Conceptual Building Information Modelling Framework for Whole-house Refurbishment based on LCC and LCA

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Doctor of Philosophy

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Thesis Summary

The UK government aims at achieving 80% CO_2 emission reduction by 2050 which requires collective efforts across all the UK industry sectors. In particular, the housing sector has a large potential to contribute to achieving the aim because the housing sector alone accounts for 27% of the total UK CO_2 emission, and furthermore, 87% of the housing which is responsible for current 27% CO_2 emission will still stand in 2050. Therefore, it is essential to improve energy efficiency of existing housing stock built with low energy efficiency standard. In order for this, a whole-house needs to be refurbished in a sustainable way by considering the life time financial and environmental impacts of a refurbished house. However, the current refurbishment process seems to be challenging to generate a financially and environmentally affordable refurbishment solution due to the highly fragmented nature of refurbishment practice and a lack of knowledge and skills about whole-house refurbishment in the construction industry. In order to generate an affordable refurbishment solution, diverse information regarding costs and environmental impacts of refurbishment measures and materials should be collected and integrated in right sequences throughout the refurbishment project life cycle among key project stakeholders. Consequently, various researchers increasingly study a way of utilizing Building Information Modelling (BIM) to tackle current problems in the construction industry because BIM can support construction professionals to manage construction projects in a collaborative manner by integrating diverse information, and to determine the best refurbishment solution among various alternatives by calculating the life cycle costs and lifetime CO_2 performance of a refurbishment solution. Despite the capability of BIM, the BIM adoption rate is low with 25% in the housing sector and it has been rarely studied about a way of using BIM for housing refurbishment projects. Therefore, this research aims to develop a BIM framework to formulate a financially and environmentally affordable whole-house refurbishment solution based on the Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) methods simultaneously. In order to achieve the aim, a BIM feasibility study was conducted as a pilot study to examine whether BIM is suitable for housing refurbishment, and a BIM framework was developed based on the grounded theory because there was no precedent research. After the development of a BIM framework, this framework was examined by a hypothetical case study using BIM input data collected from questionnaire survey regarding homeowners' preferences for housing refurbishment. Finally, validation of the BIM framework was conducted among academics and professionals by providing the BIM framework and a formulated refurbishment solution based on the LCC and LCA studies through the framework.

As a result, BIM was identified as suitable for housing refurbishment as a management tool, and it is timely for developing the BIM framework. The BIM framework with seven project stages was developed to formulate an affordable refurbishment solution. Through the case study, the Building Regulation is identified as the most affordable energy efficiency standard which renders the best LCC and LCA results when it is applied for whole-house refurbishment solution. In addition, the Fabric Energy Efficiency Standard (FEES) is recommended when customers are willing to adopt high energy standard, and the maximum 60% of CO_2 emissions can be reduced through whole-house fabric refurbishment with the FEES. Furthermore, limitations and challenges to fully utilize BIM framework for housing refurbishment were revealed such as a lack of BIM objects with proper cost and environmental information, limited interoperability between different BIM software and limited information of LCC and LCA datasets in BIM system. Finally, the BIM framework was validated as suitable for housing refurbishment projects, and reviewers commented that the framework can be more practical if a specific BIM library for housing refurbishment with proper LCC and LCA datasets is developed. This research is expected to provide a systematic way of formulating a refurbishment solution using BIM, and to become a basis for further research on BIM for the housing sector to resolve the current limitations and challenges. Future research should enhance the BIM framework by developing more detailed process map and develop BIM objects with proper LCC and LCA Information.

Keywords: BIM, Housing Refurbishment, Life Cycle Costing, Life Cycle Assessment

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Chapter 1 Introduction

1.1 Background

Today the world is facing unprecedented environmental challenges due to global climate change. According to the Stern Review report (2006), climate change causes very serious global risks that threaten the prosperity of human beings, and it requires collective efforts internationally. This report concluded that the governments should play a key role in motivating the industry sectors to tackle the global climate change issues, and promote strong policies for energy efficiency. Under the influence and consultation of the Stern Review report, the UK government legislated the Climate Change Act 2008 aiming at 80% CO_2 reduction by 2050 against 1990 CO_2 emission levels. Achieving 80% reduction is a challenging task, and will only be met by improving energy efficiency across all sectors of the UK economy. In particular, the UK possesses the oldest housing stock among developed countries with 8.5 million properties over 60-years-old (Energy Saving Trust, 2007). As a result, housing accounts for 27% of the total UK CO_2 emissions (Kelly, 2009), and furthermore, 87% of those housing responsible for the 27% CO_2 emission will still be standing in 2050 (Boardman, 2007; Power, 2010). The UK government is committed to increasing the number of new houses to 3 million by 2020 as it is projected that the housing stock and number of households will keep increasing (ONS, 2011). However, it is insufficient to replenish the 87% housing stock with new homes by 2050 since the average replacement rate of the existing housing stock to new homes has been less than 1% (50,000) per year (Power, 2008; Construction Products Association, 2010; Owen, 2011). It has been estimated that 600,000 houses per each year need to be refurbished from 2012 to achieve the 80% reduction in time (BRE, 2010). Thus, the housing sector should play a key role in improving energy efficiency, and sustainable housing refurbishment is expected to provide substantial contribution to CO_2 reduction.

Energy efficiency improvement can provide the same level of service in a house such as thermal comfort using less energy. For example, an energy efficient boiler consumes less fuel to heat a home compared to a less efficient one. Improving energy efficiency requires upfront capital cost to adopt energy efficiency measures such as housing components insulation and double glazing window installation. However, the invested capital cost will be compensated from reduced energy bill over a certain period which called a payback period. Thus, energy efficiency improvement can increase efficiency of fuel usage and reduce consumption of fuel, and consequently the amount of CO_2 emission from a house can be reduced by adopting energy efficiency measures. The Committee on Climate Change (CCC) forecasted that energy efficiency improvements could reduce annual CO_2 emissions from the UK housing sector by about 17 million tonnes by 2020 (CCC, 2013). Indeed, space heating alone consumes 66% and the energy required generating hot water consumes 17% of total domestic energy. Thus, 83% of total energy consumption in a house has a direct impact on energy efficiency and CO_2 emissions (DECC, 2013c). Therefore, it is an overarching matter to improve energy efficiency in the housing sector to reduce CO_2 emission.

To improve the energy efficiency of the housing stock, the UK government has initiated a series of government incentive schemes such as Carbon Emissions Reduction Target programme (CERT), Warm Front, Renewable Heat Incentive (RHI), and Green Deal. Most of these schemes are largely focused on refurbishment measures with relatively low upfront costs such as cavity wall insulation and loft insulation (WWF, 2008). These refurbishment measures have a short payback period, and bring less disruption to house occupants than other refurbishment measures such as solid wall insulation and floor insulation. Consequently, this measure approach has been increasingly adopted by households in order to receive government funding (Construction Products Association, 2010). However, the measure approach is capable of achieving limited CO_2 reduction by 25-35% (McMullan, 2007), which is far below the 80% reduction. As a result, there is increasing consensus amongst researchers that comprehensive whole-house refurbishments are required to achieve the reduction target in the housing sector (Boardman 2007; Killip 2008). In particular, the CESP and Heat and Energy Saving Strategy (HES) placed weight to the importance of the potential value of the whole-house refurbishment approach (Reeves, 2009), and the UK government has released a whole-house refurbishment strategy to improve the efficiency of individual homes (DECC, 2009a).

1.2 Statement of Problem

Housing refurbishment could be classified under two major approaches such as the measure approach and the whole-house approach (Boardman et al., 2005; EST, 2011; Killip, 2008). The measure approach focuses on the installation of an individual refurbishment measure such as cavity wall insulation, loft insulation and double glazing installation. In contrast, the whole-house approach considers all the potential refurbishment measures holistically, including the fabric, the services and renewable energy systems. As stated, previously, the UK government incentive schemes have placed more weight on the measure approach than the whole-house approach, since the measure approaches are economically viable and less disruptive (Utley and Shorrock, 2008). Despite the financial support from the government, the uptake of refurbishment measures is low amongst households, and particularly solid wall insulation shows extremely low uptake as shown in Figure 1.1 (DECC, 2012) due to high initial costs and disruption during refurbishment works undertaken (EST, 2011; Owen, 2011).

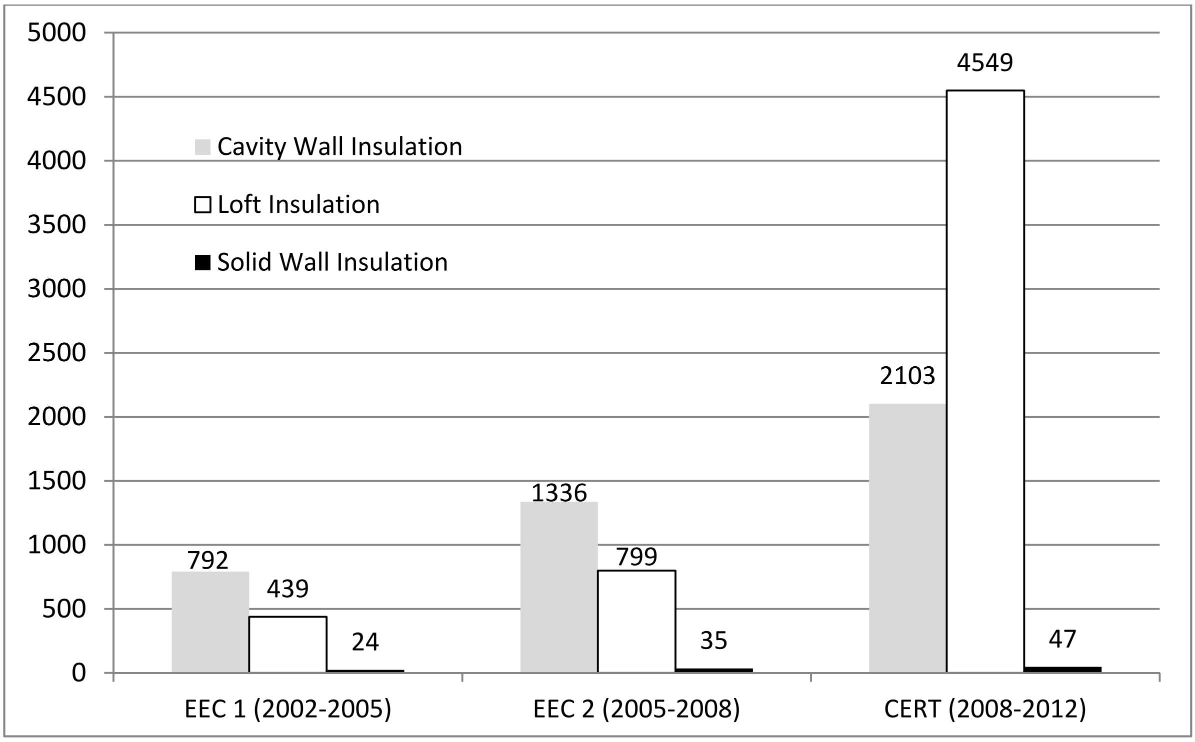


Figure 1.1 Insulation measures installed under EEC and CERT
(Y axis is Number of Households, thousands of households)
Note: EEC - Energy Efficiency Commitment; CERT - Carbon Emissions Reduction Target

The individual refurbishment measure has the limited capability to improve energy efficiency because windows and lofts account for only 15-25% of heat loss respectively, while walls account for 35% of heat loss (McMullan, 2007). Although different combinations of each refurbishment measure can provide higher energy efficiency improvement up to maximum 60%, the expected energy efficiency cannot be achieved as calculated because continuity of insulations is broken when refurbishment measures are installed separately over time, and consequently significant heat loss occurred at the joint junction between each housing component, for example between wall and roof (Burton, 2012; Plimmer et al., 2008). is installed at once. This is Thus, it seems evident that the 80% reduction target cannot be achieved unless combination of possible refurbishment measures, which is whole-house refurbishment is adopted for the existing housing stock.

However, there are three major challenges to promoting the whole-house approach. The first one is the reluctance of homeowners to adopt whole-house refurbishment. Currently, 65% of the UK housing is privately owned (DCLG, 2014b), and the housing stock is challenged to be controlled by the government unless regulations are legislated that mandate homeowners to improve energy efficiency by adopting the whole-house approach. The second is the complex decision making process for developing a whole-house refurbishment solution because various information about financial and environmental impacts of the refurbishment solution needs to be considered. The final is a lack of capability in the construction industry to generate an affordable whole-house refurbishment solution because current construction professionals involved in housing refurbishment tend to have a lack of skills and knowledge to formulate an affordable refurbishment solution based on life cycle cost and CO_2 performance of a refurbished house (Owen, 2011; DECC, 2011; Energy Saving Trust, 2011).

The details about three major challenges are addressed as follows.

Challenge 1. Reluctance of Homeowners:

Most homeowners are interested in the measure approach for refurbishing room by room rather than the whole-house approach because homeowners find it challenging to prepare financial arrangements for whole-house refurbishment at once and have a lack of information about whole-house refurbishment in general (Energy Saving Trust, 2011). Consequently, homeowners lack information about refurbishment measures, and they have a tendency to overestimate the cost and trouble involved. In addition, homeowners do not welcome the cold call or door step visit from builders or installers regarding improving energy efficiency of their homes (DECC, 2011). Since the whole-house approach explores all the potential energy improvement measures such as fabric, service and renewable energy systems, homeowners feels as if builders try to sell unnecessary extras (Energy Saving Trust, 2011). Eventually, this low awareness of refurbishment measures has lead homeowners to mistrust builders. Furthermore, most households have a negative perception about the decanting process since they are reluctant to move to alternative accommodation temporarily while refurbishment works are carried out (Construction Products Association, 2010).

