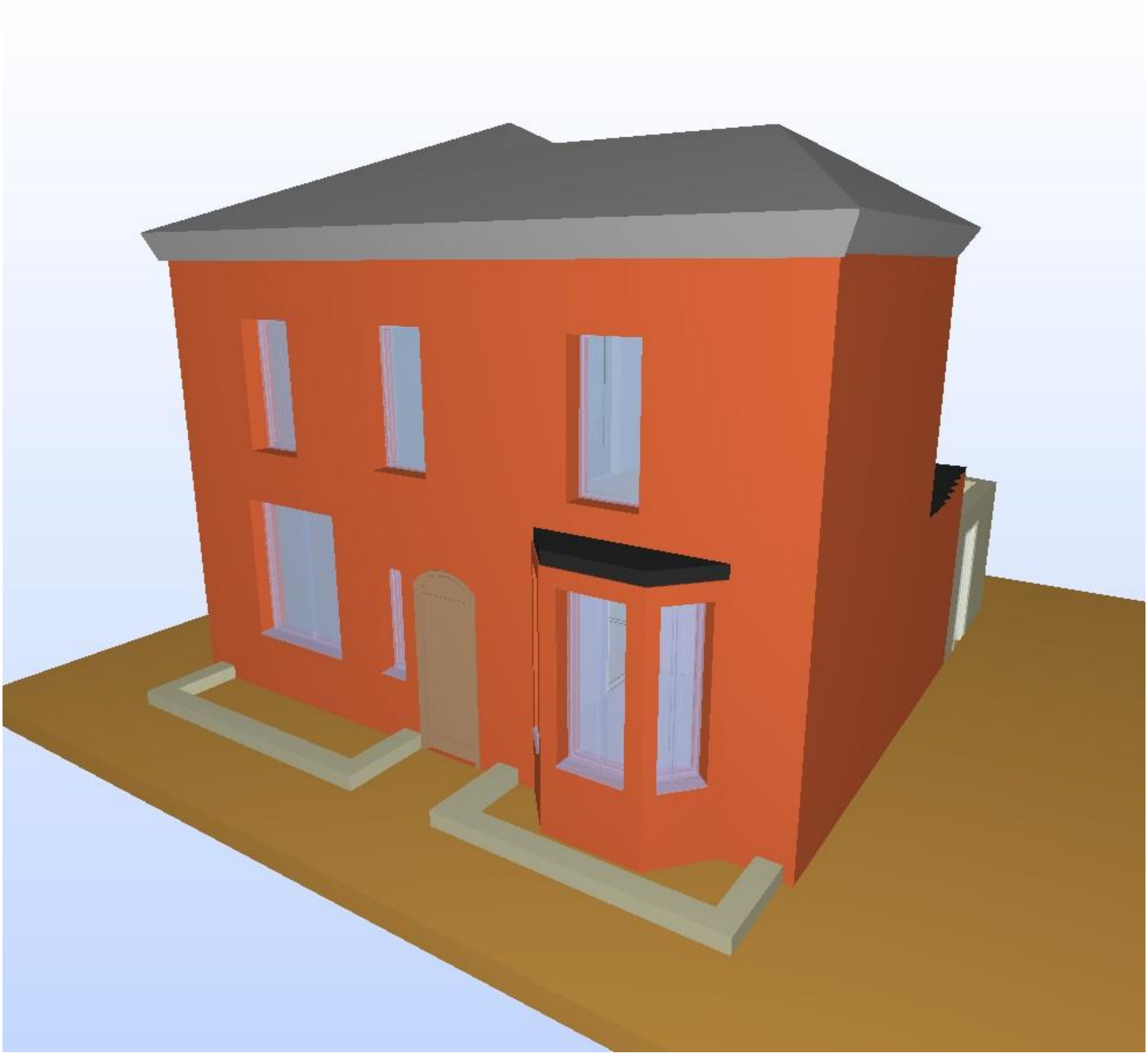
No Components

Required Components

This rule checks that the model contains components of a selected types and they all have a construction type defined.

No Components

Tracking ID: 29



EG, 31-Jan-2017: No impact on energy analysis

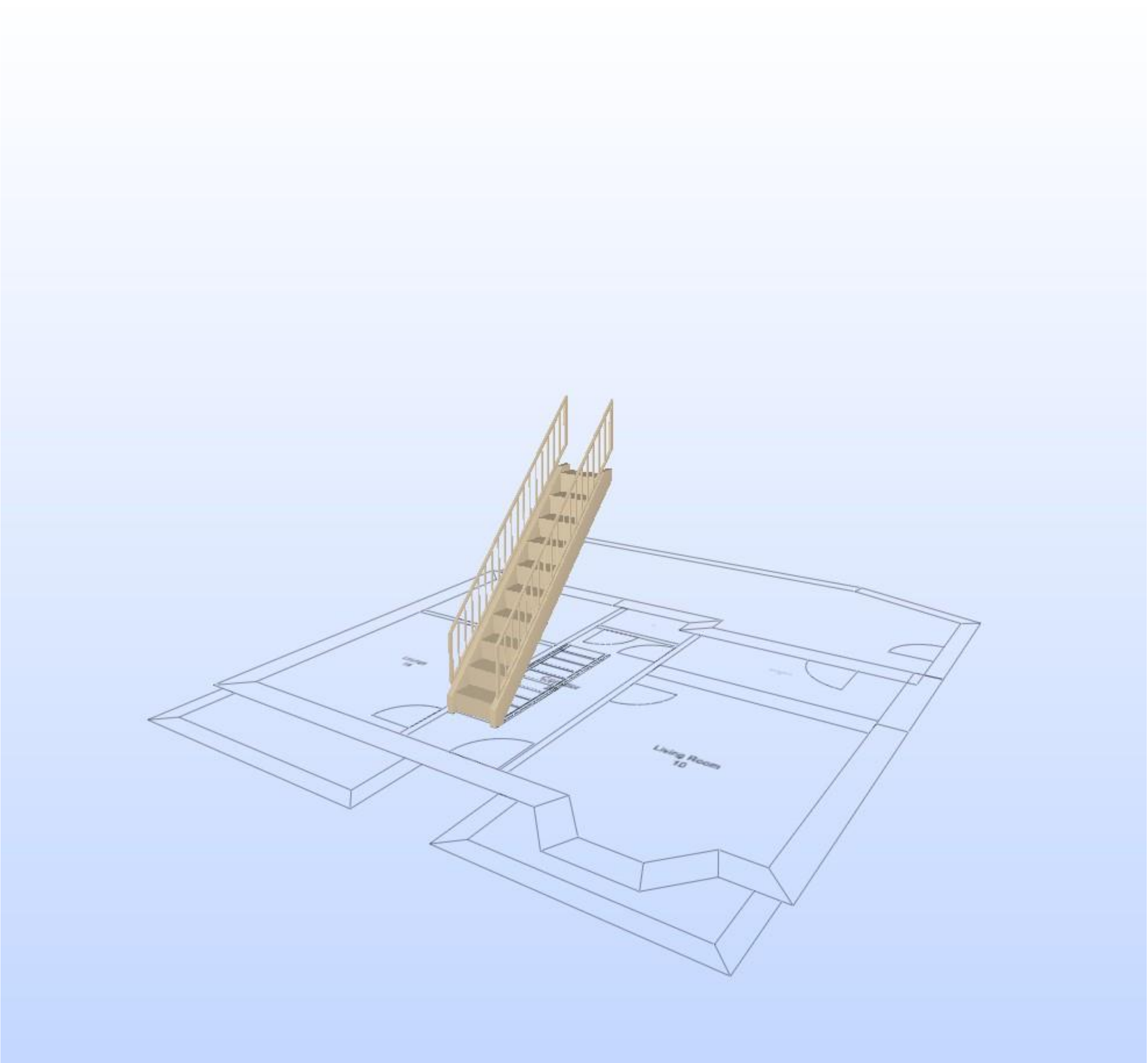
No Construction Types

Required Components

This rule checks that the model contains components of a selected types and they all have a construction type defined.

No Construction Types

Tracking ID: 30



EG, 31-Jan-2017: No impact on energy simulation

31 January2017 Corridor[28]

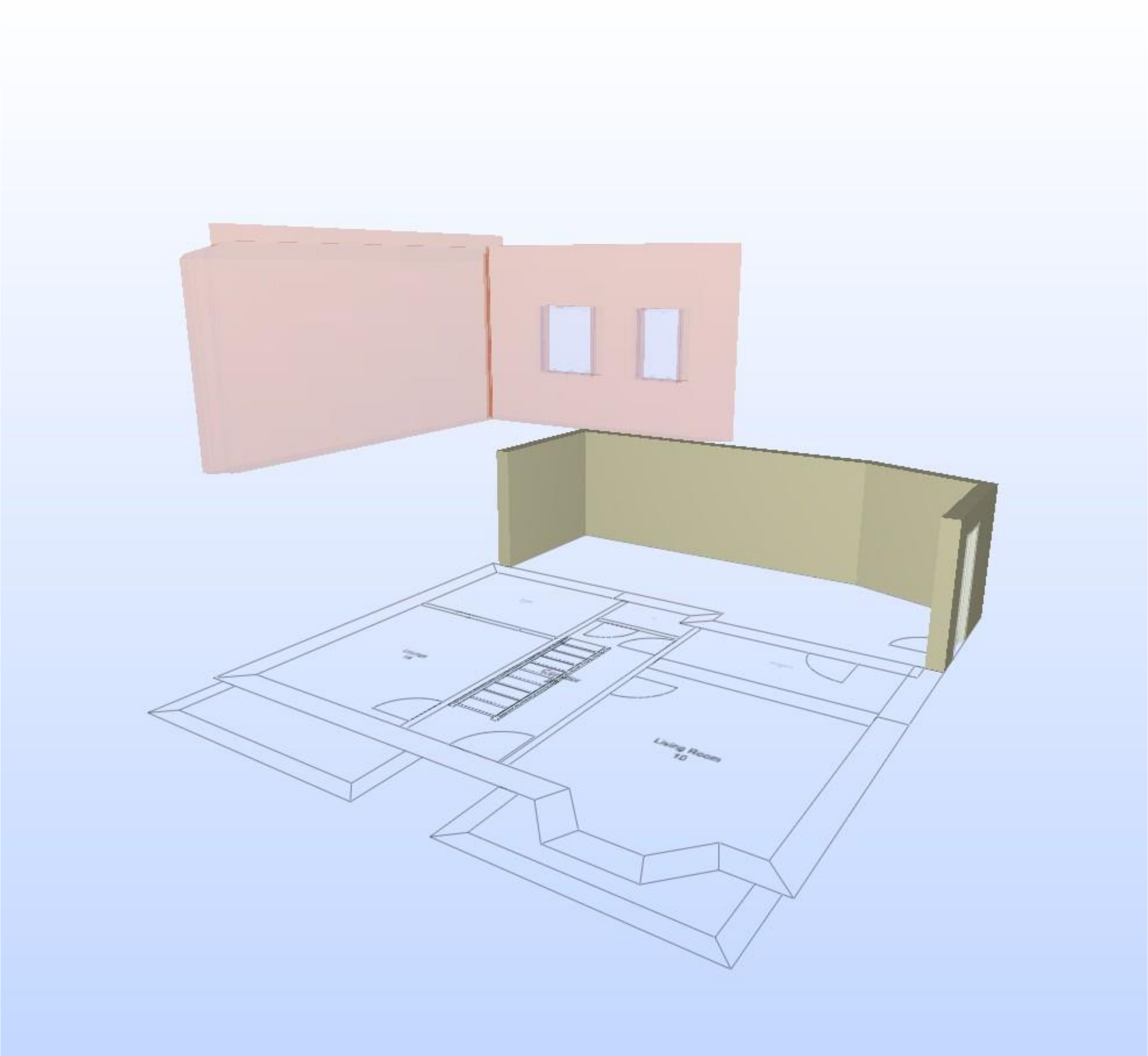
Generic Wall/Shell 300

Components Above Walls

This rule checks that each wall touches slabs, roofs, columns, or walls above itself.

Wall Components don't touch above/Generic Wall/Shell 300

Tracking ID: 31



EG, 31-Jan-2017: Sould be solved- Has impact on energy simulation

Ground Floor Conservatory[12]

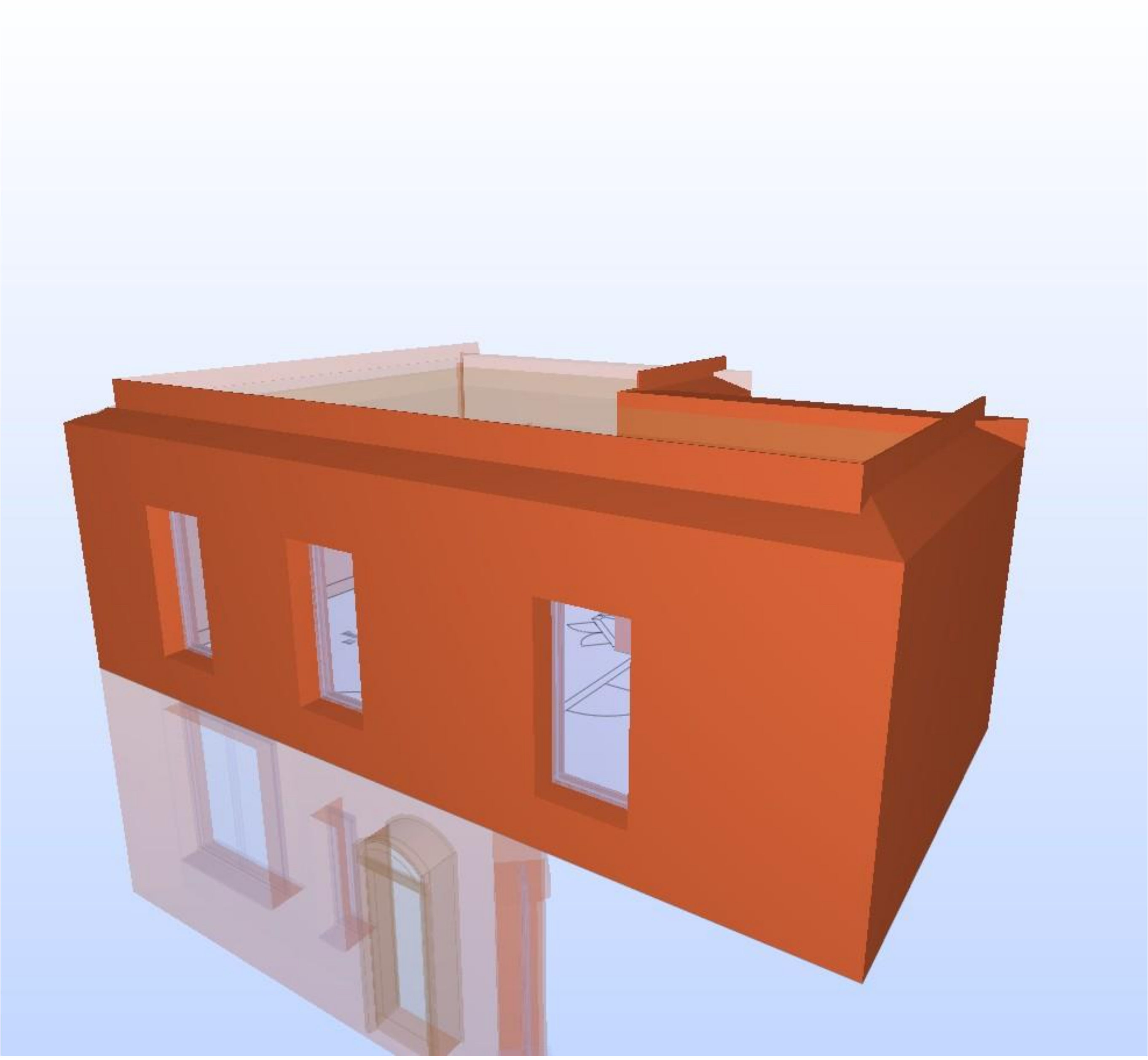
Supa WAll 448

Components Above Walls

This rule checks that each wall touches slabs, roofs, columns, or walls above itself.