Challenge 2. Complex Decision Making Process for the Whole-house Refurbishment:

Whole-house refurbishment requires careful attention to sustainability in terms of life time CO_2 performance and the financial implications of a house. As a house has a long life and shows a large variation of energy efficiency, it is critical to consider what level of sustainability can be achieved by a combination of individual refurbishment measures. Particularly, individual refurbishment measures for improving fabric, services and renewable energy systems configure a whole-house refurbishment solution, and the level of sustainability is determined based on how well individual measures are integrated. In addition, each measure has a different expected life cycle for maintenance and repair, causing additional costs along with the upfront cost for refurbishments. This uniqueness of the whole-house approach requires a comprehensive understanding of the interactions amongst individual refurbishment measures, and eventually requires a systematic way of generating a whole-house refurbishment solution based on the life time costs and CO_2 performance of a refurbished house. Since the actual energy use of a sustainable building is consumed five times more than is estimated during the design phase (Carbon Trust, 2011), an well-integrated refurbishment solution is essential to achieve 80% CO_2 reduction. Thus, the life cycle costing and environmental impact for each refurbishment measure must be considered individually and collectively to develop a whole-house refurbishment plan (Yates, 2006). However, the current prevalent refurbishment practice for improving energy efficiency is the measure approach, which has relatively short life cycle with low upfront cost compared to the whole-house approach. Without giving sufficient attention to the whole life cycle costs and CO_2 performance of a refurbished house, a suggested whole-house solution by construction professionals will have low impact on CO_2 reduction and provide a financially unaffordable solution for homeowners in the long-term.

Challenge 3. Lack of Capability to Generate a Whole-house Refurbishment Solution in the Construction Industry:

The whole-house approach requires a complex decision making process because various aspects need to be considered simultaneously such as interactions between individual refurbishment measures and the lifetime financial and environmental implications. UK housing shows a wide range of energy efficiency depending on housing conditions such as housing types, year built, construction types and location of properties. Due to these variations, it is difficult to replicate a refurbishment solution to multiple houses, and there is no 'one-size-fits-all' solution for housing refurbishment (Jenkins, 2010; Firth and Lomas, 2009). Therefore, a person managing a refurbishment project should be capable of integrating diverse information and proposing a tailored solution for each house that is technically buildable, financially feasible and environmentally responsible.

However, there are not enough experienced personnel in the housing refurbishment sector to make proper decisions how to combine technologies, a financial plan and sustainability (CIOB, 2011). Furthermore, the current fragmented nature of construction practice contributes to the complexity of housing refurbishments. It is an overwhelming task for those who have no expertise in integrating many types of construction information for whole-house refurbishment (Forum for the future, 2012). Therefore, it is necessary to develop a systematic way to integrate many kinds of construction information and generate a whole-house refurbishment solution that is financially and environmentally affordable for customers.

As a result, this research identified the following three research gaps that need to be closed in order to promote whole-house refurbishment among homeowners and achieve the UK government goal of 80% reduction by providing an affordable refurbishment solution to customers. Each challenge linked with a research gap is stated in the parenthesis.

1. **Homeowners' Preferences for Housing Refurbishment (Challenge 1)**: According to Energy Saving Trust (2011), 3.9 million homeowners are considering refurbishing their homes to improve energy efficiency within three years. In addition, 85% of these homeowners are willing to allocate about 10% more towards their budget for a major refurbishment project costing £527-£1,027. This research revealed homeowners' willingness for housing refurbishment and the positive possibility to increase the uptake of whole-house approach amongst homeowners. In addition, there is an effort to identify the key decision making factors for a sustainable housing project of stakeholders (Carter, 2005). However, these studies failed to explore homeowners' preferences for housing refurbishment and their decision-making factors for selecting refurbishment measures. There is a lack of research has been conducted about homeowners' preferences for housing refurbishment regarding their wants and needs for housing refurbishment priorities and preferences for refurbishment measures and materials. Thus, in order for builders to provide an affordable solution that is appealing to homeowners, it is critical to find out the information about decision making factors influencing the selection of refurbishment measures. The uptake of whole-house refurbishment will remain low unless there is a proper understanding about homeowners' preferences and decision-making factors for housing refurbishment.

2. **Sustainable Refurbishment Solution for Considering Whole Life Cost and CO_2 Performance (Challenge 2):** The high upfront cost of whole-house refurbishment is the most challenging issue for homeowners and builders. In the situation where the payback period and the energy cost savings are reasonable for homeowners, the whole-house refurbishment solution could be accepted. In order to clearly envisage the energy cost savings and sustainability, the whole life cycle costing and life cycle assessment about environmental impact are required. These techniques are capable of providing economic and environmental assessment of the whole-house refurbishment solution and provide a decision making criteria to determine the best refurbishment solution. Therefore, the whole life cycle costing technique should be used to assess the proposed refurbishment solution if it is feasible in terms of the financial and environmental impact. This technique will support a homeowner to make an informed decision and a builder to provide more affordable solution. Many researchers have studied the whole life cycle cost and environmental impact of individual refurbishment measures (Ding, 2005; Menzies and Wherrett, 2005; Jenkins et al., 2012). However, none have studied about how to quantify the whole life cycle cost and CO_2 performance simultaneously for the whole-house approach.

3. **Absence of an Effective Way to Generate and Manage Whole-house Refurbishment (Challenge 3):** Building Information Modelling (BIM) is a widely recognized and currently prevalent information management tool used in the construction industry to cope with financial

issues and shorten the project duration by integrating various aspects from design to use phases in 3D (three dimensional) manner. The primary advantage of BIM amongst others is that it enables all stakeholders collaborate on the same data based on shared information using 3D visualization from design to operation, and detailed information such as CO_2 performance and costs of each measure and material can also be attached to the 3D model. The current measured benefit of BIM utilization results in 38% reduction of construction cost from all stages of the building life cycle, and the potential cost reduction in the design stage alone is from 19%-40% (Government Construction Client Group, 2011). National House Building Council (NHBC) foundation (2013) reveals that BIM can offer management efficiency to builders, although this research focused on new build housing and did not investigate possibility of using BIM for housing refurbishment.

Based on the research gaps, the following section will provide the aim and objectives of this research.

1.3 Research Aim and Objectives

The research aim is as follows.

- **Develop a BIM framework to formulate a financially and environmentally affordable whole-house refurbishment solution based on the life cycle costing (LCC) and life cycle assessment (LCA) methods simultaneously.**

In order to fulfil the research aim, this research has the following objectives.

- **Theoretical studies through literature review to understand the housing sector in the UK.**
    - **Understand the current condition of UK housing**
    - **Understand the current status of sustainable housing refurbishment**
    - **Understand the current status of BIM in the housing sector**
- **Conduct a BIM feasibility study for housing refurbishment projects.**
- **Identify homeowners' preferences for housing refurbishment.**
- **Develop a BIM framework to formulate a financially and environmentally affordable whole-house refurbishment solution.**
- **Conduct a hypothetical case study to implement and validate the developed framework for a housing refurbishment.**

1.4 Structure of the Thesis

The thesis consists of nine chapters, as shown in Figure 1.2.

Chapter 1 provides the background of this research, the aims, objectives and importance, and the structure of this thesis.

Chapter 2 provides an overview of the current status of the UK housing stock, and the most critical and effective target for housing refurbishment will be identified, one which that requires immediate attention regarding energy efficiency improvement.

Chapter 3 establishes the contextual background of sustainable housing refurbishment, and identifies challenges in the UK housing sector to undertake housing refurbishment in a sustainable manner.

Chapter 4 develops the contextual background of BIM, and ascertains if BIM is suitable for sustainable whole-house refurbishment projects.

Chapter 5 provides an overview of the research design, philosophy and strategy that has been adopted to achieve the research aims and objectives of this thesis.

Chapter 6 discusses the results of a BIM feasibility pilot study and questionnaire survey about homeowners' and construction professionals' preferences for housing refurbishment.

Chapter 7 discusses a theoretical BIM framework for housing refurbishment projects to generate a whole-house refurbishment solution based on LCC and LCA. A hypothetical case study was used for explaining and examining this framework.

Chapter 8 provides the LCC and LCA study results calculated from the BIM framework using a hypothetical case study. In order to validate the suitability and practicality of the BIM framework, a questionnaire survey was conducted among academics and practitioners.

Chapter 9 concludes the key findings, results and limitations of this research. The recommendations for future research are provided in this chapter.

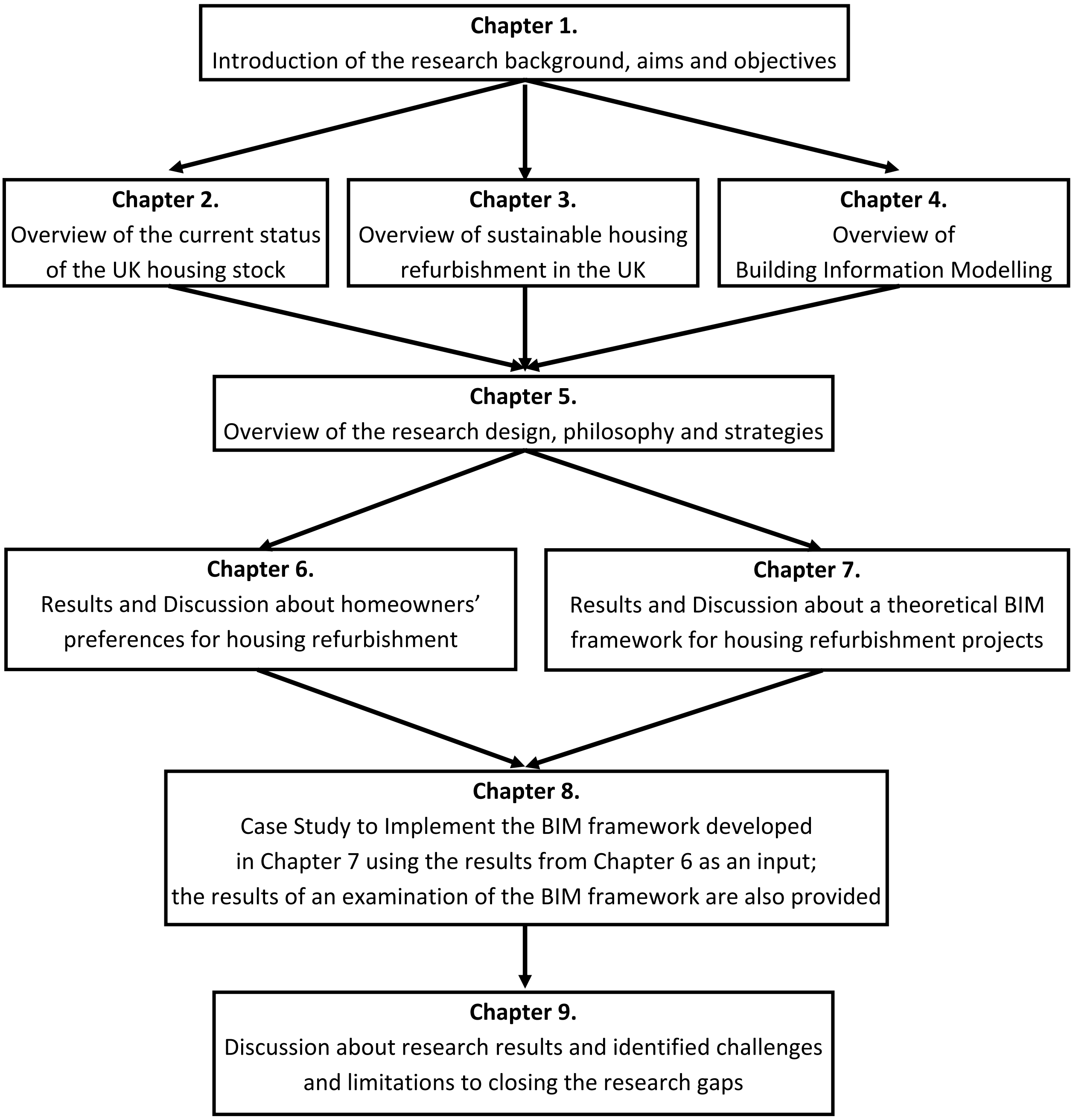


Figure 1.2 The Structure of the Thesis

Chapter 2 UK Housing Stock

2.1 Introduction

This chapter provides an overview of the current status of the UK housing stock. This chapter is comprised of five sub-chapters:

1) Background information about housing in the UK
2) UK housing stock status
3) UK housing stock construction types
4) Current status of solid wall housing stock in the UK
5) Conclusion

Based on the literature review of the UK housing status, the most critical and effective target for housing refurbishment will be identified, one which that requires immediate attention regarding energy efficiency improvement.

2.2 Background

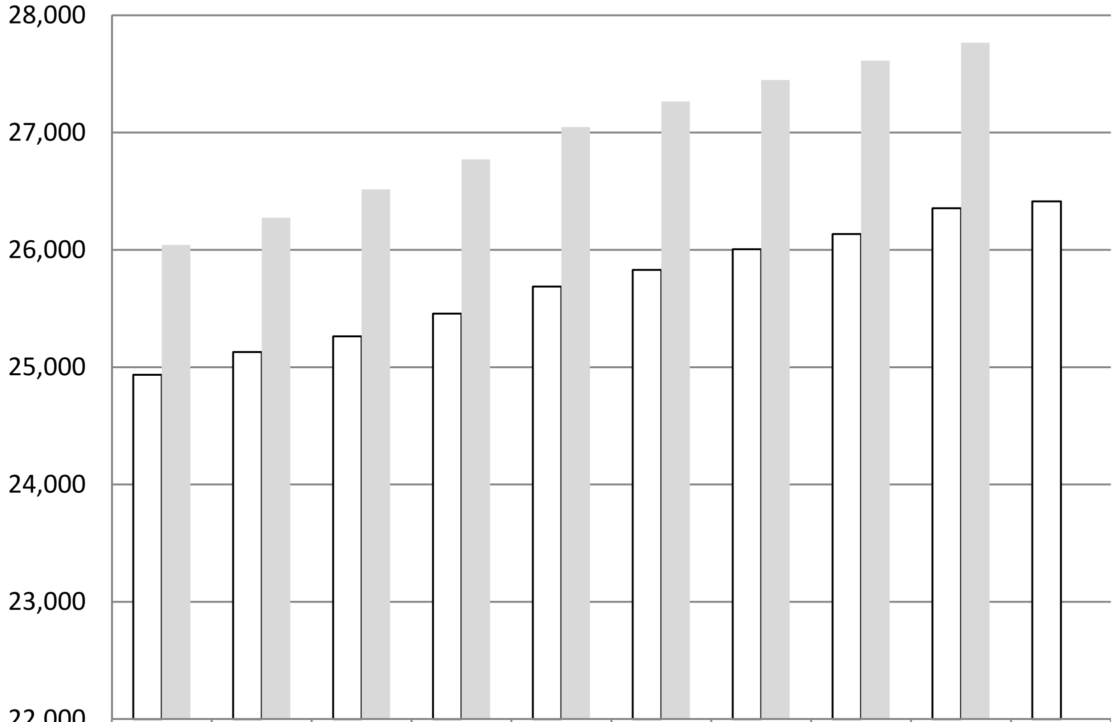
As the Kyoto Protocol has become mandatory among the world's leading economies in 2005, the majority of governments around the world have strived to reduce CO_2 levels. The UK government legislated in the Climate Change Act 2008 for an 80% CO_2 reduction by 2050 against 1990 levels. This reduction is a challenging target and could be achieved if energy efficiency across all sectors of the UK economy is improved. Many policies require and mandate more efficient use of energy in all economic sectors, and in most countries the housing sector is a major contributor to a large amount of energy consumption and CO_2 emissions (Bell and Lowe, 2000). Indeed the UK has the oldest housing stock among the developed countries as 8.5 million properties are over 60 years old (EST, 2007; National Refurbishment Centre, 2012). In particular, an old and poorly insulated house, which has been built with low energy performance standard, loses more energy through the poorly insulated housing elements (BRE, 2008; McMullan, 2007). A poorly insulated house consequently causes more energy consumption than other housing types built with high energy performance standard. Therefore, it is important to improve energy efficiency of old housing stock to reduce CO_2 emission.

Currently, 45% of total CO_2 emission in the UK is generated from the existing buildings, and particularly, existing housing stock alone accounts for 27% while non-domestic buildings accounts for 18% (Kelly, 2009). Furthermore, 87% of the housing which is responsible for current 27% CO_2 emission will still stand in 2050 (Boardman, 2007). New build housing stock has been built on higher energy standard from 1980s as the Building Regulations and the Code for Sustainable Homes were compulsory standard.

However, the existing housing stock built before 1980 was built with lower energy efficiency standards, and it is estimated that 1% of the UK housing stock meets modern thermal efficiency levels (National Refurbishment Centre, 2012). Furthermore, all new build homes have to have zero CO_2 emission from 2016 as the government mandates in the 'Zero Carbon Homes' policy (NHBC, 2013). Therefore, there is a great opportunity lying on the existing housing stock to achieve the targeted CO_2 reduction. In order to achieve the 80% CO_2 reduction, the energy efficiency of existing housing stock has to be improved substantially (Itard and Meijer, 2008; Summerson, 2011). The stock needs to be identified and assessed as it covers a large variation in house types (Firth and Lomas, 2009) each of which require specific work to improve energy efficiency.

2.3 Status of the UK Housing Stock

The UK government has mandated zero carbon emission for all new build housing from 2016, however this policy is limited as it only focuses on new build housing. 87% of housing that will be standing until 2050 has already been built therefore the focus should be directed more toward energy efficiency improvement of existing housing stock. The government's target of increasing the number of new homes by about 3 million by 2020 (equivalent to 240,000 new build homes per a year (DCLG, 2007)), is insufficient to replenish the built housing stock (about 24 million homes) as shown in Figure 2.1. This is because the average replacement rate of the existing housing stock to new homes has been less than 1% (50,000) per year (Power, 2008; Construction Products Association, 2010; Owen, 2011).



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
□ Household	24,936	25,130	25,263	25,457	25,687	25,830	26,006	26,135	26,355	26,414
■ Housing	26,042	26,274	26,516	26,772	27,047	27,266	27,448	27,614	27,767	

Figure 2.1 Trend of Housing Stock and Households in UK (DCLG, 2013a; 2014a), Unit: Thousand
Note: As of March, 2014, the number of housing stock in 2013 is not available.

Currently, the UK government estimates a short fall of 232,000 homes as of 2011 (DCLG, 2011), and the shortage of new homes will escalate as households will outnumber the housing stock in the UK circa 2030 as shown in Figure 2.2, and it is forecasted that there will still be a shortage of 800,000 homes by 2033 (Marsh, 2012).

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Figure 2.2 Household and housing stock projection (DCLG, 2013a), Unit: Thousand

Note: R^2 indicates the reliability of linear projection analysis. For example, the household and housing stock projection analysis indicates 96% and 99% reliability respectively.

According to a housing report (NHF, 2013), only 109,000 new homes were built in 2011, which is less than half of new homes that the government promised to build. In order to achieve the 80% CO_2 reduction in time, 600,000 houses are estimated as required to be refurbished every year (BRE, 2010). If the timeframe up to 2050 is taken into consideration, there is not enough time to replace old homes with new ones. In addition, the demolition rate for housing is low (DECC, 2012); and the existing housing stock for all periods remains almost the same - as shown in Table 1 and 2.

Table 1. Housing Type from 2007 to 2011 (DCLG, 2007; 2008; 2009; 2010; 2011), Unit: Thousand

Housing Type	**2007**	**2008**	**2009**	**2010**	**2011**	**Average Share (%)**
Terraced	6,240	6,352	6,450	6,353	6,428	28.4%
Semi-detached	6,103	5,786	5,727	5,860	5,917	26.2%
Detached	3,937	3,867	3,799	3,796	3,786	17.1%
Bungalow	2,102	2,092	2,052	1,996	1,996	9.2%
Converted Flat	757	825	900	948	949	4.0%
Purpose Built Flat	3,014	3,317	3,407	3,429	3,679	15.1%

Table 2. Year Built of Housing Stock from 2007 to 2011 (DCLG, 2007; 2008; 2009; 2010; 2011)

Year Built	2007	2008	2009	2010	2011	Average Share (%)
Pre 1919	4,766	4,760	4,794	4,865	4,739	21.4%
1919-1944	3,864	3,642	3,689	3,751	3,762	16.7%
1945-1964	4,345	4,363	4,504	4,397	4,502	19.8%
1965-1980	4,806	4,814	4,631	4,602	4,782	21.1%
1981-1990	1,878	1,953	1,981	1,880	1,918	8.6%
Post 1990	2,531	2,708	2,735	2,892	3,052	12.4%

Furthermore, 78% of the current existing housing stock was built before 1980, when the Building Regulations Part L was not compulsory in the housing sector as shown in Table 3. This implies that 78% of the total UK housing stock has been built based on lower energy performance standards compared to modern standards. Indeed, there are 27 million existing homes and 2 million existing non-domestic buildings in need of refurbishment (CIOB, 2011a). The Building Regulations Part L provides a minimum standard for new build housing regarding energy efficiency of the fabric, the boiler and low energy lighting of a house. Although Part L applies to existing housing for replacing windows or extensions, there is no minimum energy performance standard for existing housing to comply by law.

Table 3. Year Built of Housing Stock in 2013 (DCLG, 2014b), Unit: Thousand

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Table 4. Housing Type in 2013 (DCLG, 2014b), Unit: Thousand

Therefore, the existing housing stock needs to be improved in energy efficiency to achieve the CO_2 reduction target, and the housing sector should play a key role. However, it is challenging to improve energy efficiency in the housing sector since a house has long life span of about 50 to 100 years, and the UK housing stock has a large variation in housing types, construction types and year built. As shown in Table 3 and 4, the UK housing type and built year are not homogeneous although terraced, semi-detached and detached house are the dominant type of the UK housing. Furthermore, more than half of the existing housing stock, about 65%, is privately owned, while only 17% of the total housing stock belongs to social housing as shown in Table 3 and 4. There is an argument that the social housing sector could play a leading role in achieving sustainability in the housing sector (Hall and Purchase, 2006; SFC, 2008; Carter and Fortune, 2008; Leblanc et al., 2010a), however, the share of owned occupied housing stock outnumbers the social housing stock. Indeed, the wealthiest 10% of households who own their homes generate more than twice the amount of CO_2 than the poorest 10% of fuel poor households (Roberts, 2008). Therefore, it would be more effective to achieve the targeted CO_2 reduction by focusing on the owned occupied housing stock built before 1980.

2.4 Construction Types of Housing Stock

The UK housing stock includes a large variation in construction types. Solid wall housing was built predominantly until 1930s, and from 1930s onward, cavity wall housing was built predominantly as shown in Table 5 (EST, 2010). Solid wall housing traditionally has 220mm solid brick walls, and the heat loss through an uninsulated solid wall is typically over 50% greater than through an uninsulated cavity wall. Solid walls can be thermally improved with either external or internal insulation. Cavity wall housing has been built since the 1930s, and it is relatively easy to improve its energy efficiency by filling the cavity with insulation. It can also be used in internal and external insulation.

Table 5. Housing Construction Type (EST, 2010)

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All domestic and commercial buildings in the UK must have an Energy Performance Certificate (EPC) available to potential renters or buyers. The EPC identifies energy efficiency and environmental impact (CO_2 emission) of a building with a letter grade with a different colour from A (most efficient) to G (least efficient). The letter grade is determined by the number from 1 to 100 that is calculated by the Standard Assessment Procedure (SAP) as shown in Figure 2.3.

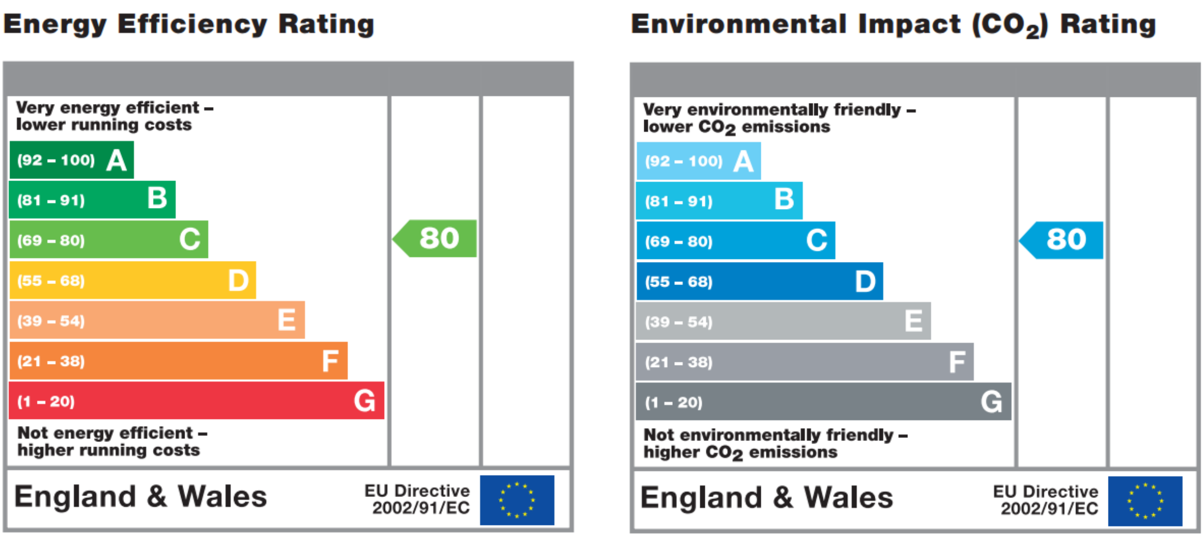

Figure 2.3 Energy Performance Certificate Example

Typically, solid wall housing has the least efficient energy performance which is EPC F, and other types of housing built before 1980 also indicate energy performance between EPC E and F (EST, 2010). As of 2011, the majority of housing stock is located between the EPC rating of D and E as shown in Figure 2.4, however an overall energy efficiency improvement can be seen in the housing stock when EPC ratings between 2011 and 1996 are compared (DCLG, 2013b; Davies and Osmani, 2011).

Figure 2.4 EPC rating (SAP 09 based) Distribution in Housing Stock, 2011 (DCLG, 2013b)

On average, the most energy inefficient homes are found in the owner-occupied sector with EPC E while the social housing sector is the most energy efficient with the average EPC D (DECC, 2013b). A house typically loses heat through various paths as shown in Figure 2.5 (McMullan, 2007). In particular, solid wall housing is more vulnerable to energy inefficiency than other types of housing with modern energy performance standard such as Building Regulation because this is an old and poorly insulated house, which is known as a hard to treat home with one skin brick wall without insulation, losing more energy through the poorly insulated housing elements (BRE, 2008).

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Figure 2.5 Typical Heat Loss in a House without Insulation (McMullan, 2007)

As shown in Figure 2.6, space heating alone consumes 66% of total domestic energy, and water, which means the energy required generating hot water, consumes 17%. Thus, 83% of total energy consumption in a house has a direct impact on energy efficiency and CO_2 emissions (DECC, 2013c), and in the end, this results in fuel poverty where households are required to spend in excess of 10 per cent of their household income on heating and powering their home to a satisfactory standard, although fuel poverty is caused by the three major reasons: low household income, poor heating and insulation standards and high energy prices (DECC, 2013a).

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Figure 2.6 Domestic Energy Consumption Distribution (DECC, 2013c)

Consequently, a poorly insulated house which has been built with low energy performance standard should be improved in energy efficiency to achieve efficient energy consumption and reduce CO_2 emission.

2.5 Solid Wall Housing Stock

There are currently 5,813,571 solid wall houses, which comprised 28.1% of the total England housing stock as of 2006 as shown in Table 6 and Figure 2.7 (Baker and Preston, 2006). According to the Department of Energy and Climate Change (2013), 19.1 million homes have cavity walls and 7.9 million homes have solid walls, which is now 29%. The proportion of solid wall housing stock remains almost the same when Northern Ireland, Wales and Scotland are included. London and the North West are the regions where the largest number of solid wall housing is distributed respectively.

Table 6. Number of Solid Wall Housing Stock in England, 2006 (Centre for Sustainable Energy, 2006)

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According to the research on energy improvement in various housing types (EST, 2009; 2010), solid wall homes have the largest potential to reduce energy demand and CO_2 emission as shown in Table 7.