Wall Components don't touch above/Supa WAll 448

Tracking ID: 32



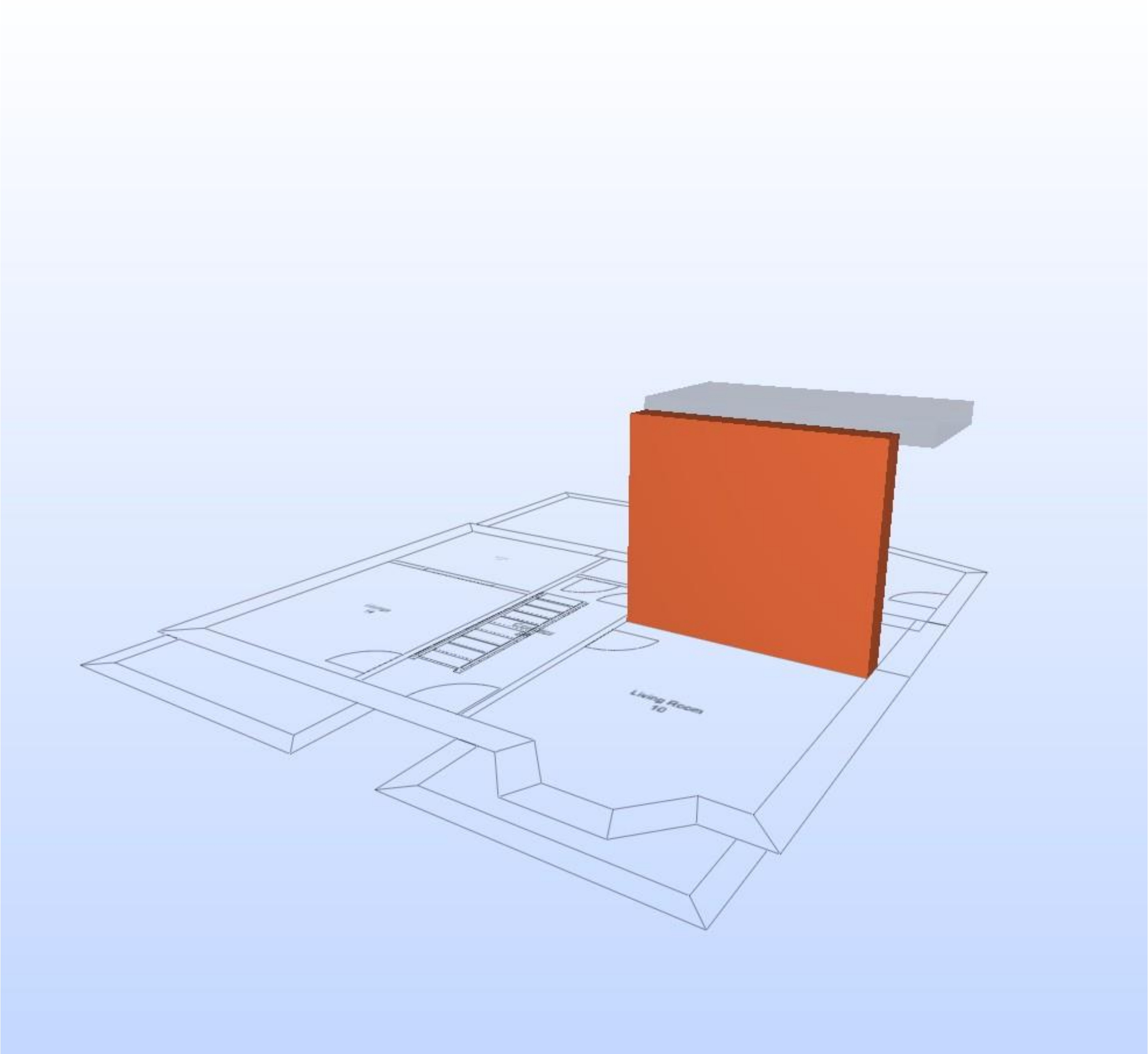
EG, 31-Jan-2017: Sould be solved. Has impact on energy analysis

First Floor Bedroom[22]

Supa WAll 448

Components Above Walls
This rule checks that each wall touches slabs, roofs, columns, or walls above itself.
Wall Components touch above partially/Supa WAll 448

Tracking ID: 33



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor Conservatory[12]

Wall.1.17, 6%

Components Below Walls

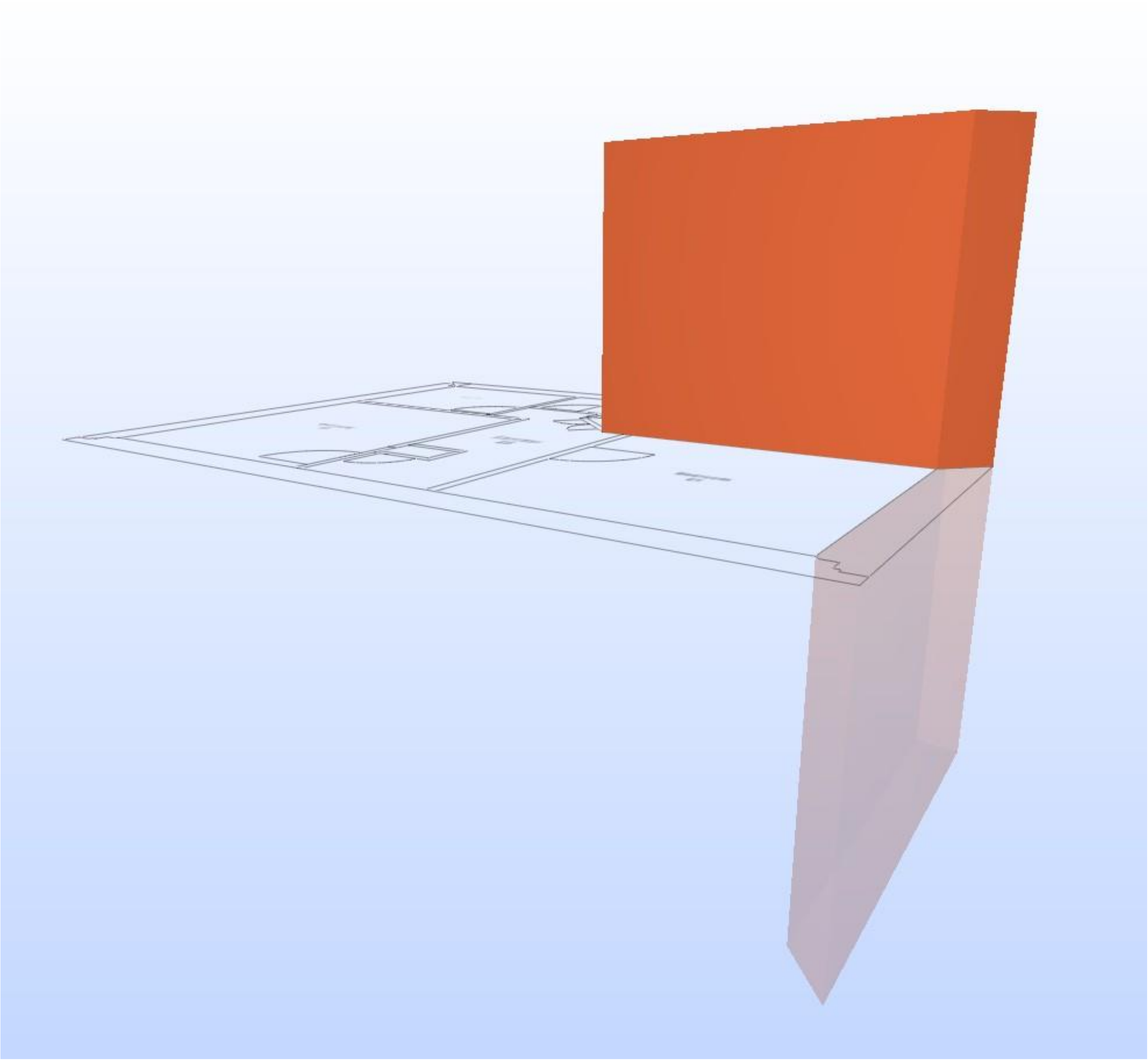
This rule checks that each wall touches slabs, roofs, columns, or walls below itself.

Wall Components touch below partially/Supa WAll 448

Wall.1.17, 6%

Wall.1.17 touches components below itself, but the touching area is only 0.10 m2, which is 6% of the component's surface.

Tracking ID: 34



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

First Floor Corridor[25]

Wall.1.4, 28%

Components Below Walls

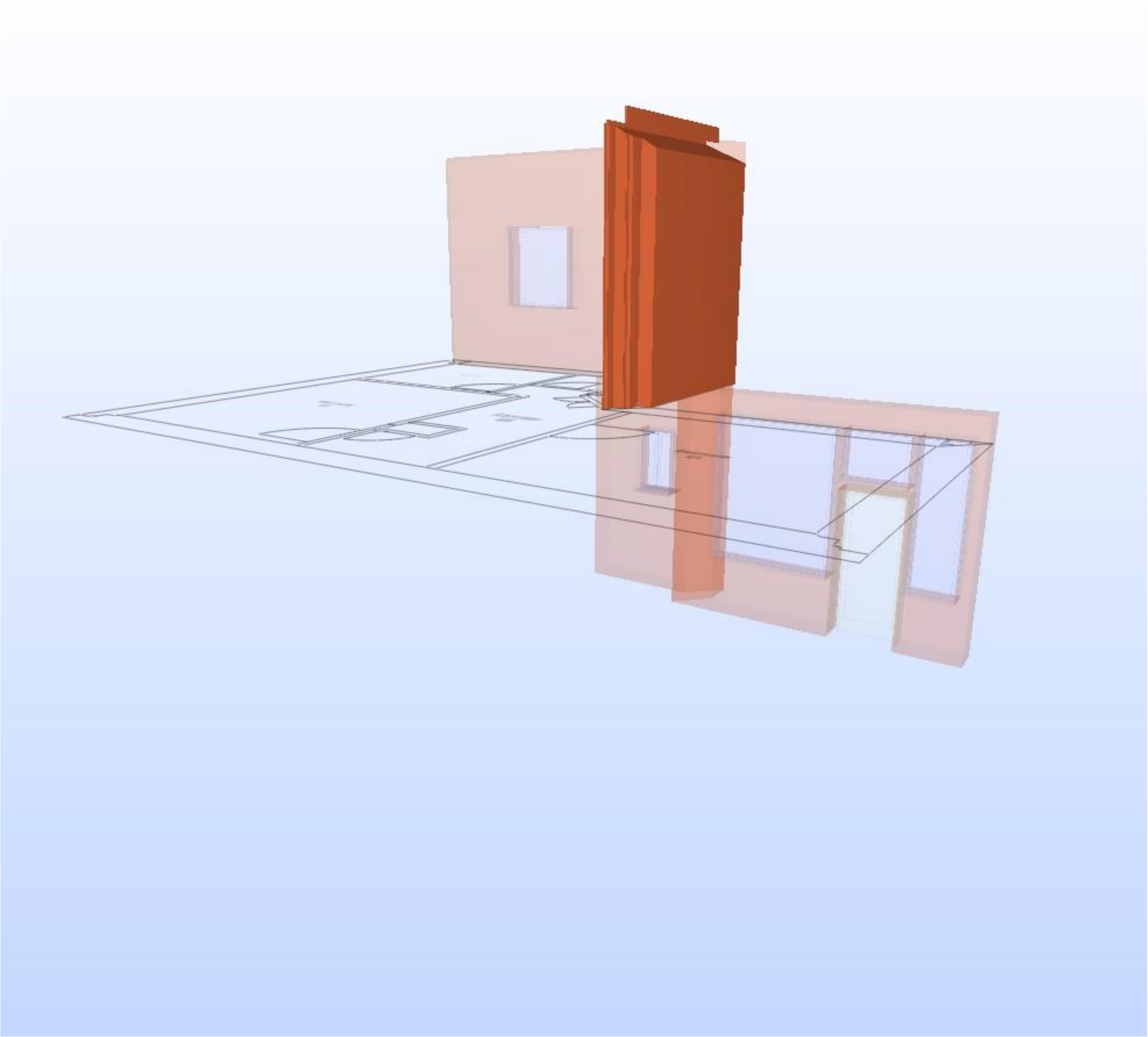
This rule checks that each wall touches slabs, roofs, columns, or walls below itself.

Wall Components touch below partially/Supa WAll 448

Wall.1.4, 28%

Wall.1.4 touches components below itself, but the touching area is only 0.32 m2, which is 28% of the component's surface.

Tracking ID: 35



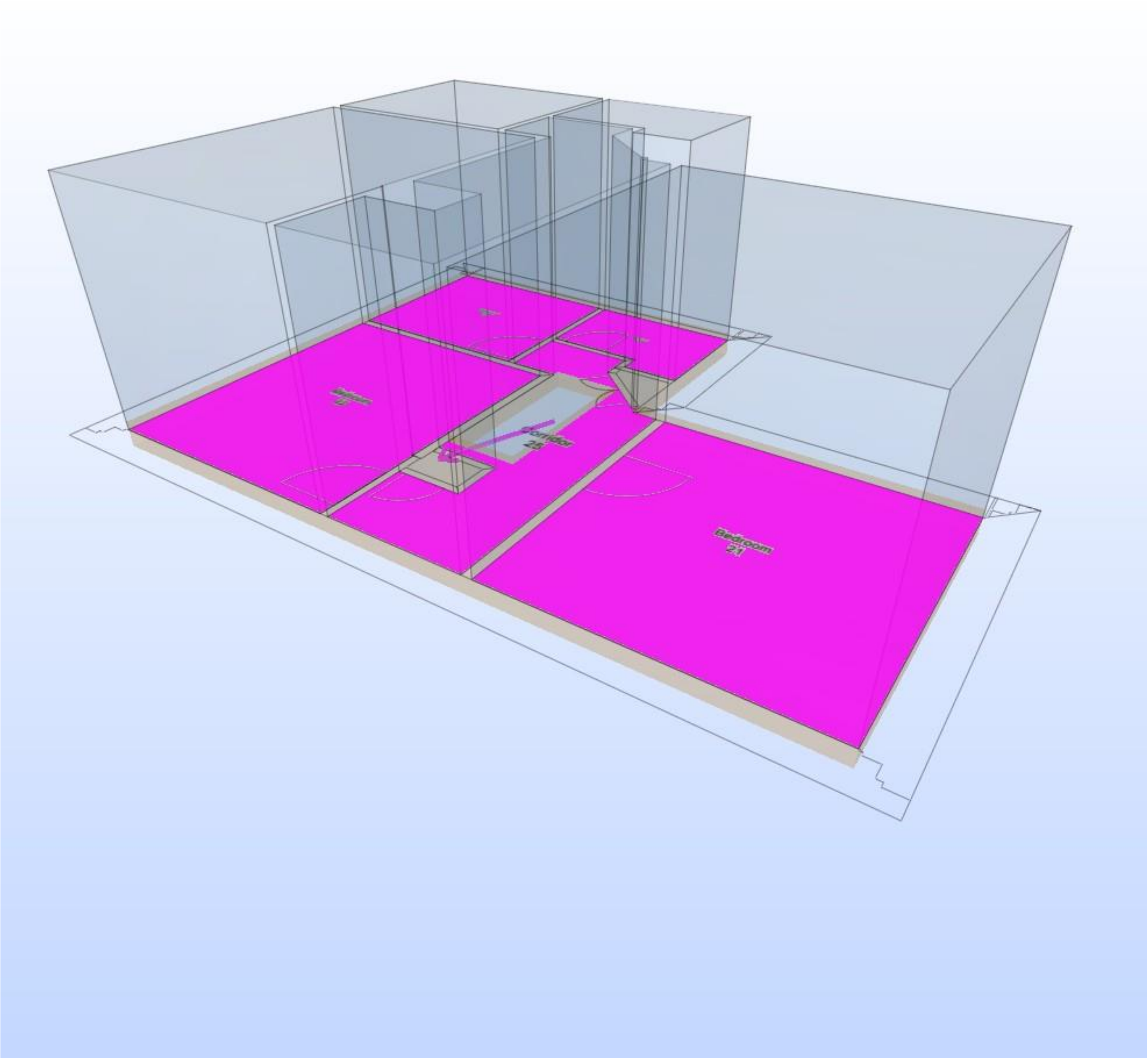
EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

First Floor Corridor[25]

Intersection & Bottom

Space Validation
This rule checks that space geometry and location are correct. It checks that boundaries are near walls, columns or other objects, and space is touching a slab surface above and below itself. It also checks space height and intersections with other components.
Intersection & Bottom

Tracking ID: 36

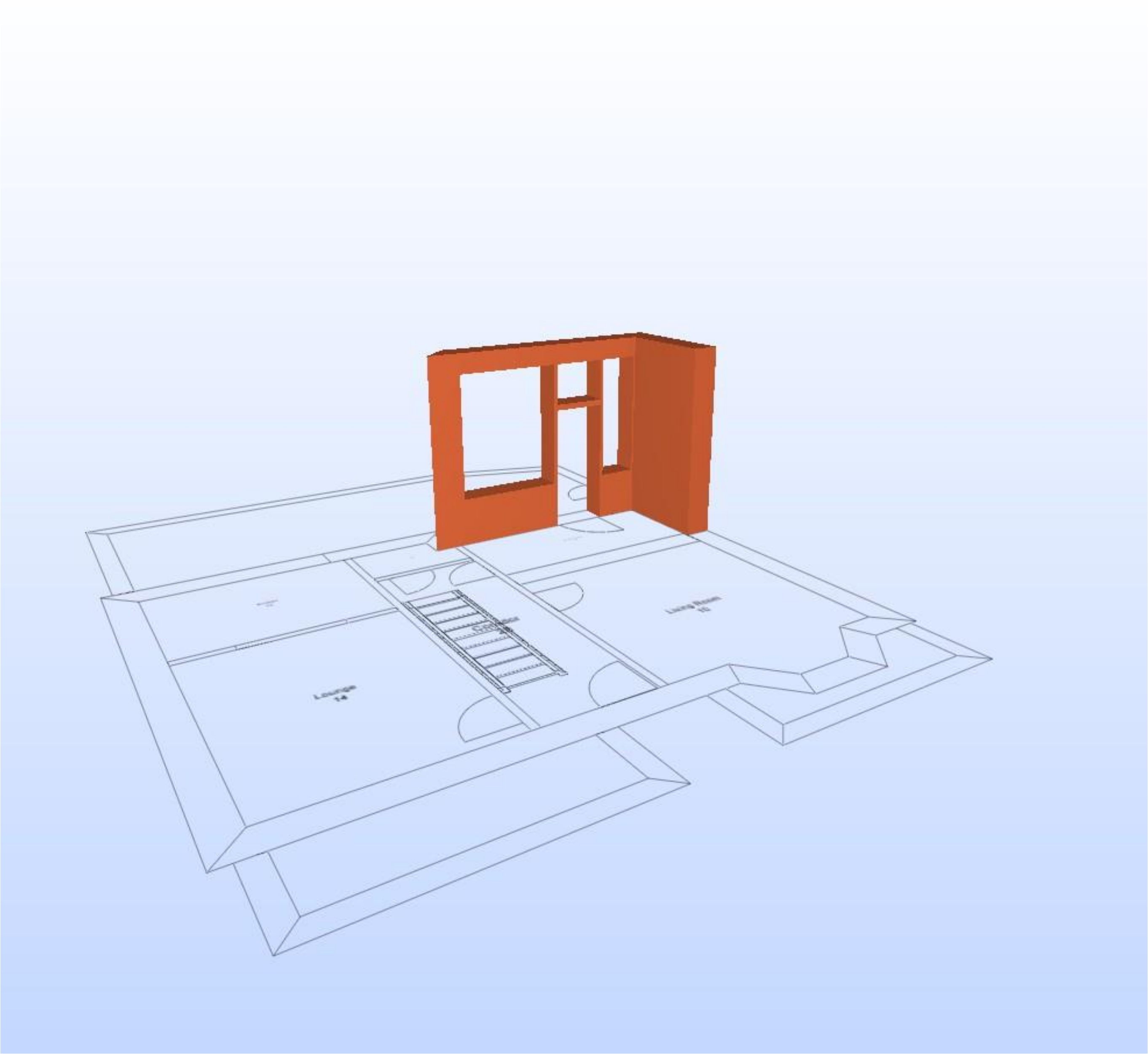


EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
First Floor

Intersecting Components

Wall - Wall Intersections
This rule checks wall - wall intersections.
Intersecting Components

Tracking ID: 37

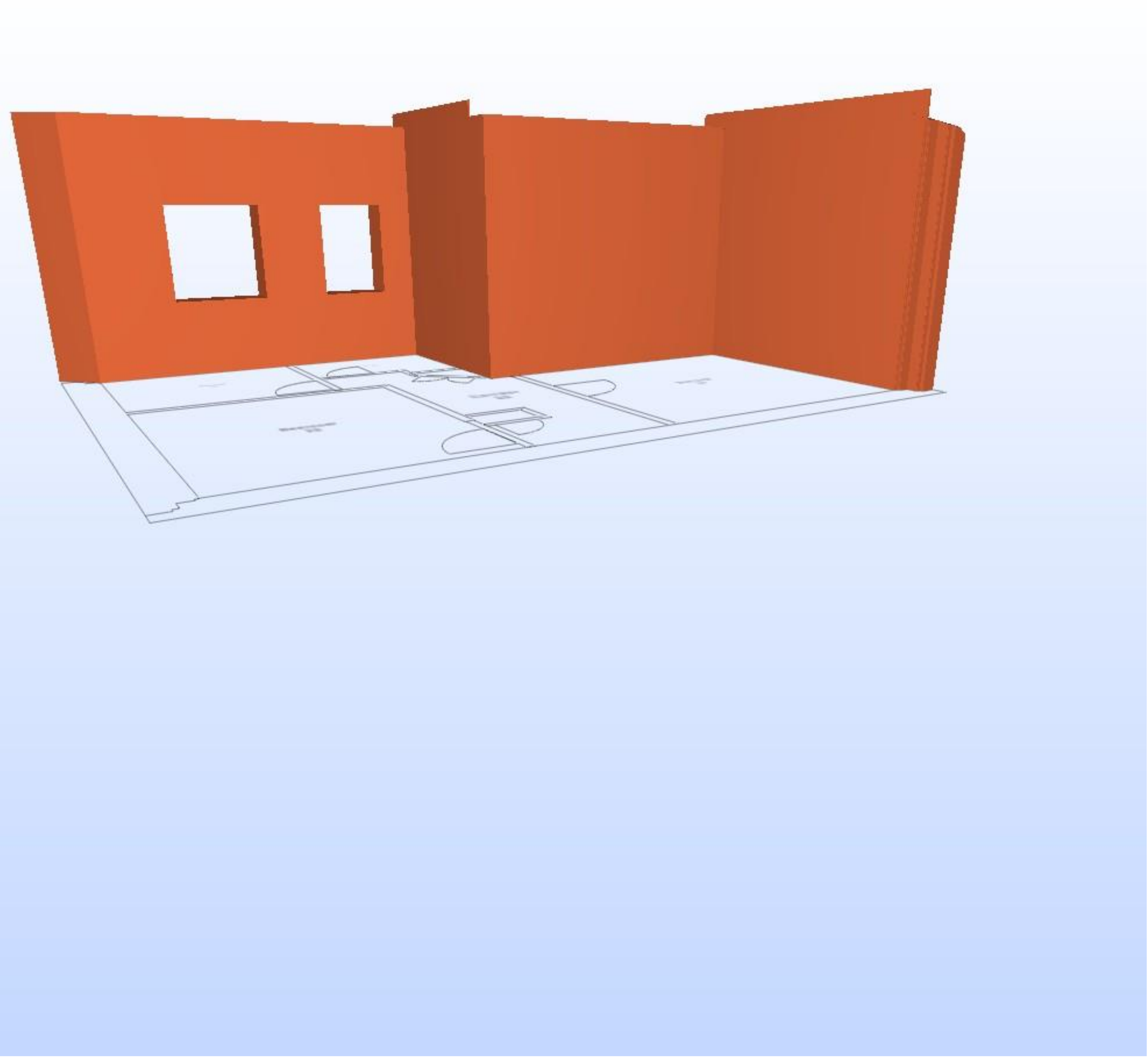


Ground Floor Conservatory[12]

Similar Intersections in One Floor

Wall - Wall Intersections
This rule checks wall - wall intersections.
Similar Intersections in One Floor

Tracking ID: 38

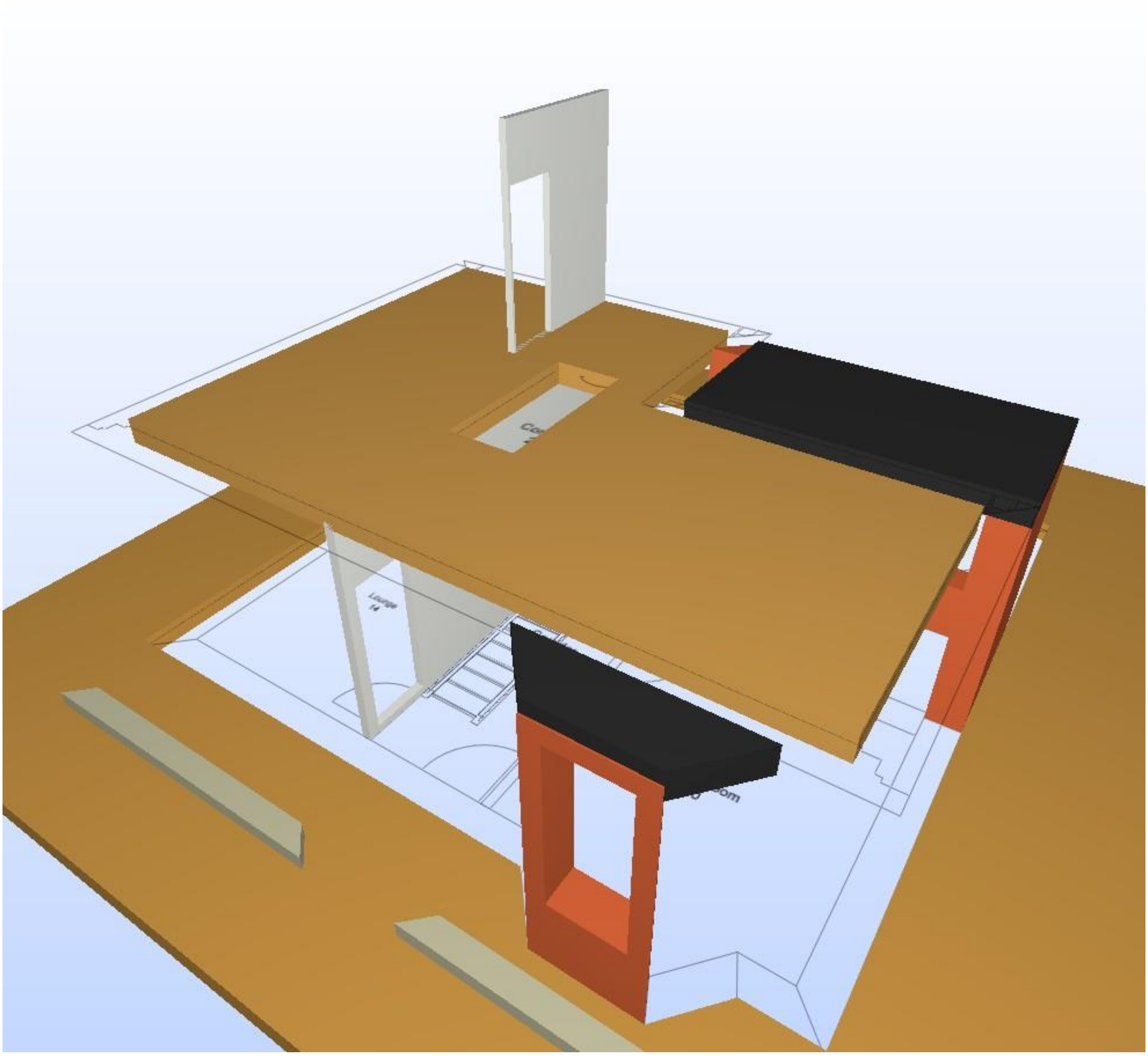


First Floor Corridor[25]

Intersections Between Slab and Wall

Wall Intersections
This rule checks intersections between walls and roofs, slabs, suspended ceilings, and ramps.
Intersections Between Slab and Wall

Tracking ID: 39



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor, First Floor

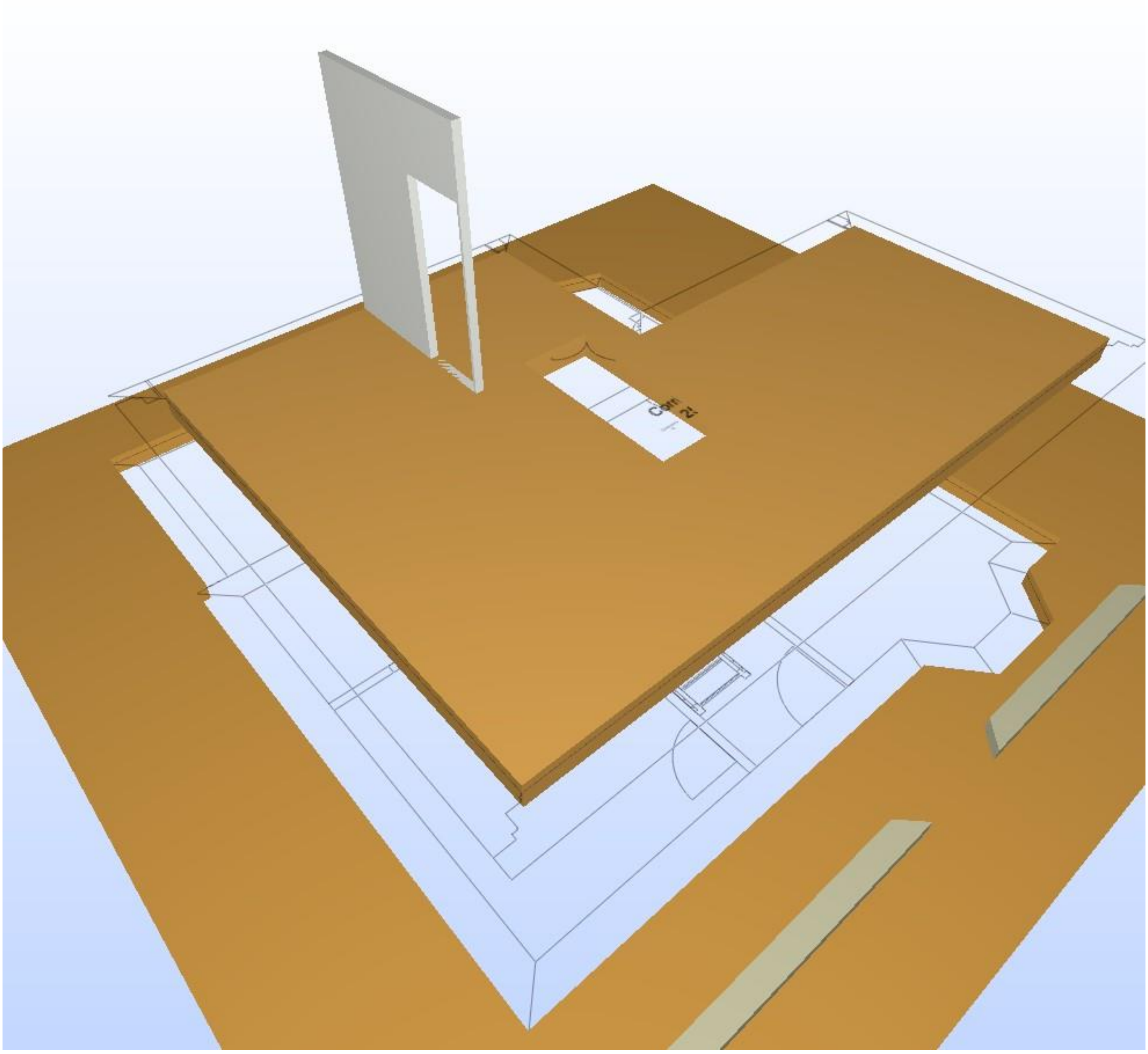
Intersecting Components

Wall Intersections

This rule checks intersections between walls and roofs, slabs, suspended ceilings, and ramps.