Table 7. Energy Efficiency Improvement Comparison Table (EST, 2009; 2010)

House type	Current EPC	CO_2 Emission (tons/yr)	Upgraded EPC	CO_2 Emission (tons/yr)	CO_2 Reduction		Energy Cost Savings
					Tonnes/year	Percentage	
Solid walled detached	F	13.7	B	3.0	10.7	78%	£1,651/yr
Solid walled end terrace	F	6.5	B	2.8	3.7	57%	£993/yr
Solid walled mid terrace	E	6.7	B	2.6	4.2	62%	£651/yr
1950s semi-detached	E	6.5	B	2.6	3.9	60%	£658/yr
1960s semi-detached bungalow	E	6.2	B	2.1	4.1	66%	£695/yr
1980s detached	E	7.7	B	3.3	4.4	57%	£663/yr
1980s mid floor flat	E	4.2	B	2.1	2	49%	£528/yr
Post 2002 mid terrace	C	3.4	B	2.4	1	29%	£171/yr

Therefore, the energy improvement of solid wall housing is an opportunity to contribute towards the 80 % CO_2 reduction. However, only 3% of solid wall stock (209,000 homes) has been insulated as of July 2013 as shown in Figure 2.8, while cavity wall and loft insulation has been adopted about 70%.

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Figure 2.7 Insulation adoption rate (DECC, 2013b)

The low adoption rate of solid wall insulation is mainly because of the cost for solid wall house refurbishment. As shown in Table 8, cavity wall insulation is financially less of a burden than solid wall insulation, and has a short payback period (EST, 2013). In addition, disruption to households is associated with solid wall insulation. As a result, relatively cheap and easy insulation measures, such as cavity wall and loft insulation, have been adopted. This is known colloquially as ‘low hanging fruit’.

Table 8. Cost and Payback Period Comparison between Cavity Wall and Solid Wall (EST, 2013)

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2.6 Conclusion

Currently, 65% of the total UK housing stock is privately owned, and 78% of total UK housing stock has been built before 1980 when energy performance standards were lower than modern standards. As a result, current energy performance shows an EPC rating of between D and E, which requires energy improvement for CO_2 and energy demand reduction. In particular, only 3% of solid wall housing is insulated while 70% of cavity wall housing is insulated, although the largest potential lies in solid wall insulation to save energy cost and reduce CO_2 emission. This situation is due to the higher costs for solid wall insulation than cavity wall insulation. Therefore, owner occupied solid wall housing is the most crucial target to improve energy efficiency (EST, 2009; 2010), and consequently, this thesis targets owner occupied solid wall housing to research a way to contribute to the 80% CO_2 reduction.

Chapter 3 Housing Refurbishment and Approach

3.1 Introduction

This chapter establishes the contextual background of sustainable housing refurbishment for improving energy efficiency, and identifies challenges faced by the UK housing sector in undertaking housing refurbishment in a sustainable manner. This chapter comprises five main sub-chapters:

1) Background information about refurbishment
2) Current status of the UK housing sector
3) Background information about sustainable housing refurbishment
4) Current status of sustainable housing refurbishment in the UK
5) Current strategy for whole-house refurbishment

This chapter will identify the importance and need for sustainable whole-house refurbishment to achieve the 80% CO_2 reduction. Then, the challenges for sustainable whole-house refurbishment will be revealed, and possible solutions for developing an affordable whole-house refurbishment will be explored.

3.2 Background

Refurbishment is considered a better option than demolish-and-rebuild because of the financial and environmental benefits from refurbishment of existing buildings. Radian housing association (2011) refurbished a hollow precast concrete wall house built in the early 1950s with the EPC E rated by insulating the wall, floor and loft, and installing new heating system. As a result, it was identified that refurbishment is financially beneficial as new build housing costs an average of £144,700 per house while it costs £91,900 for refurbishment. In addition, the total lifetime CO_2 emission (50 years of life expectancy) from refurbished houses is less than new builds as 139 tonnes CO_2 emission compared to 191 tonnes. Furthermore, environmental benefits in terms of embodied CO_2 in existing housing can be achieved when refurbishing a house rather than demolish-and-rebuild (Palmer et al, 2006; Livingstone, 2008; Riley and Cotgrave, 2011). According to Building and Social Housing Foundation (BSHF, 2008), refurbished homes can make an initial saving of 35 tonnes of embodied CO_2 per property compared to new build homes. New builds are responsible for 50 tonnes of embodied CO_2 while refurbishment is responsible for 15 tonnes, although new homes eventually make up for the high embodied CO_2 through lower operational CO_2. There are two types of CO_2 emissions associated with a building: embodied CO_2 and operational CO_2. The embodied CO_2 is associated with the quantity of CO_2 emitted to construct a building, including all the CO_2 emissions generated in the production of raw and manufactured materials for the construction. Operational CO_2 is associated with general day-to-day use of the building, primarily through water and space heating. Operational CO_2 is generally the largest contribution to CO_2 emissions in existing buildings at around 75-90%. About 10-25% of CO_2 emission from existing buildings is attributable to the embodied CO_2 of the building fabric (Construction Products Association, 2012). Therefore, poorly insulated and energy inefficient housing, in particular solid wall housing, generates more CO_2 as it loses more energy. Furthermore, the embodied CO_2 will become more important for housing refurbishment as new homes will be zero carbon homes from 2016. Indeed, two essential factors should be considered in order to achieve sustainability in housing refurbishment: good insulation and use of construction materials with low embodied CO_2 (Doran et al., 2009).

In order to reduce CO_2 emission and improve energy efficiency, many practitioners and researchers argue that the UK government should provide advices and incentives to refurbish existing housing stock (Boardman et al., 2005; Sustainable Development Commission, 2006; UK Green Building Council, 2008). Based on the increased attention to the existing housing stock, there have been various UK government schemes to encourage refurbishment such as Community Energy Saving programmes (CESP), Carbon Emissions Reduction Target programme (CERT), Warm Front and Green Deal. Most of these schemes are focused on refurbishment measures such as cavity wall insulation and loft insulation with relatively low initial costs, a short payback period, and less disruption to house occupiers than other refurbishment measures such as solid wall insulation and floor insulation (WWF 2008). Consequently, this measure approach has been increasingly adopted by households to receive government funding (Construction Products Association, 2010). For example, the cavity wall insulation was adopted by 792,000 households by 2005, and the number of households was increased to 4,549,000 by 2012 (DECC, 2012).

However, if such measures are mainly adopted in housing refurbishment, this approach is capable of achieving limited CO_2 reduction – 25% to 35% (McMullan, 2007; Thorpe, 2010), which is far below the 80% reduction needed. As a result, there is increasing consensus among researchers that comprehensive whole-house refurbishments are required to achieve the reduction target in the housing sector (Boardman, 2007; Killip, 2008). Furthermore, the UK government already placed emphasis on the importance of the potential value of a whole-house refurbishment approach by CESP and Heat and Energy Saving Strategy (HESS) (Reeves, 2009), and released the whole-house refurbishment strategy to improve the efficiency of individual homes (DECC, 2009a).

3.3 Current status of the UK housing sector

The UK Construction sector directly contributes an average of 8% to the UK GDP as shown in Figure 3.1. Construction output amount was approximately £112 billion in 2013.

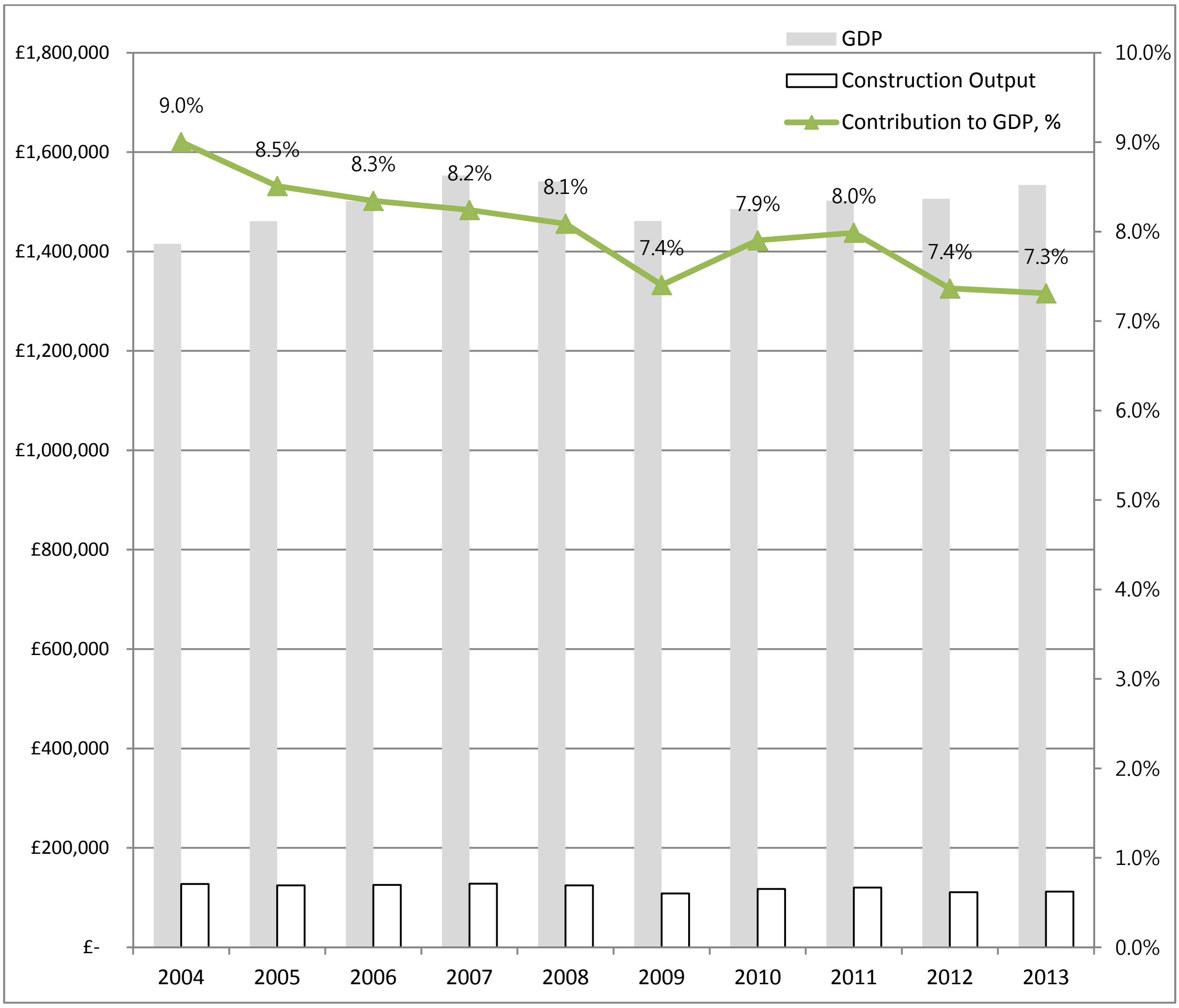

Figure 3.1 GDP (ONS, 2014b) and Construction Output in the UK (ONS, 2014c), Unit: £ million

The total construction output is divided into New Work and Repair and Maintenance Work as shown in Figure 3.2. The output of new work declined between 2007 and 2009, and bounced back after the third quarter of 2009. In contrast with new work, the output of repair and maintenance remains steady. The housing sector alone, including both new housing and repair and maintenance, contributes more than 30% of the total construction output as indicated in Figure 3.2, and as of 2013, the total housing output was £43 billion, which is equivalent to 38.5% of the total construction output.

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Figure 3.2 Distribution of construction sector output (ONS, 2014), Unit: £ million

An average of 19% of the total UK construction works is in repair and maintenance in the housing sector as shown in Figure 3.3. As of 2013, the total value of construction output was £112 billion per annum and the value of housing repair and maintenance alone was £21 billion per annum. Total repair and maintenance took 48% (out of £43 billion per annum). Based on these statistics, it is obvious that refurbishment work is undertaken extensively in the UK. The refurbishment of existing buildings is a cost effective choice, and in many ways is a more desirable option due to social, economic and environmental benefits compared with demolition (Atkinson et al., 2009). In particular, a large amount of energy is used to build a house, which is referred to as *embodied energy* that will disappear when demolition is executed. Therefore, in terms of sustainability, conserving natural resources, reusing construction materials, and improving financial effectiveness can be achieved by refurbishment. The capital cost spent on housing refurbishment alone amounts to only £4 billion a year, while most capital costs are mainly spent on repainting, essential repairs, redecoration and new bathrooms and kitchens, all of which are not related to energy efficiency improvement (ONS, 2012). If the clients' focus can be directed toward energy efficiency improvement and CO_2 reduction, the capital cost could be utilized to refurbish a house for energy efficiency improvement with repairs and redecoration.

Figure 3.3 Output of the Housing Sector and % Contribution (ONS, 2014), Unit: £ Million

3.4 Sustainable Housing Refurbishment

The construction industry has long been regarded as one of the major contributors towards a negative environmental impact due to the high amount of waste and energy consumption generated from activities related to demolition and construction (Lau et al., 2008). In particular, 10-15% of construction materials were delivered to the construction site, and ended up as wastes (HM Government, 2010). As public awareness about the importance of sustainability has grown, the construction sector has become one of the industry sectors blamed by the public for its negative influences on the environment. Consequently, sustainable buildings have become a major consideration in the construction industry with one important characteristic: a sustainable building remains environmentally responsible and energy efficient throughout its life cycle. Since major CO_2 emission, approximately 80%, is generated at the use phase of a house (Business Innovation and Skills (BIS), 2011), it is essential to carry out sustainable housing refurbishment to achieve the targeted CO_2 reduction effectively and efficiently. In particular, only 1% of existing housing stock meets modern energy performance standards, and therefore the remaining 99% of existing housing should be the main target to achieve CO_2 reduction through sustainable refurbishment.

However, due to fragmented systems, current construction projects face challenges to achieve sustainability in their daily practices. In order to achieve this sustainability and deliver a sustainable building, the final outcome of the design phase should result in an integrated design including information concerning engineering, construction and use of a building (Zeiler et al., 2011; Cotgrave and Riley, 2012). Researchers (Carter and Fortune, 2008; Hall and Purchase, 2006) argue that there is a lack of understanding regarding the implications of achieving sustainability, and sustainable refurbishment is a difficult method to apply unless there is a clear understanding of sustainability in the construction industry. Sustainability in the context of in the construction industry will be discussed in the following section.