Intersections Between Slab and Wall/Intersecting Components

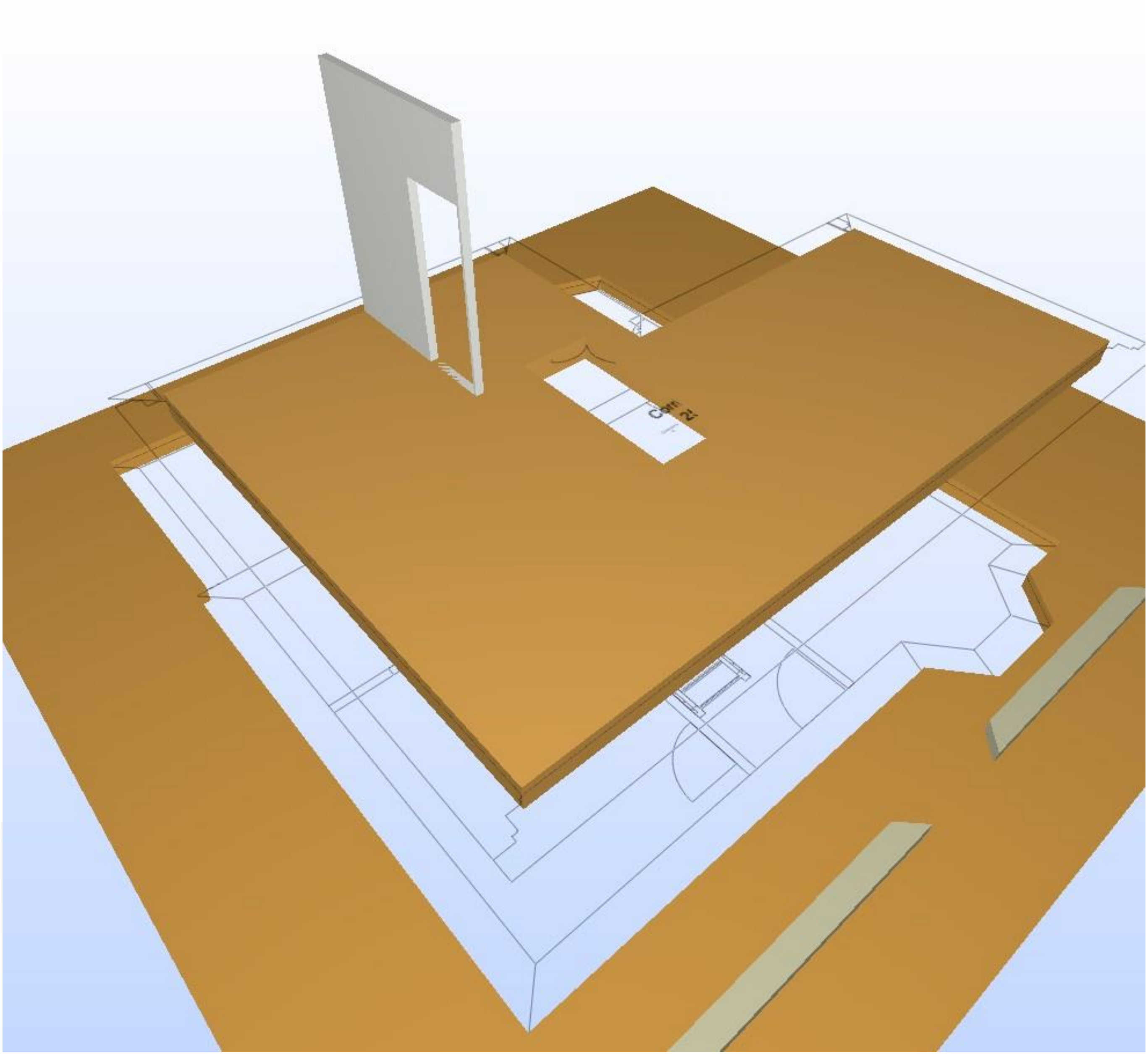
Tracking ID: 40



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

Ground Floor, First Floor

Tracking ID: 40



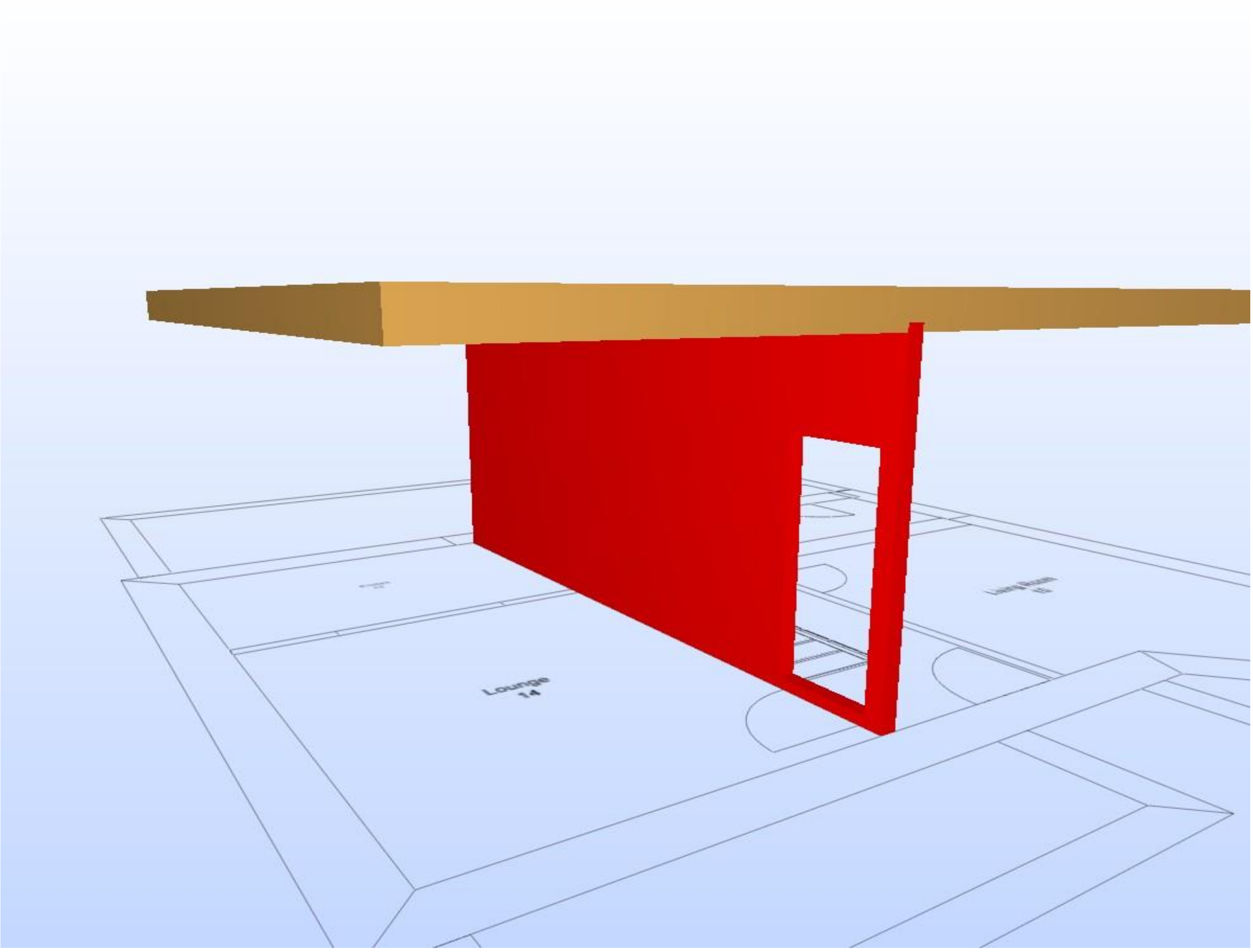
EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

Ground Floor, First Floor

Slab.1.3 (Concrete Floor Insulated with Parquet 310) and Wall.0.27 (100 Block Double Plastered 125) are intersecting

Wall Intersections
This rule checks intersections between walls and roofs, slabs, suspended ceilings, and ramps.
Intersections Between Slab and Wall/Intersecting Components in Different Floors/100 Block Double Plastered 125 and Concrete Floor Insulated with Parquet 310
Slab.1.3 (Concrete Floor Insulated with Parquet 310) and Wall.0.27 (100 Block Double Plastered 125) are intersecting
The depth, width, height, and volume of the intersections are:
Wall.0.27, Slab.1.3, 125 mm, 125 mm, 70 mm, 52 l

Tracking ID: 41

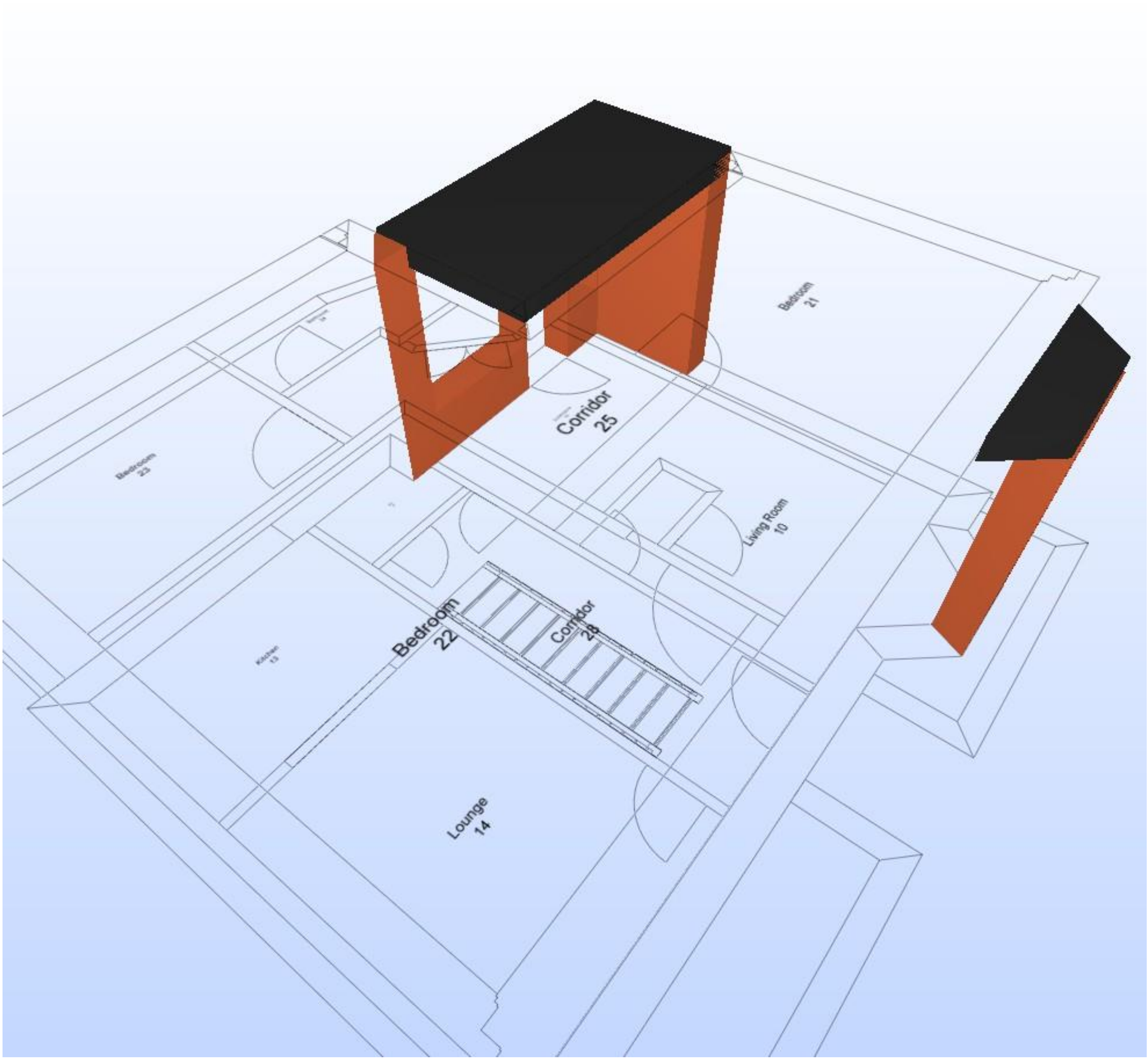


EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor Corridor[28]

Supa Ceiling Bl 319 and Supa WAll 448

Wall Intersections
This rule checks intersections between walls and roofs, slabs, suspended ceilings, and ramps.
Intersections Between Slab and Wall/Intersecting Components in Different Floors/Supa Ceiling Bl 319 and Supa WAll 448

Tracking ID: 42



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor, First Floor Conservatory[12]

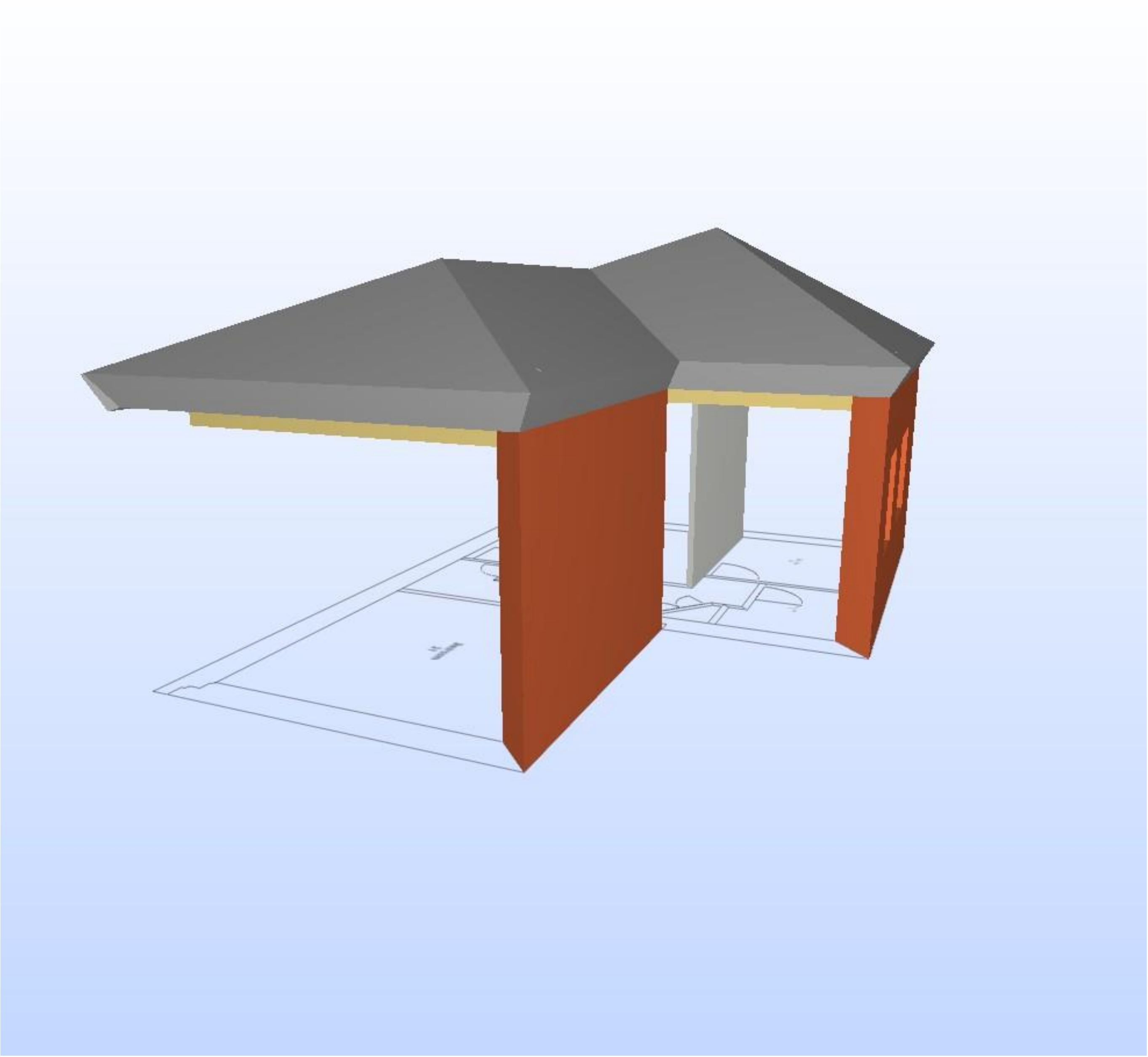
Intersections Between Roof and Wall

Wall Intersections

This rule checks intersections between walls and roofs, slabs, suspended ceilings, and ramps.

Intersections Between Roof and Wall

Tracking ID: 43



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

First Floor, Roof

'Residential and Recreation'

Space Names Must Be from Agreed List

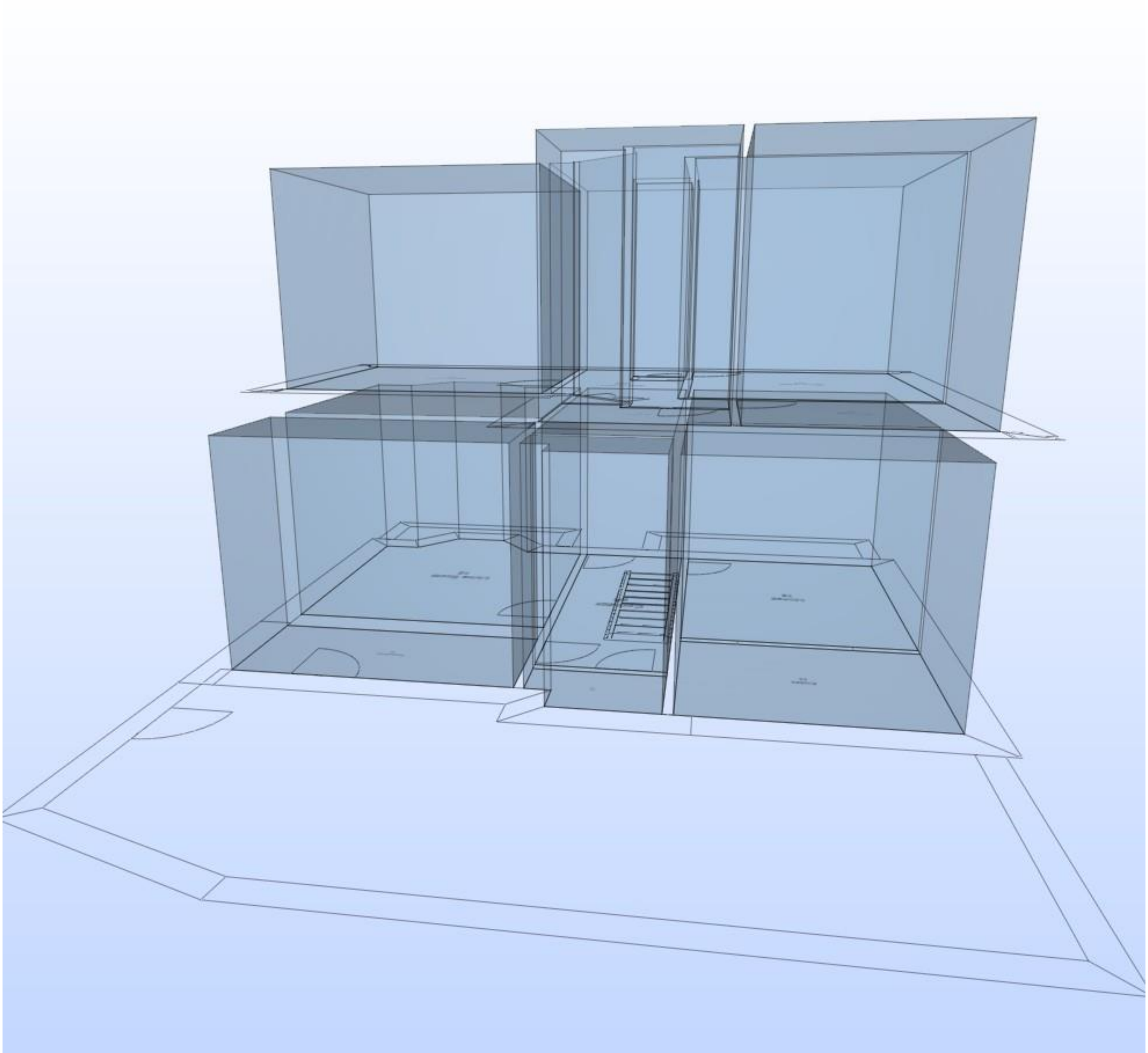
This rule checks, that the model contains only agreed space names. The rule has to be parameterized by used space names.The space name list can be read from an Excel sheet.

Unknown Spaces

'Residential and Recreation'

Unknown spaces, which name is 'Residential and Recreation'.