3.4.1 Definition of Sustainable Construction

The term Sustainable Construction is rooted in sustainable development, which is defined by the Brundtland report as:

"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987)

This definition is the most widely accepted across the world, and affects regulations and policies regarding environmental and sustainable issues (Carter and Fortune, 2008; UKSDS, 2005). Recently, sustainability has emerged as a corporate strategy and an integral part of business plans in various industry fields (Enquist et. al., 2006; Epstein, 2008). As various industries pursue sustainability in their practices, the construction industry has also shifted its focal point from profitability to sustainability (Reed, 2006; Ruddock and Ruddock, 2010).

Currently, sustainable construction is broadly defined in the literature by various researchers. Kibert (1994) splits sustainable construction into six categories: 1) the minimisation of resource consumption, 2) the maximisation of resource reuse, 3) the use of renewable or recyclable resources, 4) the protection of the natural environment, 5) the creation of a healthy, non-toxic environment, and 6) the pursuit of quality in creating a built environment.

While Kibert focused on categorizing the characteristics of sustainable construction, Eid (2002) focused on the importance of the process of sustainable construction:

“a process promoting affordable solutions to the problems of the build environment that are ecologically intelligent, use benign energy, respond to local conditions and eliminate the concept of waste”.

In addition to these early definitions, there have been various definitions of sustainable construction as shown in Table 9.

Table 9. Definition of Sustainable Construction

Sustainability Categories	Definition
Environmental	Preservation & enhancement of biodiversity
	Creation of a healthy, non-toxic environment
	Energy and water efficient over life in the built environment and construction process
	Minimisation of energy usage in construction and use
	Minimisation of resource consumption throughout project life cycle
	Maximisation of use of renewable or recyclable resources
	Conservation of water resources
Social	Respect people and the local environment
	Provide benefits to the surrounding community, for instance through economic activity and involvement
	Training and retaining skilled construction work forces
	Least social impact as is feasible both socially and economically
Economic	Continuous monitoring of companies' sustainable performance and benchmarking best practices
	Redefining construction processes to be more responsible to the environment
	A process promotes the build environment to be ecologically intelligent, use benign energy, respond to local conditions and eliminate the concept of waste.
	A construction process which incorporates the basic themes of sustainable development.
	Planning and managing a construction project to minimise the impact of the construction process on the environment.
	Process oriented principles with four pillars such as social, economic, biophysical and technical aspects
	A commitment to reduce carbon footprint and consumption of natural resources through whole life value improvement.
	Adopting lean construction practice and minimise waste
	Pursuing quality in creating the built environment
	Promotion of best practice construction procurement and supply chain integration for whole life value

References: Kibert, 1994; Holliday, 2008; Parkin, 2000; Khalfan, 2002; Eid, 2002; McLennan, 2004; DTI, 2006; HM Government, 2008; Glavinich, 2008; Tan et al, 2011

Although various researchers defined sustainable construction in many different ways, these definitions share important characteristics such as process-oriented practice, wise use of resources and minimisation of waste and energy consumption. Subsequently, to clearly understand and define sustainable refurbishment, this research identified a more comprehensive definition of sustainable construction based on Table 9.

Sustainable construction is a holistic process-oriented approach to achieve sustainability throughout the entire life cycle of the built environment via planning minimisation of waste and energy consumption and protection of the natural environment as is economically feasible through effective collaboration among project stakeholders.

Another important characteristic of sustainable construction has been added to existing definitions which is an effective collaboration among stakeholders. Collaboration is a key ingredient of sustainable construction because sustainability of a building can only be achieved by integrating diverse sustainable aspects such as building designs, energy efficiency, CO_2 performance and construction materials throughout a project life cycle based on collaboration of project stakeholders. Thus, new definition is provided to establish a common understanding of sustainable construction in this research by add another important characteristic of sustainable construction.

3.4.2 Definition of Sustainable Housing Refurbishment

The definition of sustainable construction has been discussed to clearly understand the implication of sustainable refurbishment as it is one type of sustainable construction. From this point onward, sustainable refurbishment will be discussed, and in order to do this, the definition of refurbishment should be discussed first. Indeed, William and Dair (2006) asserts that all project participants in sustainable refurbishment projects should understand the meaning of sustainability and embrace the principle in their practice in order to deliver sustainability in the housing sector. As shown in Figure 3.4, a building life cycle after the construction phase comprises a number of points that require different levels of intervention to a building such as maintenance, repair, replacement and refurbishment respectively (Riley and Cotgrave, 2011). Refurbishment occurs toward the end of a building life cycle, which is after the maintenance and repair stages, to improve performance of a building substantially.

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Figure 3.4 Life cycle of a Building (Riley and Cotgrave, 2011)

Currently, there are various terms used in conjunction with refurbishment, and they are used interchangeably among project stakeholders such as homeowners, designers and constructors. Among other terms, there are three commonly used terms in conjunction with refurbishment (Riley and Cotgrave, 2011):

a) Conservation – The main use of the building will be altered, but the main structure will not be changed.

b) Renovation and Restoration – Work consists of renewal and repair only, and the works carried out will simply address dilapidations to avoid further degradation of the building

c) Retrofit – Fitting new and more modern systems into an existing building.

Furthermore, unclear understanding and various definitions of refurbishment cause miscommunication about refurbishment among project stakeholders, and eventually produces different understanding based on stakeholders' viewpoints as shown in Table 10. For example, a homeowner might regard refurbishment as anything from changing a light bulb to upgrading insulation of walls, while designers and constructors might consider it reconstruction of an exterior/interior of a building (Mansfield, 2002). In addition, in practice there are other terms used interchangeably with refurbishment such as alteration, adaptation, renovation, rehabilitation, retrofitting, restoration, reconstruction (Thuvander et al., 2012; Mohammadpourkarbasi and

Sharples, 2013). The diverse terms are generated based on a) the various types of buildings such as domestic and non-domestic buildings, b) the diverse motivations of decision making based on economical, environmental, social and technological viewpoints and c) the scale of intervention (Thuvander et al., 2012).

Table 10. Definitions of Refurbishment

Definition	Reference
Alteration carried out on an existing building in an attempt to upgrade facilities to modem standards while retaining its current use	CIOB, 1987
Work which involves the structural alteration of buildings, the replacement of main services or finishes and/or the improvement of floor space and also any associated redecoration and repair work. Rebuilding behind the facade and other new building works are excluded	Hardcastle et al., 1997
The extensive repair, renewal and modification of a building to meet economic and/or functional criteria equivalent to those required of a new building for the same purpose. This may involve the installation of current standards of building services, access, natural lighting, equipment and finishes, using historic fabric as the carcass of what is, effectively, a new building	RICS, 1998
Rehabilitation, alteration, adaptation, extension, improvement, modernization and repair work carried out on an existing building to permit its re-use for various specific reasons	Egbu,1996
Work that includes reconstruction, renovation, upgrading, renewal, restoration, conservation, rearrangement, alteration, conversion and expansion	CIRIA, 1994
Maintenance undertaken (possibly including some project works) planned in advance to 'modernise' or alter a building to prevent it from slipping into obsolescence, or becoming obsolete for its required use.	RICS, 2009
Extending the useful life of existing buildings through the adaptation of their basic forms to provide a new or updated version of the original structure	Riley and Cotgrave, 2011

Based on the review of literature, it was found that there are various definitions to describe refurbishment, although they overlap partially in terms and meanings. The definition of these terms share the common context that sustainable refurbishment means improving the thermal performance of buildings for higher energy efficiency and focusing on carbon reduction through energy efficiency improvement (Burton, 2012; Thuvander et al., 2012; Mohammadpourkarbasi and Sharples, 2013). In addition, this context shares common characteristics with Low Carbon Design principles developed by the RIBA to encourage architects to deliver low carbon new buildings and refurbished existing buildings to tackle climate change issues associated with CO_2 emissions (RIBA, 2008). Therefore, sustainable refurbishment can be further defined by integrating the definitions and characteristics of sustainable construction and refurbishment.

Sustainable Refurbishment in this research is defined as follows:

Any work that is undertaken, after regular repairs and maintenance, to extend the use of an existing building focusing on the improvement of thermal performance and CO_2 reduction by adopting economically feasible and environmentally responsible refurbishment measures through collaboration among project stakeholders.

As the term refurbishment is broadly defined, the term 'sustainable refurbishment' uses the following terms:

- Low carbon housing refurbishment (Davies and Osmani, 2011)
- Sustainable retrofit or renovation (Thuvander et al., 2012)
- Sustainable energy conservation measure (Ma et al. 2012)
- Eco-refurbishment (Mohammadpourkarbasi and Sharples, 2013)
- Deep retrofit or renovation (Konstantinoua and Knaack, 2013)

3.4.3 Characteristics of Sustainable Housing Refurbishment

Existing housing refurbishment projects have three major unique characteristics compared to new build housing: a) Higher Risk, b) Complex Decision Making, and c) Fragmented Construction Practice (Diakaki et al., 2008; Kreith, 2008; Yudelson, 2010; Menassa, 2011; Thuvander et al., 2012; Ma et al, 2012; Doran et al., 2009; Burton, 2012).

The following describes each characteristic in detail.

a) Higher Risk – Refurbishment projects on existing housing are considered riskier than new builds due to the unforeseen conditions of existing housing and the uncertain outcome of refurbishment in terms of thermal performance and customers' satisfaction. Indeed, the cost for refurbishment is uncertain due to hidden or unexpected costs that cannot be identified during the early stage of a project (Plimmer et al., 2008). As the UK housing stock presents a wide variation in housing conditions, this creates challenging the situation of having to utilize standard construction materials and methods that are applicable to new builds (Gibb and Isack, 2001). Due to limited opportunities to use standardized materials and methods for housing refurbishment, the prefabrication of refurbishment materials is difficult and ineffective unless design professionals know the exact attributes of construction materials and housing condition. Furthermore, constructors face problematic situations when they work with other professionals, in particular housing services professionals, such as heating, ventilation and plumbing engineers (Burton, 2012). The challenge that arises from the fragmented nature of the construction industry often renders reworks associated with poor workmanship, overrun costs and time delays. According to Burton (2012), the main risks associated with housing refurbishment design, in relation to thermal insulation such as internal and external wall insulation, are:

a) Interstitial condensation
b) Cold bridging
c) Combustible insulation materials catching fire
d) Frost damage to old materials
e) Summer overheating

For example, when an internal wall insulation is not properly designed and constructed, moisture can condense behind the insulation resulting in mould growth. In addition, external wall insulation can cause overheating in the summer months unless proper ventilation is designed, and also structural damage could be caused if insulation materials are not properly constructed. In addition, there is a risk associated with occupants known as the Take-back or Rebound Effect, which is not related with design and construction. This effect is caused by occupants' physiological reasoning that they can save energy even if they set higher temperatures than usual after housing refurbishment is completed. For example, occupants may increase the temperature in a room, but open windows at the same time. However, this effect caused by human behaviour will not be included in the scope of this research since this thesis mainly focuses on housing refurbishment measures.

Therefore, from the outset of a project, a design professional should work with constraints given by the existing housing conditions. Housing refurbishment projects should demand appropriate skills, knowledge and experience of both designers and constructors to assess risks and integrate various aspects associated with refurbishment works.

b) Complex Decision Making – Sustainable housing refurbishment requires complex decision-making because it has to cope with diverse information such as effectiveness of refurbishment measures, financial feasibility (initial costs and payback period) and environmental impact (CO_2 reduction) simultaneously (Killip, 2008). As these three factors are interrelated, it is essential to understand them holistically, and then propose properly balanced refurbishment solutions in regards to the technical, financial and environmental impacts on the customers. Various refurbishment measures have different cost ranges with different environmental impacts based on construction materials and the elements of a house to be refurbished (Ma et al, 2012).

However, current housing refurbishment practices to estimate the outcome of refurbishment projects rely on simple cost estimation tools and the experience of construction professionals (Kreith, 2008). In the situation when housing refurbishment is carried out based on personal experience or simple ad-hoc designs, there is a high probability of risk associated with reworks resulting in unsatisfactory, financial and environmental outcomes because there is no 'one-size-fits-all' solution for housing refurbishment (Jenkins, 2010; Firth and Lomas, 2009). Moreover, in order to determine the most financially beneficial and environmentally responsible refurbishment solution, the financial benefits and the environmental impacts should be considered simultaneously from the outset of a project for proper decision making on refurbishment measures and materials. Without proper consideration of these two essential factors, the required and expected outcome in terms of improved thermal performance and CO_2 reduction cannot be achieved during refurbishment (Ma et al., 2012).

c) Fragmented Construction Practice – In order to make a proper decision making in the determination of the best possible refurbishment solution among various alternatives, a sufficient level of information about the construction materials and refurbishment measures should be provided by the project stakeholders. However, coordination among project stakeholders such as home occupants, designers and constructors is challenging due to the fragmented process of refurbishment projects as shown in Figure 3.5 (Thuvander et al., 2012; Konstantinoua and Knaack, 2013). Figure 3.5 illustrates that the construction information flow amongst project stakeholders is not seamless, as the design and construction phases are conducted separately, and customers' engagement at the brief stage is limited. Indeed, 50% of possible refurbishment alternatives that can render better outcomes of refurbishment are neglected due to a lack of collaboration among key project stakeholders (Schneider and Rode, 2010; Menassa, 2011).

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Figure 3.5 Schematic overview of a renovation process (Thuvander et al., 2012)

Although the collaboration among project stakeholders throughout the project life cycle is critical to deliver expected quality to clients, the current refurbishment practice in the housing sector prevents project stakeholders from integrating essential construction information to develop an affordable refurbishment solution at the early stage of a project. Since a house is a shelter for people to spend most of their time, the involvement of home occupants is critical and they should work closely with refurbishment project teams. Despite the importance of the early involvement of customers, actual involvement of home occupants occurs at the end of the design stage when there is additional cost and time associated with changes in design. As a result, the estimation of financial feasibility (reduced operation and maintenance costs) and environmental impact (reduced energy consumption and CO_2 reduction) cannot be confident enough to make proper decisions for refurbishment solutions (Thuvander et al., 2012), and this ineffective process results in decreased satisfaction of occupants (Yudelson, 2010);

The researchers matched the main benefits of refurbishment with sustainability categories such as social, economic and environmental aspects as shown in Table 11. The main benefits of sustainable refurbishment share similar characteristics with the benefits of sustainable construction (Williams and Dair, 2006).

Table 11. Comparison Table - Main benefits of sustainable construction and refurbishment

Sustainability Categories	Benefits of Sustainable Refurbishment
Social	- Increased employee motivation and enhanced productivity - Increased capacity to innovate and improve efficiency - Improves communication and collaborations among project participants - Reshaping tenant behaviour. - Support local economy and employment
Economic	- Reduced risks and costs through whole life cycle costing - Improving project economic viability: The project must achieve value for money in the long term - Improving technological efficiency: Choosing energy efficient materials with low maintenance - Better decision-making through informed balance of quality and cost - Increased shareholders' value and satisfaction
Environmental	- Reduce waste and reserve natural resources - Improved thermal performance, and minimised energy consumption and pollution - Recovering waste, reuse and recycle materials. - Protect biodiversity and the natural environment. - Use of new technologies that can reduce the dependence on non-renewable energies.

3.5 Current Status of Sustainable Housing Refurbishment in the UK

There are two major approaches to housing refurbishment: the measure approach and the whole-house approach. The measure approach focuses on the installation of an individual refurbishment measure such as cavity wall insulation, loft insulation or double glazing installation. In contrast, the whole-house approach considers all the potential refurbishment measures holistically including the fabric, services and renewable energy systems. Currently, the UK government has initiated a series of government incentive schemes such as Community Energy Saving Programmes (CESP), the Carbon Emissions Reduction Target programme (CERT), Warm Front, the Renewable Heat Incentive (RHI) and Green Deal to improve the energy efficiency of the existing housing stock. Most of these schemes have placed more weight on the measure approach than the whole-house approach due to the relatively low upfront costs such as cavity wall insulation and loft insulation (WWF, 2008). Consequently, due to its economically viable and less disruptive nature, the measure approach has been increasingly adopted by households (Construction Products Association, 2010). As of 2012, loft, cavity wall and solid wall insulation have been adopted in UK households at 17.5%, 8% and 0.2% respectively as shown in Figure 3.6 (DECC, 2012).

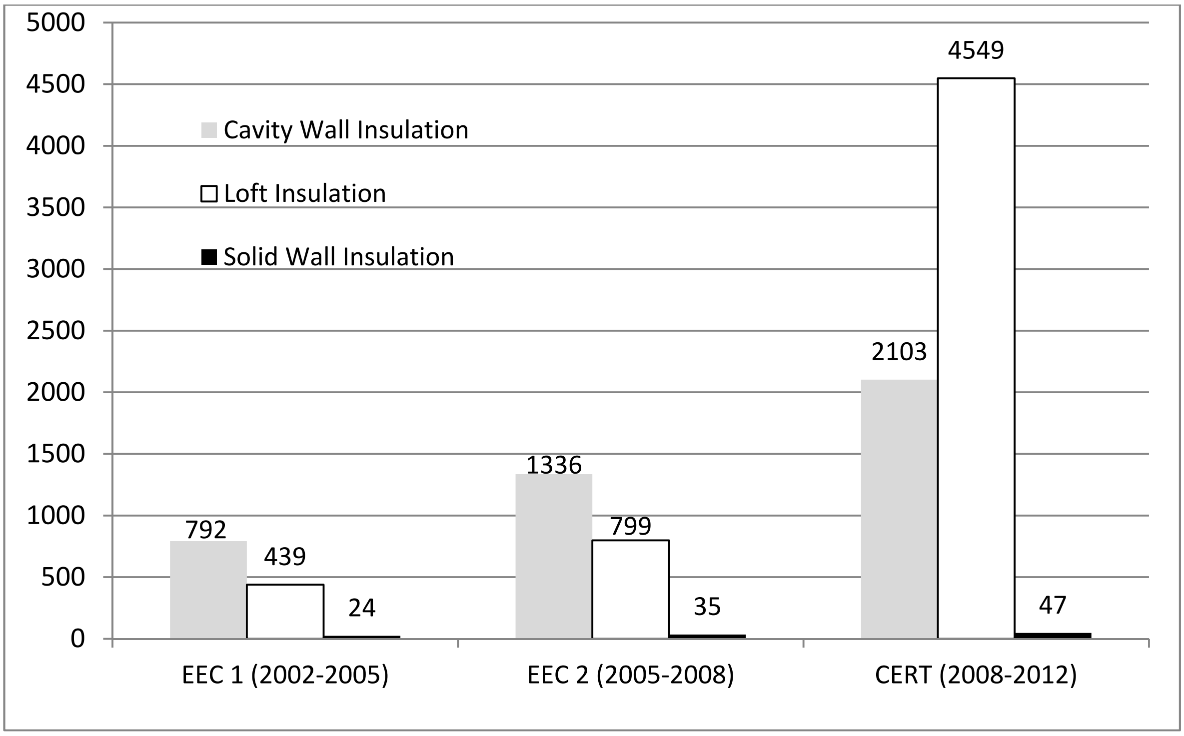

Figure 3.6 Insulation measures installed under EEC and CERT (thousands of households)
(Y axis is Number of Households, thousands of households)

However, despite government schemes and the benefits of sustainable housing refurbishment (see Table 11), the uptake of refurbishment measures is low regardless of the approaches, as shown in Figure 3.6. Particularly, solid wall insulation, which requires high initial cost and disruption, shows extremely low uptake (See Figure 3.6). Based on various studies regarding the 80% reduction by 2050, it is technically feasible to achieve the target through housing refurbishment (BRE 2005; Johnston et al. 2005; Boardman et al. 2005; Boardman 2007; WWF 2008), and the whole-house approach is required since the measure approach can achieve only limited energy efficiency improvement. However, the measure approach should not be ignored because this could be used as a starting point to improve the whole house up to a higher energy standard. Jenkins et al. (2012) assert that it is unlikely to achieve more than 50% CO_2 reduction by adopting measure approaches based on short payback periods. There are also critiques about the refurbishment measure approach among researchers that the current piecemeal approach to housing refurbishment will eventually lead housing refurbishment projects to be carried out in an unsustainable manner (Hall and Purchase, 2006; Thorpe, 2010; DECC, 2012).

As a response to this problematic situation, there is increasing consensus among researchers that comprehensive whole-house refurbishments, a combination of fabric refurbishment measures and renewable energy systems, are required to achieve the 80% reduction target in the housing sector (Reeves, 2009; Boardman, 2007; Killip 2008; SDC, 2005). In particular, the CESP and Heat and

Energy Saving Strategy (HESS) placed weight on the importance of the potential value of whole-house refurbishment approach (BRE, 2008; Reeves, 2009), and the UK government released the whole-house refurbishment strategy, which is named as the 'Great British Refurbishment' policy, that aims to refurbish 80% of the housing stock by adopting whole-house refurbishment approach by 2020 (DECC, 2009a; 2009b).

Olgyay and Seruto (2010) argue that whole building retrofit is the best way to tackle current problems and issues caused by climate change. Currently, there are 100 homes being refurbished by adopting whole-house refurbishment supported by the government programme 'Refurbishment for Future'. However, the majority of the homes being refurbished are in the social housing sector, and the focus of housing refurbishment still leans more toward the existing social housing sector (Killip, 2008), which only accounts for 17% of the UK housing stock, while 65% of UK housing is privately owned (DCLG, 2014).

Therefore, it seems evident that substantial whole-house refurbishments in the owner-occupied housing stock should be undertaken in order to achieve the 80% CO_2 reduction target. The current government strategies for housing refurbishment could be unsuccessful in improving the overall energy efficiency and reducing CO_2 emission in the housing sector, as there is a limited control over private owned housing.

3.5.1 Barriers in the Whole-house Refurbishment

The most important benefit of the whole-house approach is that houses can be refurbished in a sustainable manner with the correct sequence using appropriate construction materials. This approach could be more expensive and disruptive since the whole house will be refurbished, however significant energy savings and CO_2 reduction can be achieved immediately since all the refurbishment works will be carried on at once (Construction Products Association, 2010). Furthermore, the whole-house-refurbishment approach involves a comprehensive energy simulation to identify all the required refurbishment measures (DECC, 2009a; HM Government, 2009a), and to provide the best refurbishment solutions that are feasible to customers both economically and environmentally. In addition, whole-house refurbishment reduces demolition waste and landfill usage. Since it reuses structures, components and materials of existing housing where possible, it enhances embodied energy conservation. Furthermore, there is the benefit of social sustainability as the outcome of refurbishment brings positive social effects such as improved conditions for local communities and transport, schools and facilities (Power, 2008).

However, currently there are few housing refurbishment projects that are adopting the whole-house approach and even the simple refurbishment measure approach such as loft and cavity wall insulation is not widely adopted. This is because barriers are caused by two essential project stakeholders: clients and the construction sector. Depending on the viewpoint of stakeholders, the barriers to whole-house refurbishment are summarized in Table 12.

Table 12. Barriers to whole-house refurbishment

Viewpoint	Barriers
Clients	Little understanding about home occupants' preferences
	Perceived costs exceed perceived benefits (High initial cost and disruption)
	Little knowledge about sustainable refurbishment technologies
The Construction Sector	Fragmented nature of the construction sector
	Ineffective process to determine refurbishment solution
	Lack of skilled construction personnel

Source: Menassa, 2011; Owen, 2011; Energy Saving Trust, 2011; DECC, 2011; Konstantinoua and Knaack, 2013; Thuvander et al., 2012; Davies and Osmani, 2011

Viewpoint of Clients

The primary barrier is a lack of understanding about home occupants' preferences. Sustainable refurbishment should provide satisfaction and meet their requirements. However, in reality, householders do not usually receive the satisfaction from the outcome of sustainable refurbishment, since the required designs and materials based on their expectation and preferences are not fully understood by construction professionals (Burton, 2012; EST, 2011; DECC, 2011). Various researchers emphasize the importance of a balance between technical refurbishment solutions and occupants' preferences because technical solutions appealing to home occupants can improve customer satisfaction, and will increase the uptake of refurbishment (Bordass and Leaman, 2005; Crosbie and Baker, 2009; Steemers and Yun, 2009; Gram-Hanssen, 2010). In addition, Loveday et al. (2011) argue that housholders have different levels of acceptability of refurbishment solutions proposed by construction professionals. Rysanek and Choudhary (2013) assert that instant visualisation and comparative analysis of different refurbishment alternatives about financial and environmental benefits should be provided to customers in order to improve their satisfaction and to increase uptake of refurbishment solutions.

Furthermore, various researchers (Klotz, 2011; Gillingham et al., 2009; Schleich and Gruber, 2008) assert that customers' preferences should be scrutinized first because customers do not always select the financially and environmentally best refurbishment solutions when the solutions are not satisfactory compared to their requirements or priorities.

The secondary barrier to adopting whole-house refurbishment is identified as the high initial cost. According to a customer survey report (DECC, 2011), the overall annual savings from refurbishment measure approaches - loft and cavity wall insulation and window replacement - are between £5 and £30. The majority of surveyed households consider that the amount of energy savings too small to be worth investment, and want a shorter payback period of less than ten years. Therefore, it is more challenging to convince customers to adopt the whole-house approach since customers have the perception that even simple measure approaches are not worth investment. Indeed, according to EST (2014), the whole-house approach, when loft, wall and floor insulation are installed at once, will cost about £14,140 with annual savings of £595, while the loft and cavity wall insulation costs an average of £240 and £545 respectively with annual energy saving £5 to £30. According to a report released by St Vincent's housing association (SVHA, 2013), a whole-house refurbishment project, which adopts whole-house fabric insulation and renewable energy installation, costs £24,277 with annual energy savings of £651. As a result, customers consider that the benefits of whole-house approach is low because this requires high initial cost along with disruption during the project, which is not worth tolerating due to the small amount of energy savings and long payback period (Owen, 2011; BRE Trust, 2005; Mansfield, 2009).

The tertiary barrier is a lack of knowledge about sustainable refurbishment technologies. Most households have limited information about refurbishment measures and find it difficult to understand the refurbishment solution proposed by construction professionals (Juan et al., 2009). Thus, this weakness makes customers vulnerable since they can easily misjudge or cannot determine which refurbishment solution is the best choice for them financially and environmentally compared to other proposed alternatives (Owen, 2011). Furthermore, frequently the housing refurbishment projects are carried out by SMEs who are recommended by personal referrals, or even sometimes by unskilled and inexperienced contractors who are known as “cowboy” builders (Ranaweera and Prbhu, 2003). As a result, customers have trust issues about construction professionals, resulting in a perception among customers that construction professionals often suggest untrustworthy refurbishment cost estimations and solutions (Forum for the future, 2012; Juan et al., 2009). In addition, the NHBC Foundation (2012) addressed issues about terminologies for refurbishment technologies since these terms are often complex and not easy for homeowners to understand, and also not easy for construction professionals to explain. Therefore, the use of simplified terminologies is recommended for the effective and efficient explanation about a refurbishment solution.

Viewpoint of the Construction Sector

The construction industry has long been regarded as deeply unfriendly to its customers, and fragmented in practice (NHBC, 2013; CIC, 2013a). From the Latham (1994) report to recent research (Klotz, 2011; Rysanek and Choudhary; 2013), there have been arguments that clients' needs and requirements should be incorporated into a design from the outset of project to deliver quality outcome and satisfy clients. In particular, ineffective decision-making at the early design stage will lead to significant impacts on the time and cost of a project, and also generate reworks (Basbagill et al., 2013; Konstantinoua and Knaack, 2013; Schlueter and Thesseling, 2009). Rysanek and Choudhary (2013) assert that refurbishment projects should utilize a tool to support informed decision making among various refurbishment alternatives, while considering multiple criteria such as the implication of cost and the environmental impact. Thus, in order to provide a technically buildable, financially feasible and environmentally responsible refurbishment solution for customers, diverse information regarding refurbishment measures should be communicated and coordinated among key project stakeholders from the early design stage.

The second barrier is associated with an ineffective refurbishment process to determine proper refurbishment solutions. In particular, whole-house refurbishment requires careful decision making processes to formulate a financially and environmentally feasible solution by considering life cycle costs and CO2 performance of a refurbished house. As individual refurbishment measures for improving fabric, services and the installation of renewable energy systems configure a whole-house refurbishment solution collectively, it is critical to make the right decision on refurbishment measures and materials, which impacts the level of sustainability of a refurbishment solution. According to the Carbon Trust (2011), the actual energy use of a sustainable building is consumes five times more than that estimated during the design phase, and the total amount of energy savings is actually measured as less than half of the estimated savings (Hong et al., 2009). Thus, it is important to carry out a whole-house refurbishment project with proper management of information and activities following the right process.