Tracking ID: 44

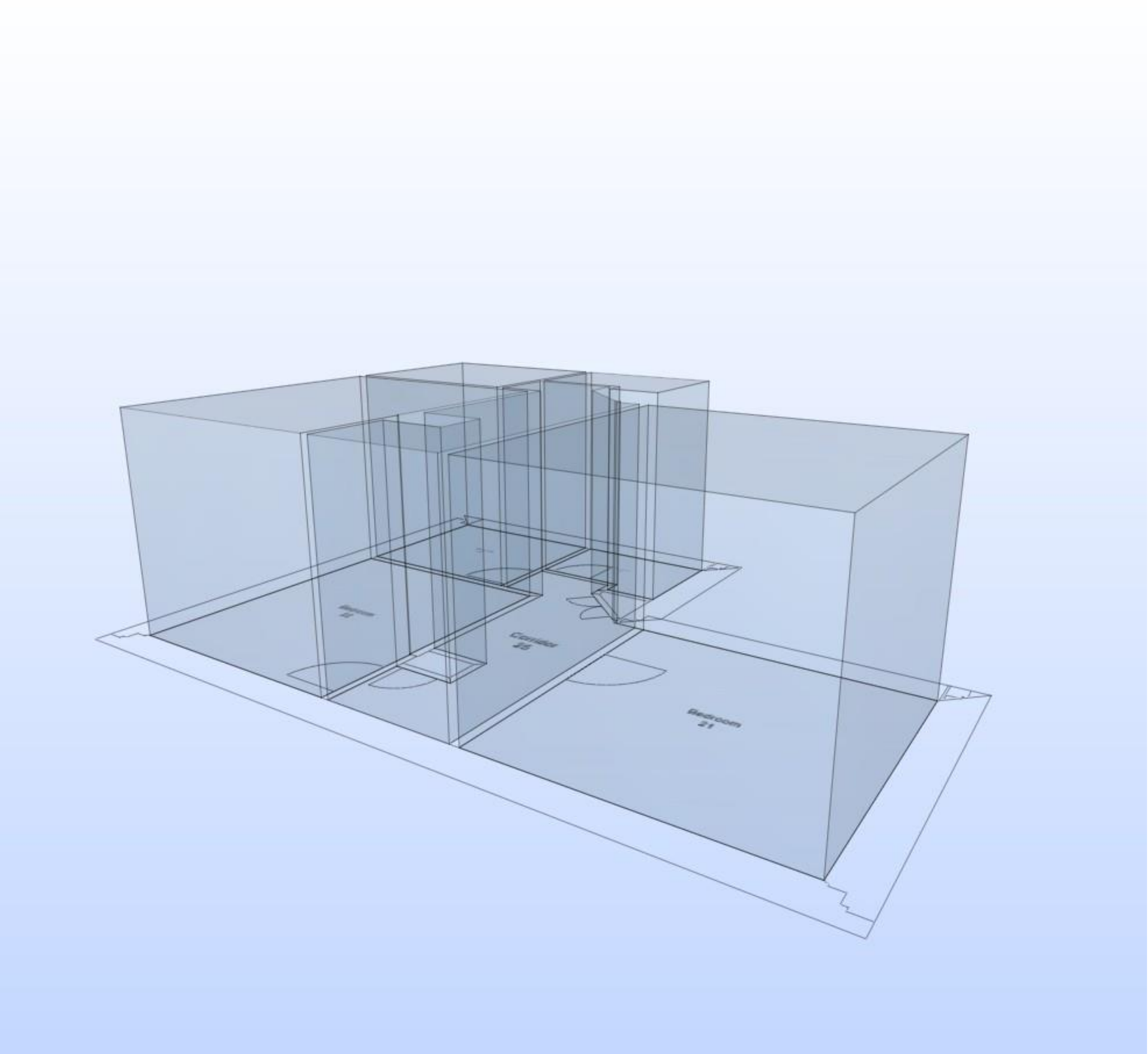


Ground Floor, First Floor

Bottom

Space Validation
This rule checks that space geometry and location are correct. It checks that boundaries are near walls, columns or other objects, and space is touching a slab surface above and below itself. It also checks space height and intersections with other components.Spaces intersecting each other, or inside each other are not accepted. SPACE INTERSECTION Category is important.In Energy analysis it is ofen important that space perimeters touch walls around themselves. BOUNDARY Category is important.
Bottom

Tracking ID: 45

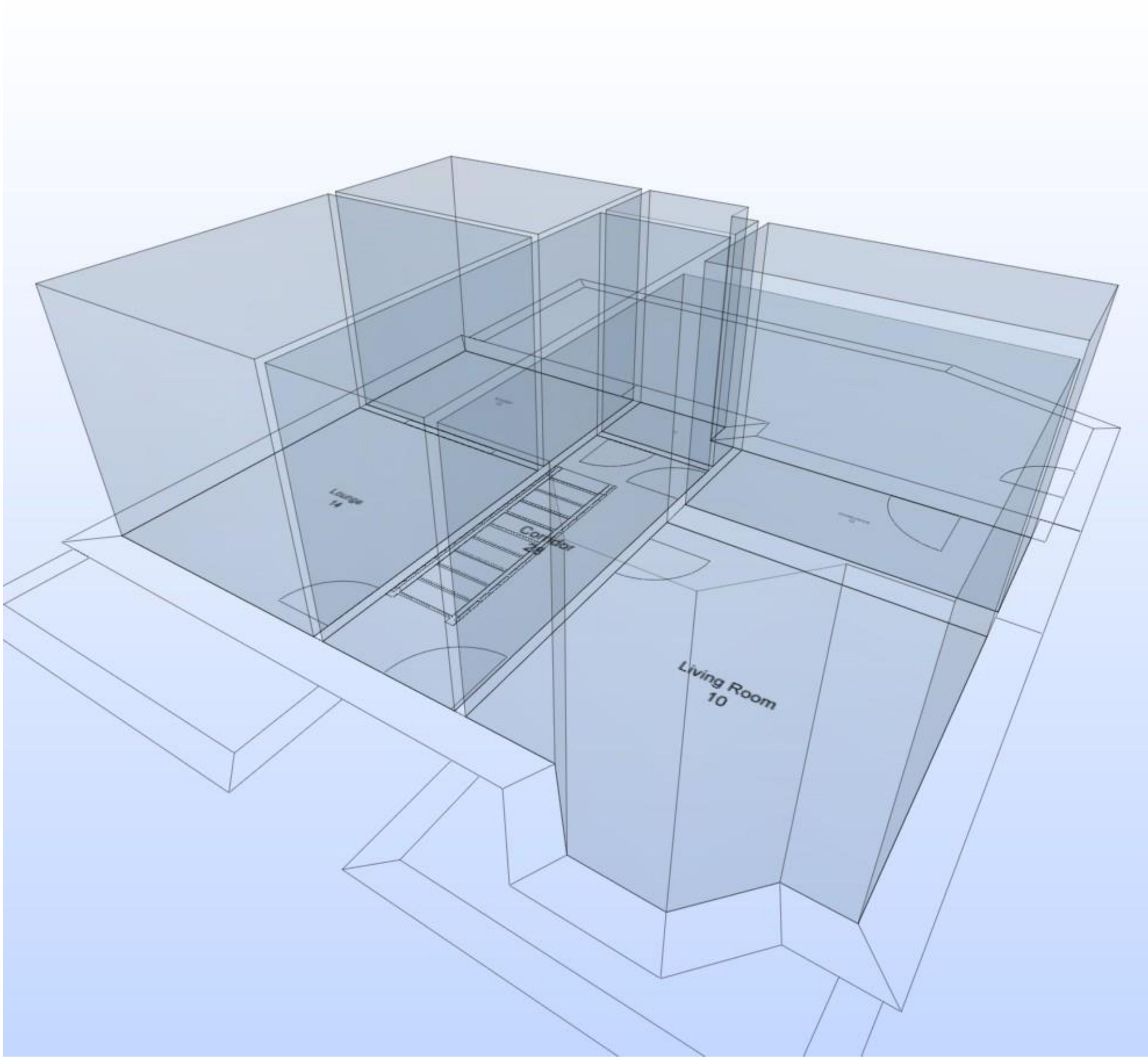


EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
First Floor

Top

Space Validation
This rule checks that space geometry and location are correct. It checks that boundaries are near walls, columns or other objects, and space is touching a slab surface above and below itself. It also checks space height and intersections with other components.Spaces intersecting each other, or inside each other are not accepted. SPACE INTERSECTION Category is important.In Energy analysis it is ofen important that space perimeters touch walls around themselves. BOUNDARY Category is important.
Top

Tracking ID: 46

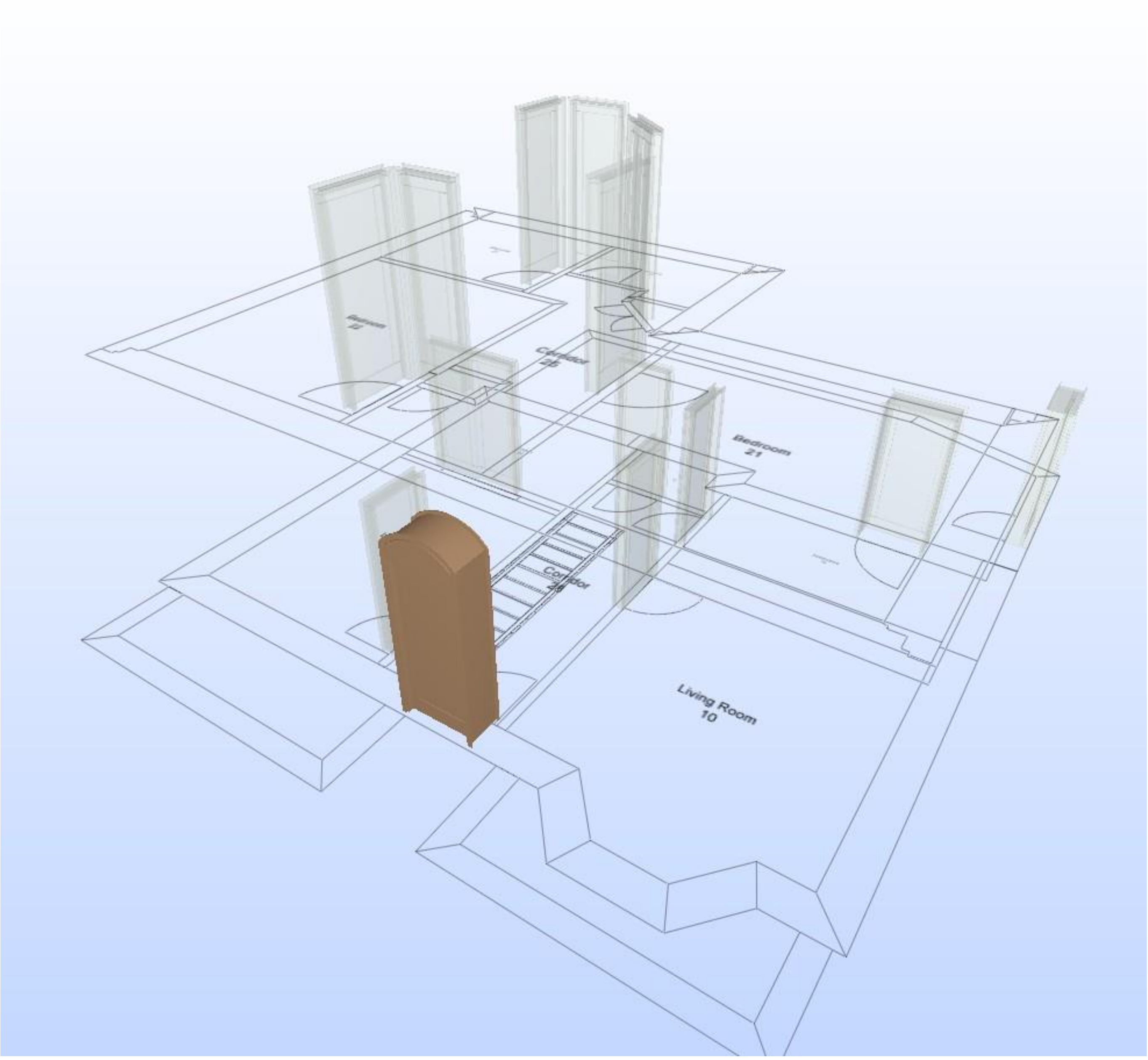


EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor

Door

Doors and Windows Must Be Connected to Spaces
This rule checks that all doors have Referencing relation at least to one space.
Door

Tracking ID: 47

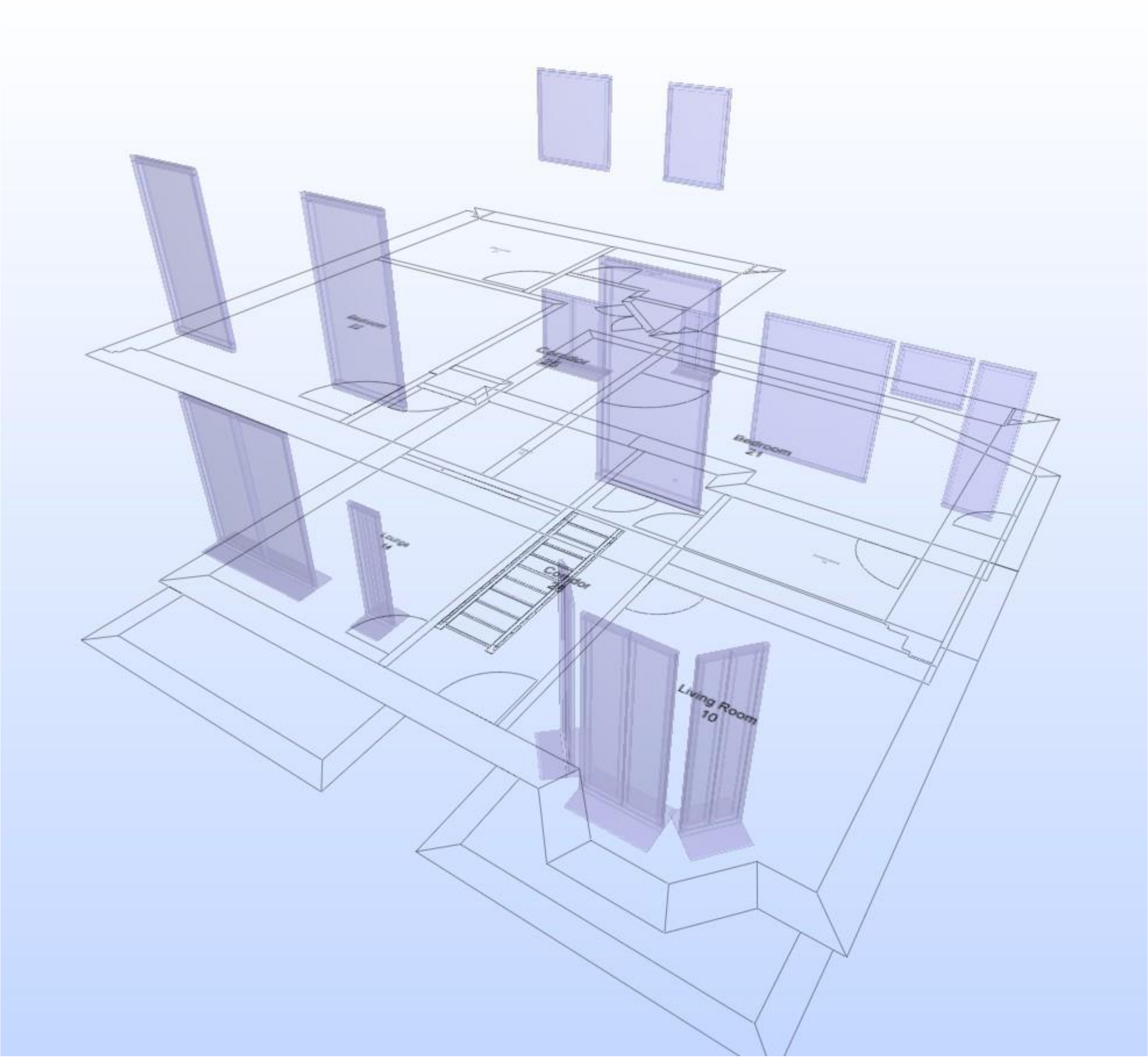


EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor, First Floor Corridor[28]

Window

Doors and Windows Must Be Connected to Spaces
This rule checks that all doors have Referencing relation at least to one space.
Window

Tracking ID: 48



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor, First Floor

Building Envelope

External Wall Validation

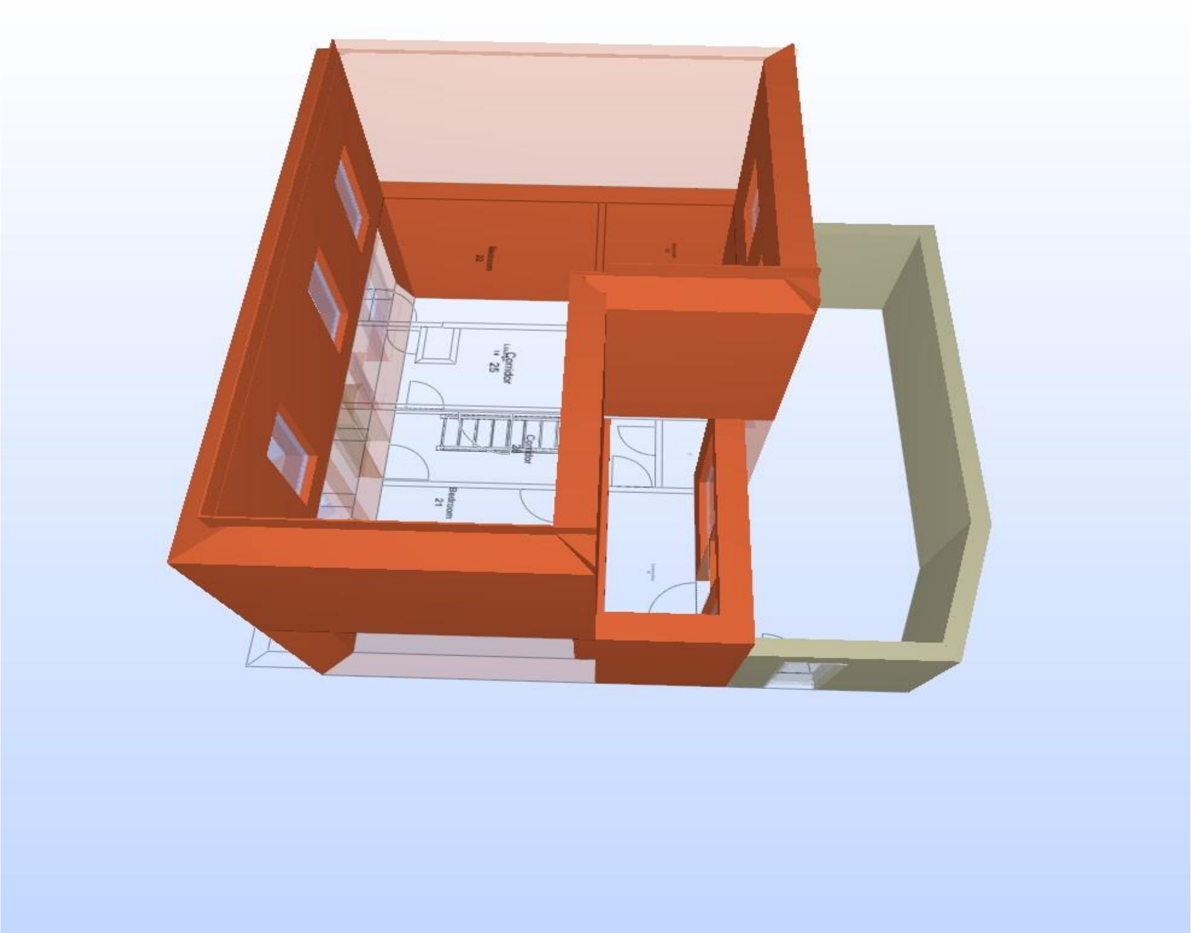
This rule checks that external walls defined in then model (ref. Is External property in the Info View of a wall) are same as walls surrounding gross area spaces and/or all spaces in the model. You can manually set external walls in the Compartmentation View.In Energy Analysis this rule is used to because doors and windows has to be related to spaces. And a door or a window in external wall has to be related only one space - it has to be known what walls are external walls.Please define external walls when needed by using Tools View of this rule, or directly from the Compartmentation View.

Building Envelope Elements Around Spaces Differ from Building Envelope

Building Envelope

Building envelope elements around Spaces differ from defined Building Envelope. Building envelope elements are attached to this issue. You can set building envelope elements in the Tools View.

Tracking ID: 49



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

Ground Floor, First Floor Living Room[10]

Building Envelope Elements Around Spaces

External Wall Validation

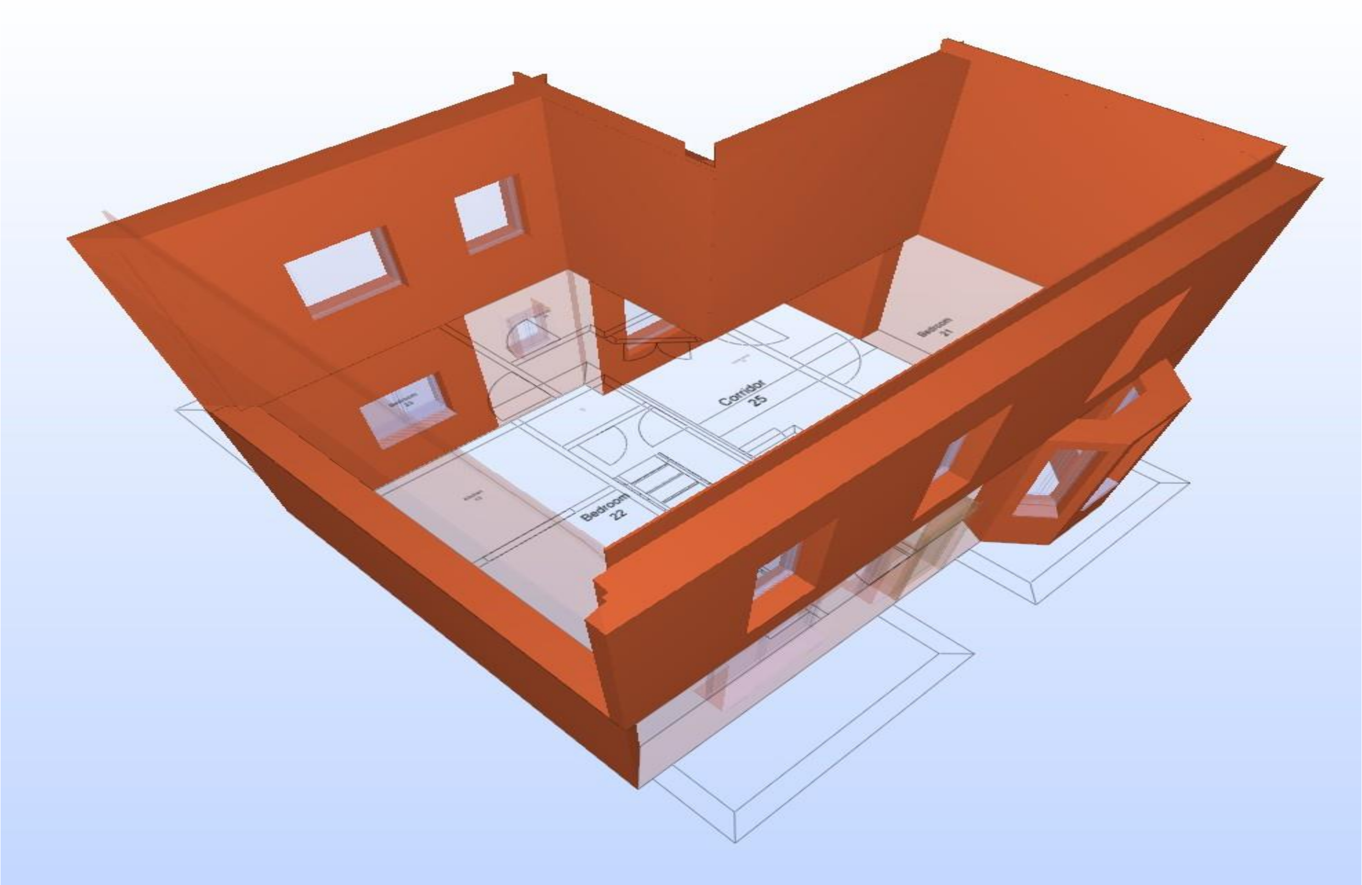
This rule checks that external walls defined in then model (ref. Is External property in the Info View of a wall) are same as walls surrounding gross area spaces and/or all spaces in the model. You can manually set external walls in the Compartmentation View.In Energy Analysis this rule is used to because doors and windows has to be related to spaces. And a door or a window in external wall has to be related only one space - it has to be known what walls are external walls.Please define external walls when needed by using Tools View of this rule, or directly from the Compartmentation View.

Building Envelope Elements Around Spaces Differ from Building Envelope

Building Envelope Elements Around Spaces

Building envelope elements around Spaces differ from defined Building Envelope. Building envelope elements around spaces are attached to this issue. You can set building envelope elements in the Tools View.

Tracking ID: 50



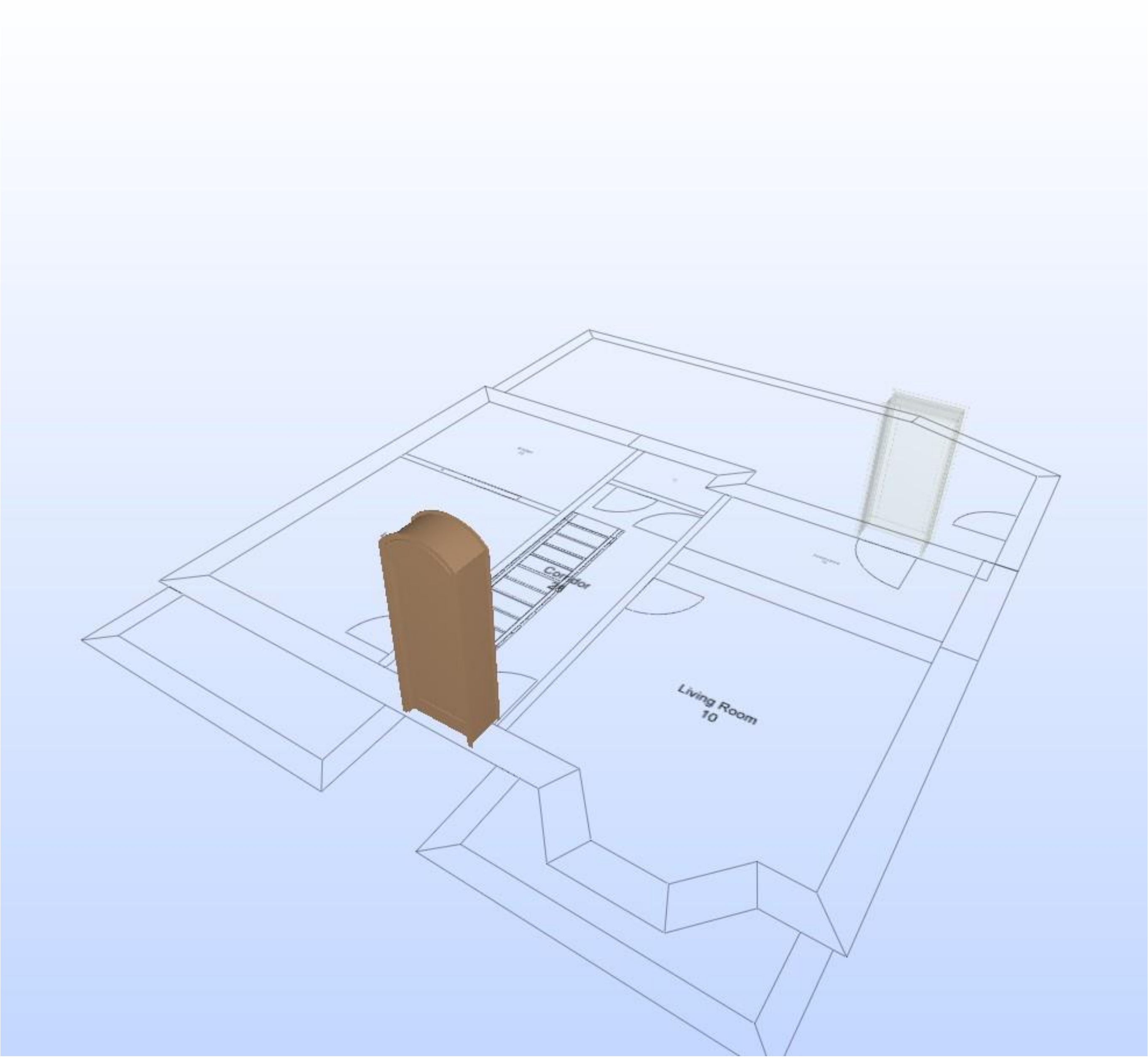
EG, 31-Jan-2017: Should be solved. Has impact on energy simulation

Ground Floor, First Floor Living Room[10]

Door

External Doors Must Be Connected to One Space
This rule checks that all external doors have Referencing relation only to one space.
Door

Tracking ID: 51

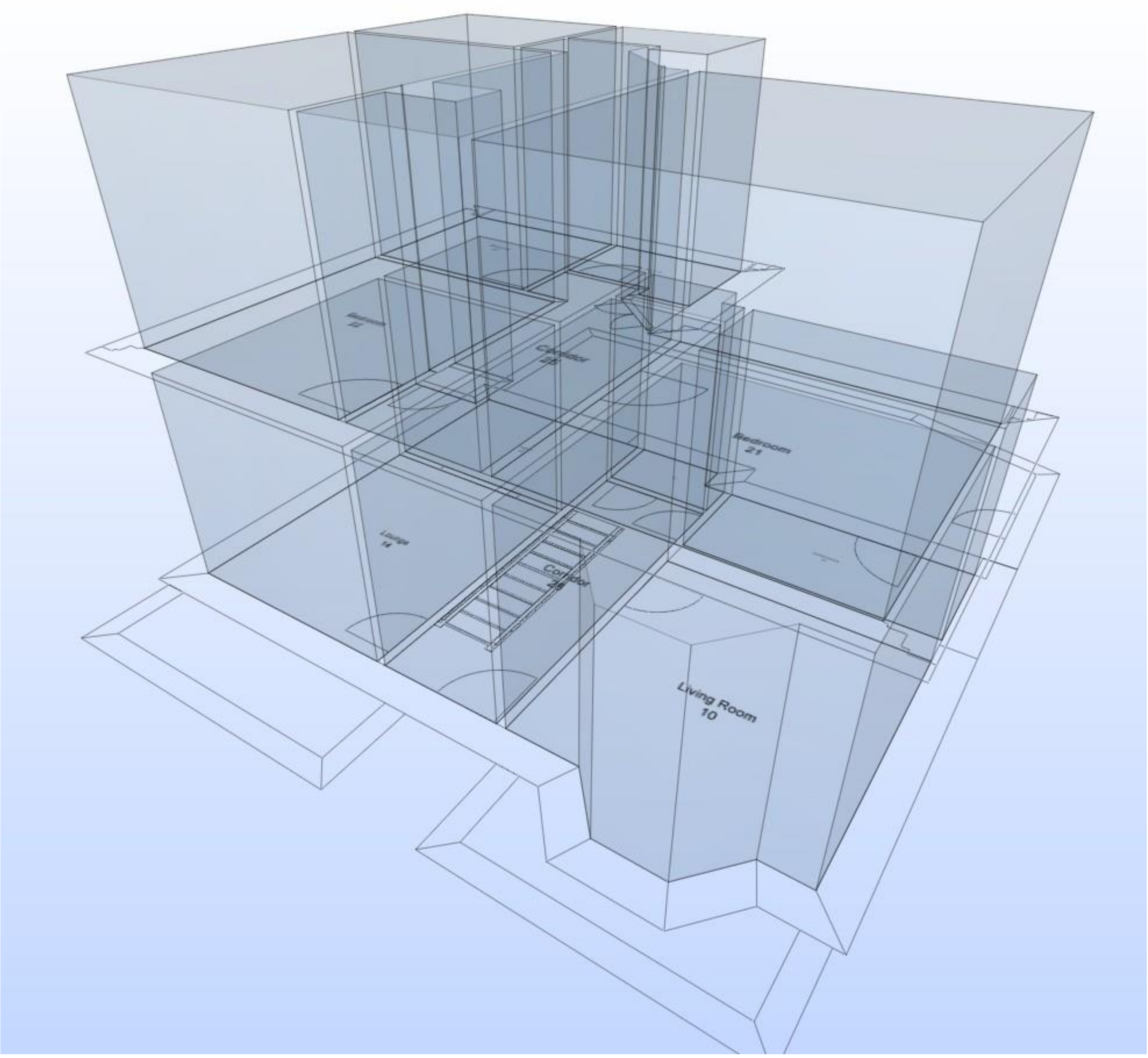


EG, 31-Jan-2017: Should be solved. Has impact on energy simulation
Ground Floor Corridor[28]

Space Boundary Problems

Space Boundaries
There must be space boundary components between spaces and walls (and other components) around them.
Space Boundary Problems

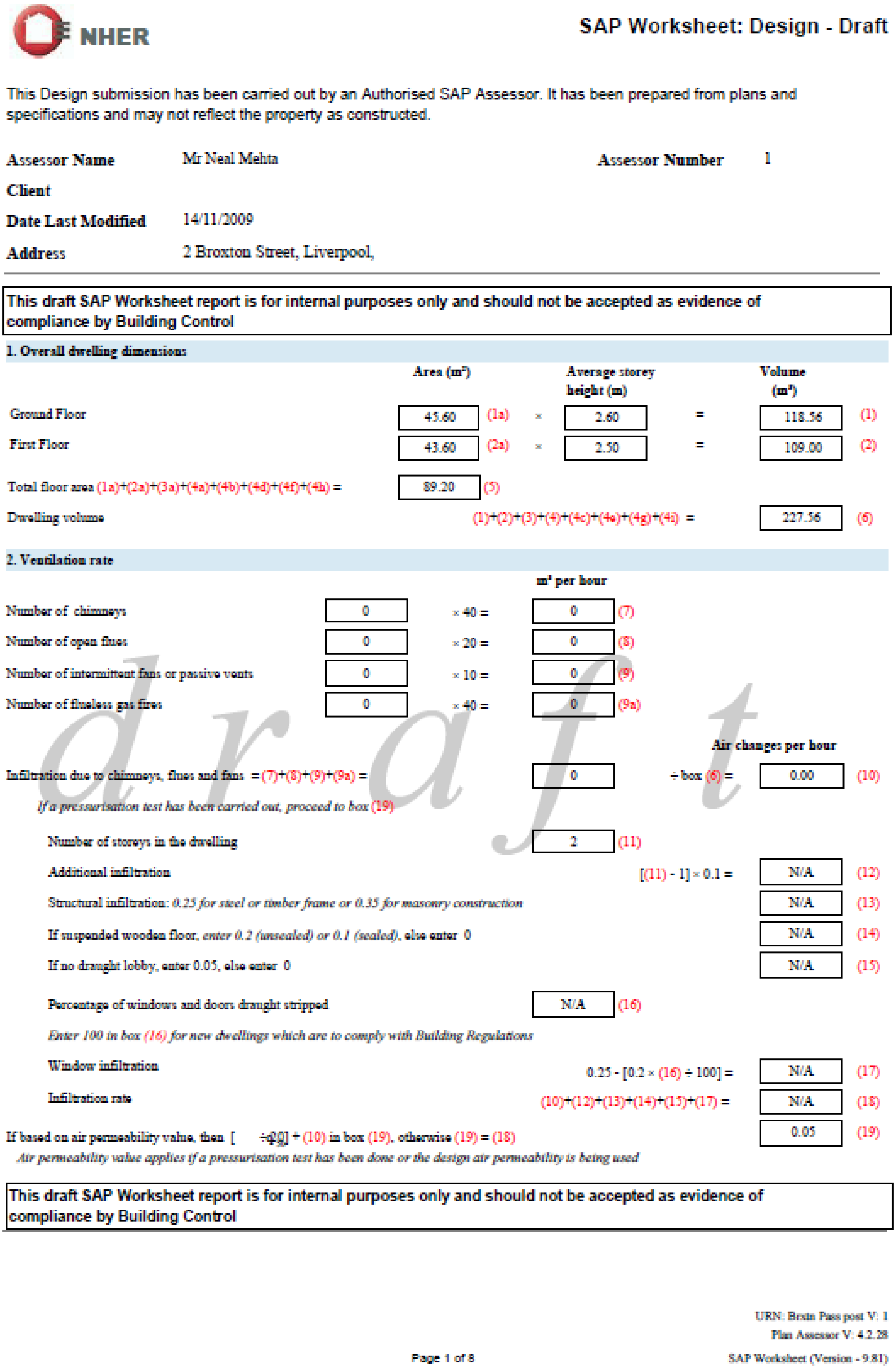
Tracking ID: 52



EG, 31-Jan-2017: Should be solved. Has impact on energy simulation Ground Floor, First Floor