However, the current construction practice cannot integrate project stakeholders from the outset of a project as it is fragmented, and this situation causes unnecessary reworks and waste derived from data conflicts of design and communication among project stakeholders. Reworks due to poor detailed drawings and miscommunication cost about £1 billion annum in the UK (Autodesk, 2008). When changes occur in a design, labour-intensive works are mandated to integrate all the modifications into various separate design documents and to generate updated design documents and information accordingly.

Finally, there is a skill shortage problem in the construction sector (CIOB, 2011b). As previously stated in the sub-section 3.4.3, sustainable housing refurbishment has higher risks and complex decision-making processes. Thus, various factors of refurbishment such as the financial viability, technical feasibility and environmental impacts should be considered and well integrated to provide a reliable refurbishment solution to customers. However, currently there are not enough skilled and experienced personnel to make informed decisions about sustainable refurbishment solutions (Forum for the future, 2012; CIOB, 2011b), and furthermore, there are no incentives or compensation for construction professionals to adopt sustainable housing refurbishment practices (Davies and Osmani, 2011). SMEs represent 92% of the UK construction industry (UKCG, 2009), and SMEs are especially dominant in the housing sector. They are influential in the outcome of refurbishment projects, however they are not engaged in the sustainable refurbishment practice since they have insufficient skills and knowledge regarding sustainable refurbishment (Brammer and Walker, 2011; Studer et al., 2006).

Eventually, this problematic situation causes trust issues between customers and construction personnel since customers are unsure where to obtain informed advice and good quality work. Furthermore, there is a lack of standards and guidance for existing housing refurbishment to facilitate proper decision-making. The Code for Sustainable Homes and Building Regulations mandates the construction of new houses for energy performance standards, and there is a BREEAM Domestic Refurbishment methodology, however it is not a compulsory scheme.

In summary, there is a vicious cycle presented between customers and construction professionals in the housing sector. Currently, refurbishment solutions are proposed to customers based on construction professionals' priorities although it should more focus on occupants' needs. Furthermore, there is no standardized process to generate a financially and environmentally feasible whole-house refurbishment solution by considering life cycle cost and CO_2 performance. Consequently, a lack of trust about construction professionals is presented among customers. Therefore, in the following chapters, home occupants' needs, the sustainable housing refurbishment process and the proper tools to formulate financial and environmental impacts will be discussed.

3.5.2 Home Occupant's Preferences for Housing Refurbishment

Currently, high initial cost for whole-house refurbishment is the primary barrier to clients, and indeed the high capital investment could be a burden for people to prepare in a short time period. Nevertheless, whole-house refurbishment should be adopted to tackle CO_2 issues and energy problems in the housing sector. According to the research carried out by Ipsos MORI (SSN, 2006), 92%

of survey respondents addressed their preference to have sustainability features in their new homes. 52% of respondents indicated that they are willing to pay more for sustainable features in addition to the price of their homes, with 31% of these saying they are willing to pay from £2,000 to £10,000 more. In addition to this survey, the Energy Saving Trust (2011) recently surveyed 3.9 million homeowners, and revealed that they are considering refurbishing their homes to improve energy efficiency within the next three years. 85% of these homeowners are willing to allocate about 10% more to their budget for a major refurbishment project of between £527 and £1,027. Based on this survey, it has been revealed that homeowners are willing to refurbish their houses which indicate the positive possibility of increasing the uptake of whole-house refurbishment.

Currently, the capital cost spent on repair and maintenance in the UK housing sector alone is equivalent to £21 billion a year (See Section 3.3), which spent mainly for redecoration, and new bathrooms and kitchens rather than energy efficiency improvement such as fabric insulation. If the clients' focus can be directed toward energy efficiency improvement and CO_2 reduction, the capital cost could be utilized to refurbish a house for energy efficiency improvement along with repairs and redecoration. For example, when home owners consider a kitchen improvement or an extension to their house, it is the trigger point to carry out energy improvement refurbishments such as wall or/and floor insulation as shown in Figure 3.7. Based on this information, Energy Saving Trust (EST, 2011) proposed a trigger point approach for the whole-house refurbishment. This approach requires an understanding of the refurbishment trigger-points and processes of regular home improvements based on home occupants' standpoints.

Aston University

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Figure 3.7 Trigger points for energy efficiency improvement (EST, 2010)

Indeed, Killip (2008) asserts that whole-house refurbishment can be carried out in a room-by-room approach, and emphasized that potential refurbishment measures which will be undertaken as a next step, should not be compromised by previous refurbishment works. For example, the researcher suggests considering a potential solar energy system installation when the roof refurbishment is carried out, with the installation of the necessary electric components in the roof. The most important consideration for the room-by-room approach and trigger point approach is not to compromise any potential refurbishment works which ultimately achieve the whole-house refurbishment in the future. By adopting this approach, construction professionals can provide affordable refurbishment solutions to homeowners, and have more opportunities to provide what they want, and finally gain more trust from them.

Therefore, in order for construction professionals to provide an acceptable and affordable solution that is appealing to homeowners, it is critical to understand their preferences and decision-making factors for housing refurbishment (Banfill et al., 2012). Lomas (2010) emphasizes that construction professionals should research and integrate technical and socio-technical (occupants' intention and preference) for a refurbishment solution in order to select the right refurbishment measures. Although some homeowners have an interest in understanding the complex refurbishment technologies and suggest their own combination of refurbishment measures for whole-house refurbishment, most of them are interested in what kind of combination gives the best result for their homes based on their preference in housing refurbishment (Burton, 2012). However, there is no research about homeowners' preferences for housing refurbishment and their decision making factors for selecting refurbishment measures, although there have been various studies regarding relationships between homeowners' psychological factors and refurbishment measures.

Nair et al. (2010a) carried out research on the relationship between energy efficiency improvement and the decision-making factors of homeowners. As shown in Figure 3.8, there were two main decision making factors identified: homeowners' personal factors and contextual factors.

Figure 3.8 Homeowners' decision making factors for energy efficiency measures (Nair et al., 2010a)

Based on this research, homeowners' financial status has a strong relationship with the level of investment in the adoption of refurbishment measures. It is common sense that homeowners with more financial availability would invest more on expensive refurbishment measures. However, the research revealed that homeowners' with low incomes also invested in expensive refurbishment measures such as building fabric refurbishment. The adoption rate of building fabric refurbishment shows a difference of 1% to 8% between high income homeowners and low income ones. Furthermore, the more important message from this research is that the experience of past investment in refurbishment is a strong influential factor. This research concluded that positive experiences of investing in refurbishment in the past have a positive impact on the homeowner's attitude towards future refurbishment measures.

Indeed, this statement is supported by recent studies (Davies and Osmani, 2011; Stieß and Dunkelberg, 2013) that emphasized the importance of knowledge transfer between homeowners and construction professionals regarding refurbishment measures. This research indicates that a successful refurbishment experience facilitates the adoption of further energy improvement measures. These studies reinforce the argument of Nair et al. (2010a; 2010b) that past positive experience will increase the uptake of energy efficiency measures and motivate homeowners. Eventually, the uptake of refurbishment among individual homeowners will inevitably increase to the community level of energy efficiency improvement, and finally this will contribute to achieving sustainability in the housing sector and the 80% CO_2 reduction. Mills and Schleich (2012) identified the relationship between the adoption of refurbishment and individual characteristics such as education, age and family types. This research found that a refurbishment solution that suits one person may not always be applicable to others because the acceptance is determined based on homeowners' characteristics and life style.

As mentioned in section 3.4.3, a one-size-fits-all solution cannot be achievable technically, and furthermore, the same refurbishment solutions may be accepted or rejected depending on individuals' characteristics and preferences. Therefore, researchers recommended developing a framework for generating refurbishment solutions providing feasible targets of energy efficiency improvement without compromising clients' needs. As mentioned in section 3.5.1, the interaction and balance between technical solutions and co-operation of homeowners is critical to increase refurbishment uptake. Therefore, it can be inferred that there is a room for improving energy efficiency and achieving CO_2 reduction in the housing sector by providing more homeowners' preferences focused refurbishment solutions to customers.

In spite of the importance of homeowners' preference, very little research has been done in this area. There were early efforts to identify the key decision-making factors for a sustainable housing project of stakeholders (Carter, 2005; Ding, 2005). However, the identified decision-making factors based on financial and environmental aspects are limited to the viewpoint of the construction professionals. Whole-house refurbishment requires more careful decision-making for both construction professionals and home owners; it is important to understand clients' desires and needs, and make the most feasible and energy-wise solution for clients. Gupta and Chandiwala (2010) assert the importance of home occupants' early involvement at the briefing stage of a refurbishment project in order to make refurbishment solutions appealing to clients. This early involvement would allow construction professionals to make informed decisions by understanding clients' requirements clearly from the outset of a project. The clear understanding of a customer's goal would be more productive as construction professionals could decide refurbishment measures based on the customer's preference, and eventually reworks could be reduced. Stevenson and Leaman (2010) also support the early involvement of homeowners to improve customer satisfaction, and researchers specifically pointed out that the 'Soft Landing' approach is essential to get home occupants directly involved in the refurbishment process.

In summary, homeowners' preference should be studied and identified clearly from the outset of a refurbishment project in conjunction with the improvement in the refurbishment project processes that can accommodate early involvement of customers and facilitate active communication between construction professionals and homeowners. Therefore, without efforts to better understand customers and to improve the current refurbishment project processes simultaneously, sustainable housing refurbishment will continue facing challenges in adopting whole-house refurbishment, and eventually the government mandated 80% CO_2 reduction will not be achieved.

3.6 Life Cycle Cost and Life Cycle Assessment for Whole-house Refurbishment

As energy prices continue to increase and operational energy costs become more expensive, it has become more important to keep operational energy costs lower in the use phase of the entire building life cycle. Since new builds have been constructed with higher energy performance standards with low operational energy costs, existing buildings - in particular existing housing with inefficient energy performance such as solid wall housing - are vulnerable to increasing operational energy costs. Indeed, more than 80% of the energy is consumed during a home's operation and maintenance phase (United Nations Environment Program, 2007; Hacker et al, 2008), and operation and maintenance costs are 5 times larger than initial construction cost (Evans et al., 1998). Furthermore, more than 80% of CO_2 emission comes from the operation and maintenance phase of the entire building life cycle as shown in Figure 3.9 (HM government, 2010). In addition, as each refurbishment material has a different lifespan and a different cycle for maintenance and repair, additional costs are required in addition to the initial refurbishment cost. Bowsell and Walker (2004) and the British Standards Institution (2008) emphasize the importance of Life Cycle Costing (LCC) because a small amount of savings in the construction phase could result in larger operating costs with less thermal performance than expected. Indeed, when the LCC is considerately planned, 60% of operational cost savings can be achieved over 30 years by investing 20% more capital cost in the construction phase (Flanagan and Jewell, 2005).

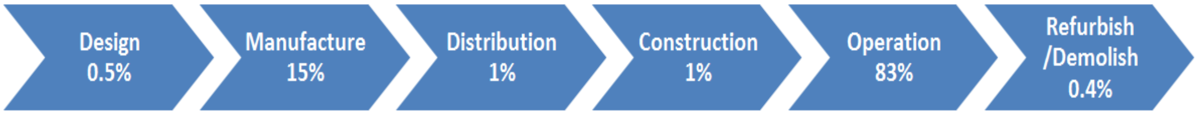

Figure 3.9 CO_2 emission of a building at each phase of entire life cycle

In order for design and construction professionals to manage the costs and environmental impacts associated with housing refurbishment through the entire life cycle of a house, the LCC should be utilized as a decision-making support tool to maximise value of investment in terms of low operational cost and life cycle CO2 emission. As shown in Figure 3.10, there is a higher potential to improve value to customers and to save on life cycle costs in the planning and design phases compared to the construction and operation phases. As changes in the later phases of a construction project tend to increase costs (PMI, 2013), consideration should be given when selecting construction materials and building designs. These should be based on LCC as this can minimise life cycle costing and extra unnecessary cost for reworks.

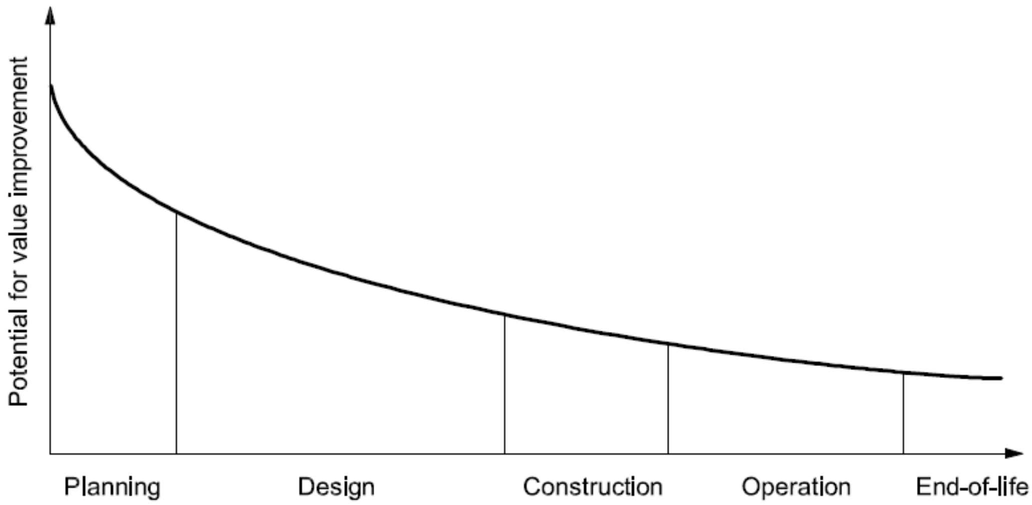

Figure 3.10 Scope to influence LCC savings over time

Currently, there are diverse economic analysis methods such as net present value (NPV), internal rate of return (IRR) and simple payback period to help make the right decision for refurbishment measures (Ma et al., 2012). However, these methods only focus on the relationship between refurbishment measures and their cost-effectiveness, although there is always a trade-off relationship between financial investment and environmental benefits (Beccali et al., 2013; Blengini and Di Carlo, 2010). Furthermore, the importance of embodied CO_2 from existing housing refurbishment is increasing since new build housing from 2016 must have zero operation energy consumed and zero CO_2 emission as shown in Figure 3.11 (NHBC Foundation, 2012). Various researchers assert that Life Cycle Assessment (LCA) enables design and construction professionals to satisfy the customers' requirements financially and environmentally because LCA quantifies the environmental impacts in terms of CO_2 emission, and supports professionals to decide the most energy efficient and environmental friendly solutions throughout the life cycle (Assiego de Larrivaa et al., 2014; Burton, 2012; Gustavsson and Joelsson, 2010).