Appendices

Appendix C: SAP Worksheet: Design - Draft



NHER

SAP Worksheet: Design - Draft

This Design submission has been carried out by an Authorised SAP Assessor. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor Name	Mr Neal Mehta	**Assessor Number**	1
Client			
Date Last Modified	14/11/2009		
Address	2 Broxton Street, Liverpool,		

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1. Overall dwelling dimensions

	Area (m²)			Average storey height (m)		Volume (m³)	
Ground Floor	45.60	(1a)	×	2.60	=	118.56	(1)
First Floor	43.60	(2a)	×	2.50	=	109.00	(2)
Total floor area (1a)+(2a)+(3a)+(4a)+(4b)+(4d)+(4f)+(4h) =	89.20	(5)					
Dwelling volume				(1)+(2)+(3)+(4)+(4c)+(4e)+(4g)+(4i)	=	227.56	(6)

2. Ventilation rate

			m³ per hour	
Number of chimneys	0	× 40 =	0	(7)
Number of open flues	0	× 20 =	0	(8)
Number of intermittent fans or passive vents	0	× 10 =	0	(9)
Number of flueless gas fires	0	× 40 =	0	(9a)

	m³ per hour		Air changes per hour	
Infiltration due to chimneys, flues and fans = (7)+(8)+(9)+(9a) =	0	÷ box (6) =	0.00	(10)

If a pressurisation test has been carried out, proceed to box (19)

Number of storeys in the dwelling	2	(11)		
Additional infiltration		[(11) - 1] × 0.1 =	N/A	(12)
Structural infiltration: *0.25 for steel or timber frame or 0.35 for masonry construction*			N/A	(13)
If suspended wooden floor, *enter 0.2 (unsealed) or 0.1 (sealed)*, else enter 0			N/A	(14)
If no draught lobby, enter 0.05, else enter 0			N/A	(15)
Percentage of windows and doors draught stripped	N/A	(16)		

Enter 100 in box (16) for new dwellings which are to comply with Building Regulations

Window infiltration	0.25 - [0.2 × (16) ÷ 100] =	N/A	(17)
Infiltration rate	(10)+(12)+(13)+(14)+(15)+(17) =	N/A	(18)
If based on air permeability value, then [÷20] + (10) in box (19), otherwise (19) = (18)		0.05	(19)

Air permeability value applies if a pressurisation test has been done or the design air permeability is being used

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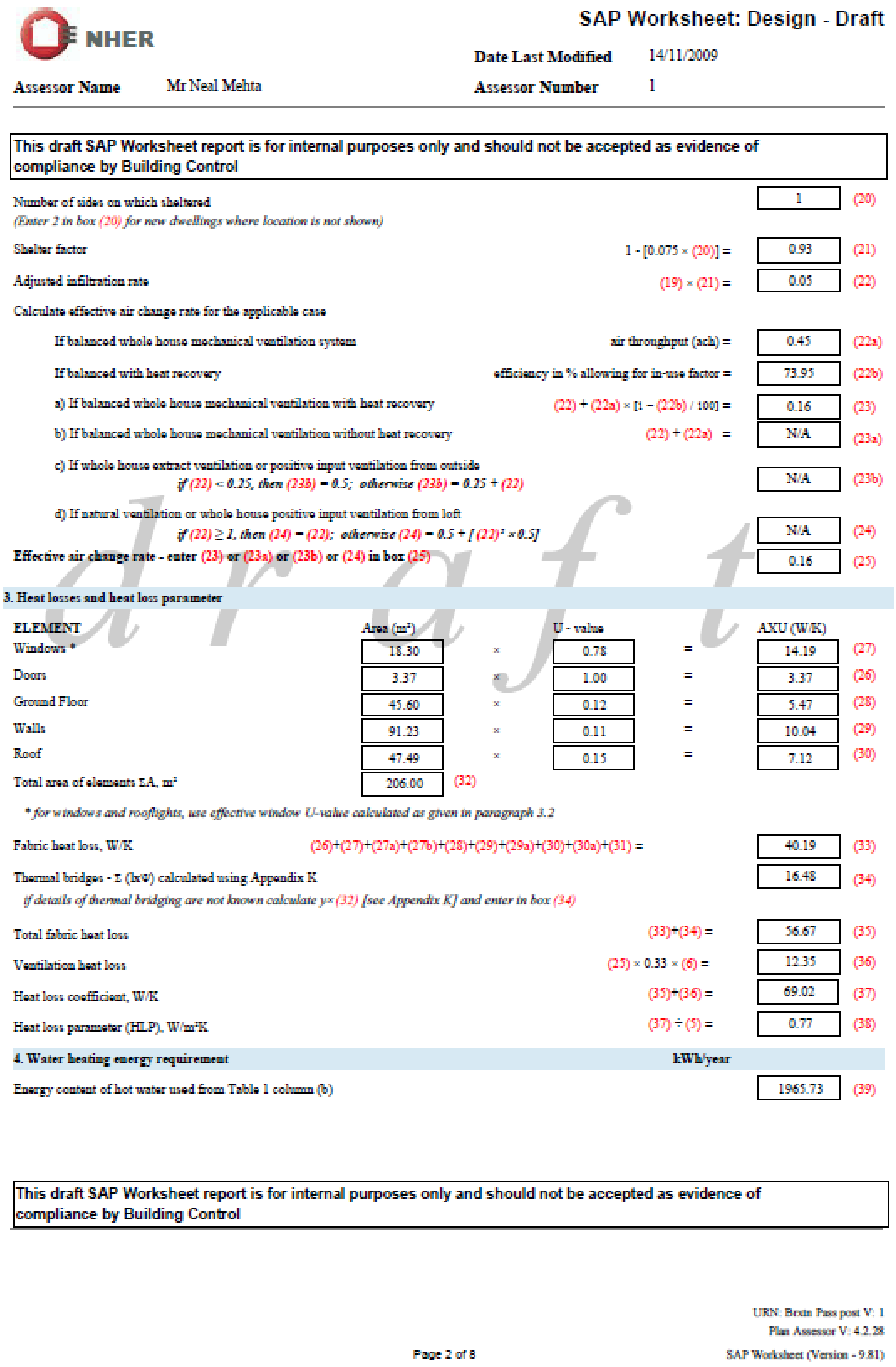

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SAP Worksheet: Design - Draft

Date Last Modified 14/11/2009

Assessor Name Mr Neal Mehta **Assessor Number** 1

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Number of sides on which sheltered *(Enter 2 in box (20) for new dwellings where location is not shown)*		1	(20)
Shelter factor	1 - [0.075 × (20)] =	0.93	(21)
Adjusted infiltration rate	(19) × (21) =	0.05	(22)
Calculate effective air change rate for the applicable case			
If balanced whole house mechanical ventilation system	air throughput (ach) =	0.45	(22a)
If balanced with heat recovery	efficiency in % allowing for in-use factor =	73.95	(22b)
a) If balanced whole house mechanical ventilation with heat recovery	(22) + (22a) × [1 − (22b) / 100] =	0.16	(23)
b) If balanced whole house mechanical ventilation without heat recovery	(22) + (22a) =	N/A	(23a)
c) If whole house extract ventilation or positive input ventilation from outside *if (22) < 0.25, then (23b) = 0.5; otherwise (23b) = 0.25 + (22)*		N/A	(23b)
d) If natural ventilation or whole house positive input ventilation from loft *if (22) ≥ 1, then (24) = (22); otherwise (24) = 0.5 + [(22)² × 0.5]*		N/A	(24)
Effective air change rate - enter (23) or (23a) or (23b) or (24) in box (25)		0.16	(25)

3. Heat losses and heat loss parameter

ELEMENT	**Area (m²)**		**U - value**		**AXU (W/K)**	
Windows *	18.30	×	0.78	=	14.19	(27)
Doors	3.37	×	1.00	=	3.37	(26)
Ground Floor	45.60	×	0.12	=	5.47	(28)
Walls	91.23	×	0.11	=	10.04	(29)
Roof	47.49	×	0.15	=	7.12	(30)
Total area of elements ΣA, m²	206.00 (32)					

** for windows and rooflights, use effective window U-value calculated as given in paragraph 3.2*

Fabric heat loss, W/K	(26)+(27)+(27a)+(27b)+(28)+(29)+(29a)+(30)+(30a)+(31) =	40.19	(33)
Thermal bridges - Σ (lxΨ) calculated using Appendix K *if details of thermal bridging are not known calculate y× (32) [see Appendix K] and enter in box (34)*		16.48	(34)
Total fabric heat loss	(33)+(34) =	56.67	(35)
Ventilation heat loss	(25) × 0.33 × (6) =	12.35	(36)
Heat loss coefficient, W/K	(35)+(36) =	69.02	(37)
Heat loss parameter (HLP), W/m²K	(37) ÷ (5) =	0.77	(38)

4. Water heating energy requirement **kWh/year**

Energy content of hot water used from Table 1 column (b)		1965.73	(39)

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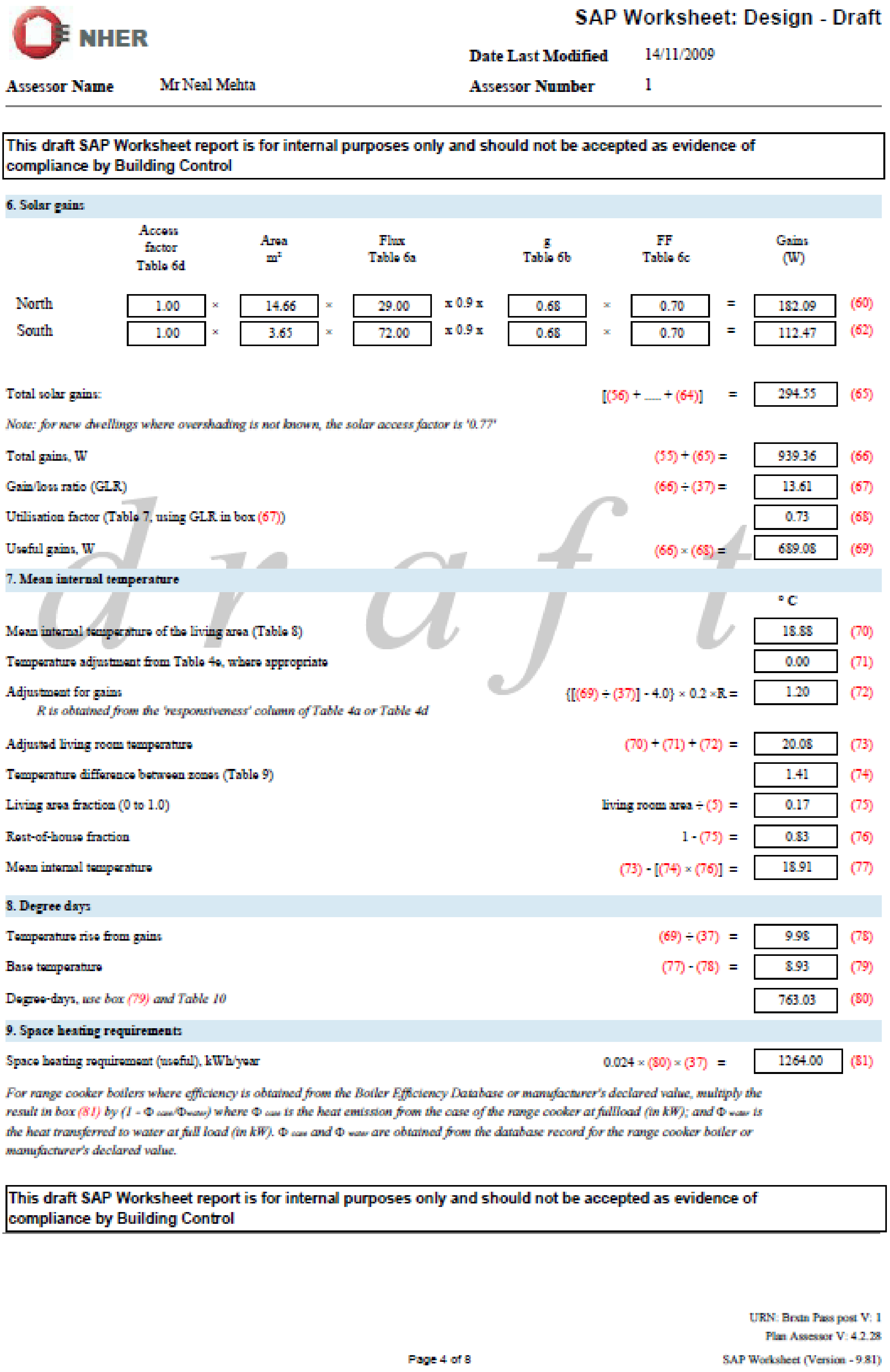
URN: Brxtn Pass post V: 1
Plan Assessor V: 4.2.28
Page 2 of 8
SAP Worksheet (Version - 9.81)

Distribution loss from Table 1 column (c)		346.89	(40)
If instantaneous water heating at point of use, enter 0 in boxes (40) to (45)			
For community heating use Table 1 (c) whether or not hot water tank is present			
Water storage loss:			
a) If manufacturer's declared loss factor is known (kWh/day):		N/A	(41)
Temperature factor from Table 2b		N/A	(41a)
Energy lost from water storage, kWh/year	(41)×(41a)×365 =	N/A	(42)
b) If manufacturer's declared cylinder loss factor is not known:			
Cylinder volume (litres) including any solar storage within same cylinder		210.00	(43)
If community heating and no tank in dwelling, enter 110 litres in box (43)			
Otherwise, if no stored hot water (this includes instantaneous combi boilers), enter '0' in box (43)			
Hot water storage loss factor from Table 2 (kWh/litre/day)		0.01	(44)
If community heating and no tank in dwelling, use cylinder loss from Table 2 for 50 mm factory insulation in box (44)			
Volume factor from Table 2a		0.83	(44a)
Temperature factor from Table 2b		0.54	(44b)
Energy lost from water storage, kWh/year	(43)×(44)×(44a)×(44b)×365 =	410.86	(45)
Enter (42) or (45) in box (46)		410.86	(46)
If cylinder contains dedicated solar storage, box (47) = (46) × [(43) - (H11)] / (43), else (47) = (46)		215.21	(47)
Primary circuit loss from Table 3		360.00	(48)
Combi loss from Table 3a (enter "0" if no combi boiler)		0.00	(49)
Solar DHW input calculated using Appendix H (enter "0" if no solar collector)		995.33	(50)
Output from water heater, kWh/year	(39)+(40)+(47)+(48)+(49)-(50) =	1892.51	(51)
Heat gains from water heating	0.25 × [(39)+(49)]+0.8×[(40)+(47)+(48)] =	1056.95	(52)
include (47) in calculation of (52) only if cylinder is in the dwelling or hot water is from community heating			

5. Internal gains

		Watts	
Lights, appliances, cooking and metabolic (Table 5)		524.16	(53)
Reduction of internal gains due to low energy lighting (calculated in Appendix L)		0.00	(53a)
Additional gains from Table 5a		0.00	(53b)
Water heating	(52) ÷ 8.76 =	120.66	(54)
Total internal gains	(53) + (53b) + (54) - (53a) =	644.81	(55)



6. Solar gains

	Access factor Table 6d		Area m²		Flux Table 6a		g Table 6b		FF Table 6c		Gains (W)	
North	1.00	×	14.66	×	29.00	x 0.9 x	0.68	×	0.70	=	182.09	(60)
South	1.00	×	3.65	×	72.00	x 0.9 x	0.68	×	0.70	=	112.47	(62)

Total solar gains:	[(56) + ... + (64)] =	294.55	(65)

Note: for new dwellings where overshading is not known, the solar access factor is '0.77'

Total gains, W	(55) + (65) =	939.36	(66)
Gain/loss ratio (GLR)	(66) ÷ (37) =	13.61	(67)
Utilisation factor (Table 7, using GLR in box (67))		0.73	(68)
Useful gains, W	(66) × (68) =	689.08	(69)

7. Mean internal temperature

		°C	
Mean internal temperature of the living area (Table 8)		18.88	(70)
Temperature adjustment from Table 4e, where appropriate		0.00	(71)
Adjustment for gains *R is obtained from the 'responsiveness' column of Table 4a or Table 4d*	{[(69) ÷ (37)] - 4.0} × 0.2 × R =	1.20	(72)
Adjusted living room temperature	(70) + (71) + (72) =	20.08	(73)
Temperature difference between zones (Table 9)		1.41	(74)
Living area fraction (0 to 1.0)	living room area ÷ (5) =	0.17	(75)
Rest-of-house fraction	1 - (75) =	0.83	(76)
Mean internal temperature	(73) - [(74) × (76)] =	18.91	(77)

8. Degree days

Temperature rise from gains	(69) ÷ (37) =	9.98	(78)
Base temperature	(77) - (78) =	8.93	(79)
Degree-days, *use box (79) and Table 10*		763.03	(80)

9. Space heating requirements

Space heating requirement (useful), kWh/year	0.024 × (80) × (37) =	1264.00	(81)

For range cooker boilers where efficiency is obtained from the Boiler Efficiency Database or manufacturer's declared value, multiply the result in box (81) by (1 - Φ_{case}/Φ_{water}) where Φ_{case} is the heat emission from the case of the range cooker at fullload (in kW); and Φ_{water} is the heat transferred to water at full load (in kW). Φ_{case} and Φ_{water} are obtained from the database record for the range cooker boiler or manufacturer's declared value.

9a. Energy requirements - individual heating systems, including micro-CHP

Note: when space and water heating is provided by community heating use the alternative worksheet 9b

Space heating:

Fraction of heat from secondary/supplementary system (*use value from Table 11, Table 12a or Appendix F*)		0.00	(82)
Efficiency of main heating system, %		90.20	(83)
(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c)			
Efficiency of secondary/supplementary heating system, % (use value from Table 4a or Appendix E)		0.00	(84)
Space heating fuel (main) requirement, kWh/year	[1- (82)] × (81) ×100 ÷ (83) =	1401.33	(85)
Space heating fuel (secondary), kWh/year	(82) × (81) ×100 ÷ (84) =	N/A	(85a)

Water heating:

Efficiency of water heater, % *(SEDBUK or from Table 4a or 4b, adjusted where appropriate by the amount shown in the 'efficiency adjustment' column of Table 4c)*		90.20	(86)
Energy required for water heating, kWh/year	(51) × 100 ÷ (86) =	2098.12	(86a)

Electricity for pumps and fans:	**kWh/year**			
each central heating pump, (Table 4f)	130.00	(87a)		
each boiler with a fan-assisted flue (Table 4f)	0.00	(87b)		
warm air heating system fans (Table 4f)	0.00	(87c)		
mechanical ventilation -balanced, extract or positive input from outside (Table 4f)	331.56	(87d)		
maintaining keep-hot facility for gas combi boiler (Table 4f)	0.00	(87e)		
pump for solar water heating (Table 4f)	0.00	(87f)		
Total electricity for the above equipment, kWh/year		(87a)+(87b)+(87c)+(87d)+(87e)+(87f) =	461.56	(87)

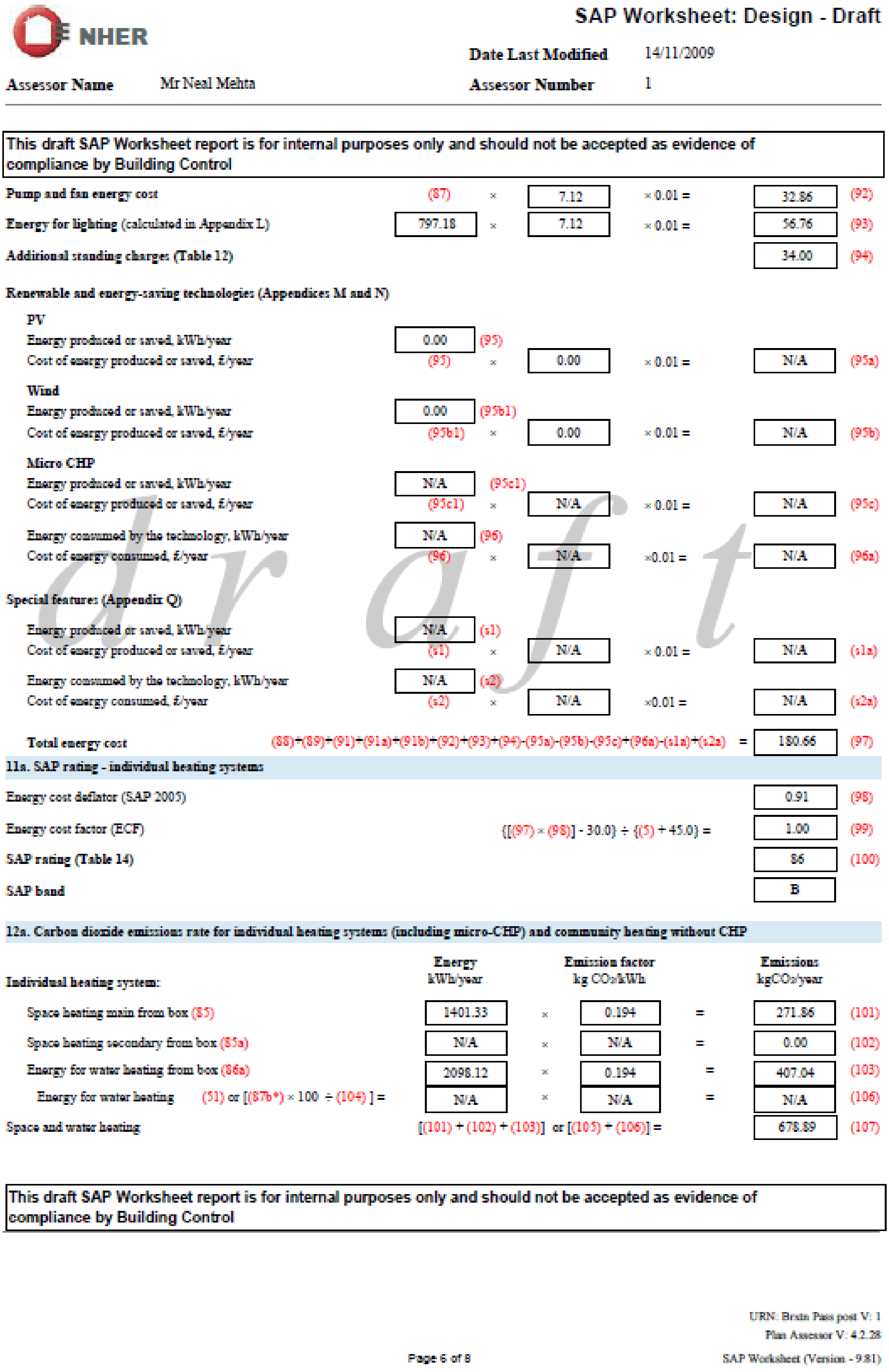
10a. Fuel costs - individual heating systems

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system	(85)	×	1.63	×0.01 =	22.84	(88)
Space heating - secondary	(85a)	×	N/A	× 0.01 =	0.00	(89)

Water heating

Water heating cost (electric, off-peak tariff)

On-peak fraction (Table 13, or Appendix F for electric CPSUs)			0.00	(90)			
Off-peak fraction	1.0 - (90) =		1.00	(90a)			
			Fuel price				
On-peak cost	(86a) × (90)	×	N/A		× 0.01 =	0.00	(91)
Off-peak cost	(86a) × (90a)	×	N/A		× 0.01 =	0.00	(91a)
Water heating cost (other fuel)	(86a)	×	1.63		× 0.01 =	34.20	(91b)



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Assessor Number 1

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Pump and fan energy cost	(87)	×	7.12	× 0.01 =	32.86	(92)
Energy for lighting (calculated in Appendix L)	797.18	×	7.12	× 0.01 =	56.76	(93)
Additional standing charges (Table 12)					34.00	(94)
Renewable and energy-saving technologies (Appendices M and N)						
PV						
Energy produced or saved, kWh/year	0.00	(95)				
Cost of energy produced or saved, £/year	(95)	×	0.00	× 0.01 =	N/A	(95a)
Wind						
Energy produced or saved, kWh/year	0.00	(95b1)				
Cost of energy produced or saved, £/year	(95b1)	×	0.00	× 0.01 =	N/A	(95b)
Micro CHP						
Energy produced or saved, kWh/year	N/A	(95c1)				
Cost of energy produced or saved, £/year	(95c1)	×	N/A	× 0.01 =	N/A	(95c)
Energy consumed by the technology, kWh/year	N/A	(96)				
Cost of energy consumed, £/year	(96)	×	N/A	×0.01 =	N/A	(96a)
Special features (Appendix Q)						
Energy produced or saved, kWh/year	N/A	(s1)				
Cost of energy produced or saved, £/year	(s1)	×	N/A	× 0.01 =	N/A	(s1a)
Energy consumed by the technology, kWh/year	N/A	(s2)				
Cost of energy consumed, £/year	(s2)	×	N/A	×0.01 =	N/A	(s2a)
Total energy cost	(88)+(89)+(91)+(91a)+(91b)+(92)+(93)+(94)-(95a)-(95b)-(95c)+(96a)-(s1a)+(s2a)			=	180.66	(97)

11a. SAP rating - individual heating systems

Energy cost deflator (SAP 2005)		0.91	(98)
Energy cost factor (ECF)	{[(97) × (98)] - 30.0} ÷ {(5) + 45.0} =	1.00	(99)
SAP rating (Table 14)		86	(100)
SAP band		B	

12a. Carbon dioxide emissions rate for individual heating systems (including micro-CHP) and community heating without CHP

Individual heating system:	**Energy** kWh/year		**Emission factor** kg CO_2/kWh		**Emissions** kgCO_2/year	
Space heating main from box (85)	1401.33	×	0.194	=	271.86	(101)
Space heating secondary from box (85a)	N/A	×	N/A	=	0.00	(102)
Energy for water heating from box (86a)	2098.12	×	0.194	=	407.04	(103)
Energy for water heating (51) or [(87b*) × 100 ÷ (104)] =	N/A	×	N/A	=	N/A	(106)
Space and water heating [(101) + (102) + (103)] or [(105) + (106)] =					678.89	(107)

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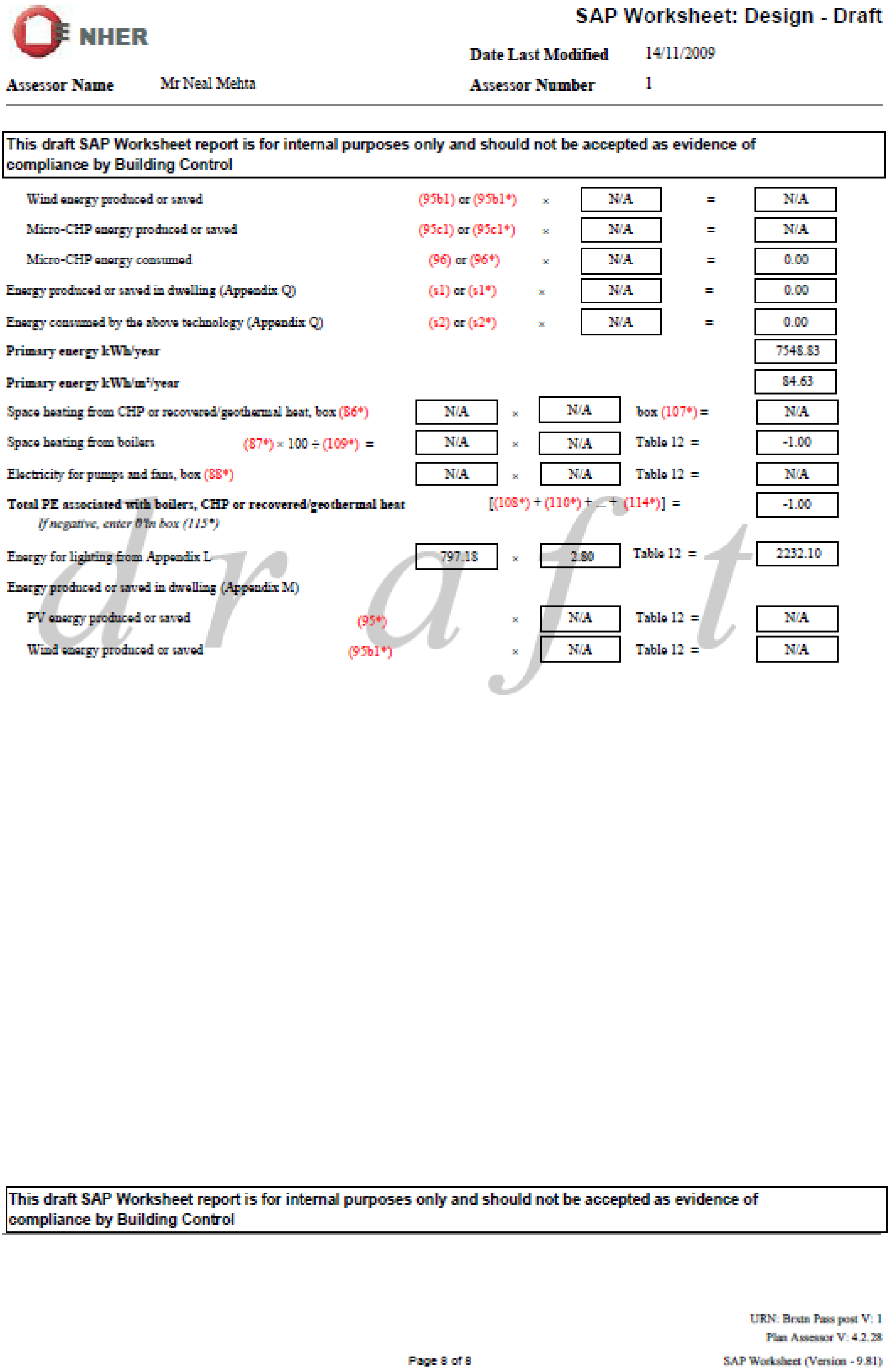
Energy for water heating	(Type 1 fraction) × (87*) × 100 ÷ (104a)	=	N/A	×	N/A	=	N/A	(106a)
Energy for water heating	(Type 2 fraction) × (87*) × 100 ÷ (104b)	=	N/A	×	0.000	=	N/A	(106b)
Space and water heating	[(105a) + (106a) + (105b) + (106b)] =						678.89	(107)
Electricity for pumps and fans from box (87) or (88*)			461.56	×	0.422	=	194.78	(108)
Energy for lighting from Appendix L			797.18	×	0.422	=	336.41	(109)
Energy produced or saved in dwelling (Appendices M and N)								
PV energy produced or saved	(95) or (95*)			×	N/A	=	N/A	(110)
Wind energy produced or saved	(95b1) or (95b1*)			×	N/A	=	N/A	(110b)
Micro-CHP energy produced or saved	(95c1) or (95c1*)			×	N/A	=	N/A	(110c)
Micro-CHP energy consumed	(96) or (96*)			×	N/A	=	0.00	(111)
Energy produced or saved in dwelling (Appendix Q)	(s1) or (s1*)			×	N/A	=	0.00	(s1a)
Energy consumed by the technology (Appendix Q)	(s2) or (s2*)			×	N/A	=	0.00	(s2a)
Total CO_2 kg/year	(107) + (108) + (109) - (110) + (111) - (s1a) + (s2a)					=	1210.08	(112)
Carbon dioxide emissions rate	(112) ÷ (5)					=	13.57	(113)
EI rating							88	
EI band							B	

13a. Primary energy, for individual heating systems (including micro-CHP) and community heating without CHP

Individual heating system:		**Energy kWh/year**		**Primary energy factor**		**Primary energy (kWh/year)**	
Space heating main from box (85)		1401.33	×	1.150	=	1611.53	
Space heating secondary from box (85a)		N/A	×	N/A	=	0.00	
Energy for water heating from box (86a)		2098.12	×	1.150	=	2412.84	
Energy for water heating	(87b*) × 100 ÷ (104) =	N/A	×	N/A	=	N/A	
Space and water heating						4024.37	
Energy for water heating	(Type 1 fraction) × (87*) × 100 ÷ (104a) =	N/A	×	N/A	=	N/A	
Energy for water heating	(Type 2 fraction) × (87*) × 100 ÷ (104b) =	N/A	×	N/A	=	N/A	
Space and water heating					=	4024.37	
Electricity for pumps and fans from box (87) or (88*)		461.56	×	2.800	=	1292.36	
Energy for lighting from Appendix L		797.18	×	2.800	=	2232.10	
Energy produced or saved in dwelling (Appendices M and N)							
PV energy produced or saved	(95) or (95*)		×	N/A	=	N/A	



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Wind energy produced or saved	(95b1) or (95b1*)		×	N/A	=	N/A
Micro-CHP energy produced or saved	(95c1) or (95c1*)		×	N/A	=	N/A
Micro-CHP energy consumed	(96) or (96*)		×	N/A	=	0.00
Energy produced or saved in dwelling (Appendix Q)	(s1) or (s1*)		×	N/A	=	0.00
Energy consumed by the above technology (Appendix Q)	(s2) or (s2*)		×	N/A	=	0.00
Primary energy kWh/year						7548.83
Primary energy kWh/m²/year						84.63
Space heating from CHP or recovered/geothermal heat, box (86*)		N/A	×	N/A	box (107*) =	N/A
Space heating from boilers	(87*) × 100 ÷ (109*) =	N/A	×	N/A	Table 12 =	-1.00
Electricity for pumps and fans, box (88*)		N/A	×	N/A	Table 12 =	N/A
Total PE associated with boilers, CHP or recovered/geothermal heat *If negative, enter 0 in box (115*)*	[(108*) + (110*) + ... + (114*)] =					-1.00
Energy for lighting from Appendix L		797.18	×	2.80	Table 12 =	2232.10
Energy produced or saved in dwelling (Appendix M)						
PV energy produced or saved	(95*)		×	N/A	Table 12 =	N/A
Wind energy produced or saved	(95b1*)		×	N/A	Table 12 =	N/A

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