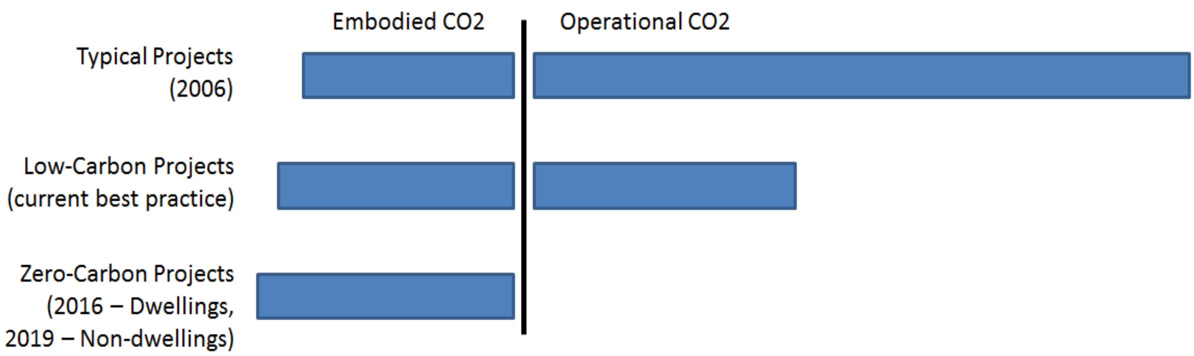

Figure 3.11 Embodied CO2 and Operational CO2 based on the UK government policy (RICS, 2012)

Therefore, a whole-house refurbishment solution has to consider the financial and environmental impacts of the life cycle of a house. In order to do this, each refurbishment measure should be considered based on LCC and LCA along with the initial refurbishment costs, although currently the majority of home occupants mainly focus on the initial refurbishment costs and payback period.

The LCC is a holistic approach to assess the financial implications of a building through its life cycle as shown in Figure 3.12.

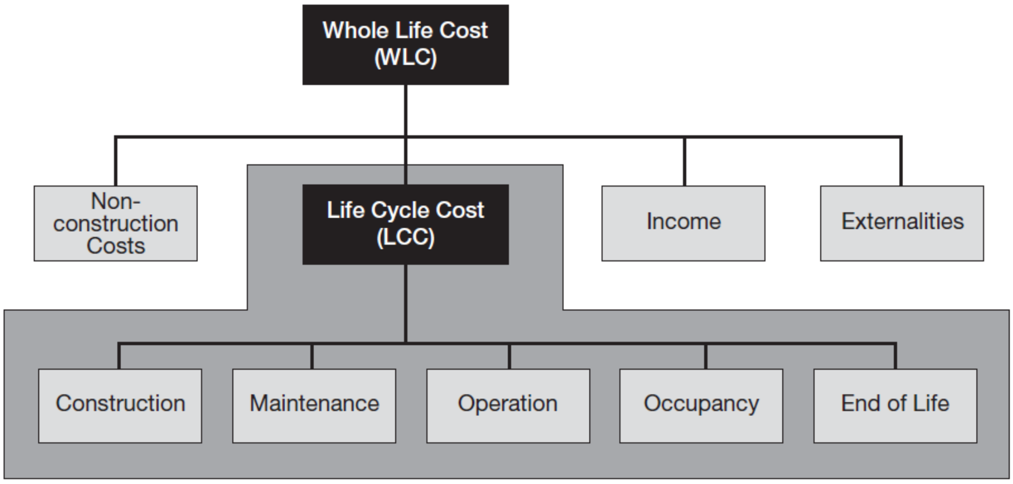

Figure 3.12 Life Cycle Cost

Life Cycle Cost is defined as:
"a methodology for the systematic economic evaluation of life cycle costs over a period of analysis, as defined in the agreed scope (BSI, 2008)."

By considering the entire life cycle of a building, the LCC methodology provides a process that enables project stakeholders to make more financially and environmentally beneficial decisions among various refurbishment alternatives from the outset of a construction project.

Secondly, LCA is defined as:

> "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (BSI, 2006)."

Embodied energy is the most important quantified criteria for an environmental impact assessment that a building generates through its life cycle (Shukla et al., 2009). Embodied energy includes direct and indirect energy consumed for the entire building life cycle, from construction materials to a constructed building and the disposal stage, as shown in Figure 3.13. Embodied energy can be assessed in term of the amount of CO_2 that is generated at each stage of life cycle assessment as follows:

- **Cradle to Gate** – Construction Material, Product Level
- **Cradle to Site** – Building Level (Housing and Refurbishment)
- **Cradle to Grave** – Entire life cycle of a building from raw material to disposal.

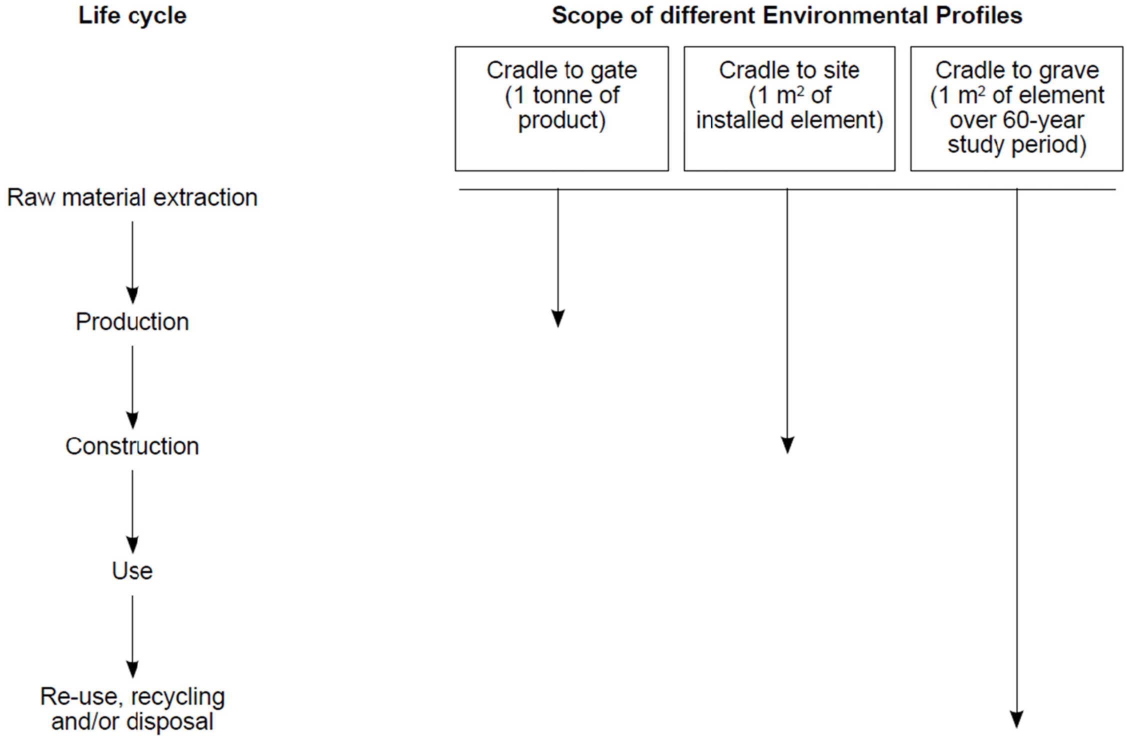

Figure 3.13 Different Stages of LCA

Currently, LCA methodology is gaining increased international attention, and particularly the European Union is focusing on LCA to quantify the environmental impacts depending on refurbishment measures (Monteiro and Freire, 2012). LCC and LCA need to be used simultaneously to determine which refurbishment measures with what kind of materials can render the most financially and environmentally appropriate refurbishment solutions. As a result, various researchers emphasize that early consideration of the sustainability of refurbishment measures regarding life cycle cost and CO_2 emission can reduce significant amounts of operational costs and CO_2 emissions after the refurbishment is completed (Anderson et al., 2009; Kreith and Goswami, 2008; Krarti, 2011). The UK government (2010) recommends that embodied energy analysis should be included in the decision-making processes at the design stage, and recently, Brighton and Hove City Council (2011) made the cradle-to-gate embodied CO_2 assessments a mandatory process when planning applications are prepared, and without complete calculation of embodied CO2, applications cannot be registered. Furthermore, these two methodologies can minimise risks associated with costs and environmental impacts through a building life cycle because the proper refurbishment solution can minimise unnecessary extra costs for repair, maintenance and reworks in the future, and eventually it will reduce the entire life cycle cost and CO_2 emissions. Thus, the LCC and LCA should be the primary methodology to compare various refurbishment solutions and to make proper decisions.

Despite the importance of LCC and LCA methodologies, there have been very few studies utilizing the LCC and LCA simultaneously in the housing sector, and even the life cycle approach is mainly considered for new builds, although this approach should be used for existing housing refurbishment projects, as can be seen in the studies conducted in Table 13.

Table 13. LCC and LCA studies in the housing sector around the world

Researchers	LCC or LCA Study Scope	Building Type	Location
Wang et al., 2005	Refurbishment and New Build (LCC)	Residential Building	Canada
Martinaitis et al., 2007	Refurbishment (LCC)	Residential Building	Lithuania
Juan et al., 2009b	Refurbishment (LCC)	Residential Building	Taiwan
Tsai et al., 2011	Refurbishment and New Build (LCC)	Residential Building	Taiwan
Asif et al., 2007	Construction Materials (LCA) - New Build	Three Bedroom Semi-detached House	UK
Hacker et al., 2008	Construction and Use Stages (LCA) - New Build	Two Bedroom Semi-detached House	UK
Hammond and Jones, 2008	Construction Materials (LCA) - Existing Houses	Apartments	UK
Monahan and Powell, 2011	Construction Stage (LCA) - New Build	Three Bedroom Semi-detached House	UK
Peuportier, 2001	Cradle to Grave (LCA) - New Build	Typical French House	France
Zabalza-Bribian et al., 2009	Construction and Operation Stages (LCA) - New Build	Single House	Spain
Ortiz et al., 2009	Construction and Operation Stages (LCA) - New Build	Single House	Spain
Adalberth et al., 2001	Cradle to Grave (LCA) - Existing Houses	Multi-Family Buildings	Sweden
Blengini, 2009	Cradle to Grave (LCA) - Existing Houses	Residential Building	Italy

Moreover, none of the above studies considered the trade-off relationship between LCC and LCA. This trade-off relationship is essential to determine a sustainable refurbishment solution because this holistic life cycle approach should provide the most sustainable refurbishment solution by identifying the intersecting point between the construction phase and operation phase as shown in Figure 23. Beccali et al. (2013) and Blengini and Di Carlo (2010) proved that operational energy and embodied energy are in inverse proportion to each other as shown in Figure 3.14.

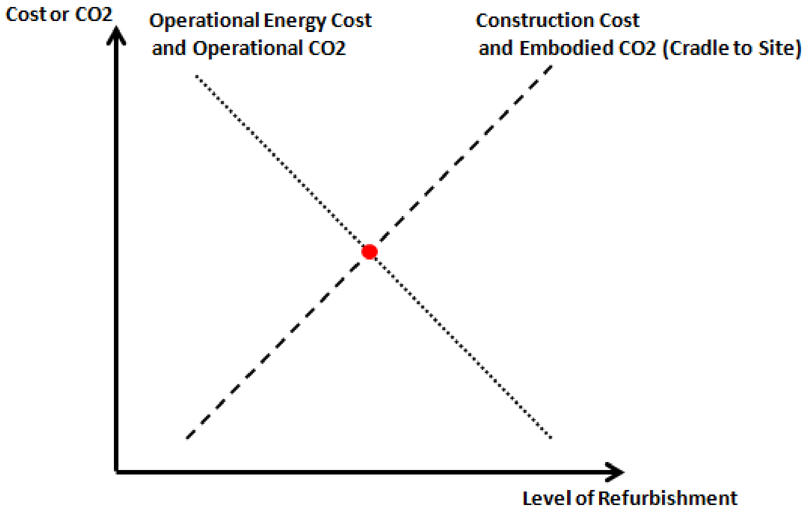

Figure 3.14 Inverse proportion between Operation phase and Construction Phase

In order to achieve lower operational energy cost and CO_2 emission in the use phase of a house, a higher amount of embodied CO_2 with larger capital investment is required in the construction phase. Minimizing the energy demands in the use phase results in an increase in the embodied CO_2 of a building due to the increase in materials and other installations, and, according to Sartori and Hestnes (2007), the amount of embodied CO_2 in a low carbon building is three times higher than in a conventional building. As a result, various researchers assert the simultaneous use of LCC and LCA for sustainable housing refurbishment is highly relevant since decision making for construction materials and refurbishment measures at each phase of a refurbishment project life cycle influence one another (Construction Products Association, 2012; Bin and Parker, 2012; Ardente et al., 2011; Sartori and Hestnes, 2007). However, LCC and LCA methodologies are not easy to use for construction projects because proper LCC and LCA datasets for construction materials and building are not available at the early design phase, and it is challenging to retrieve the necessary data from various project stakeholders due to the fragmented nature of the construction industry (Assiego de Larrivaa et al., 2014; Monteiro and Freire, 2012; Finnveden et al. 2009; Flanagan and Jewell, 2005). Furthermore, without a proper dataset for LCC and LCA, informed decisions on refurbishment solutions cannot be made (Bribian et al., 2009). Thus, these two methodologies require information sharing and collaboration among project stakeholders. If a company or organization starts using LCC and LCA, the data can be reused and updated as they continue with similar projects. Eventually, all the data they have been using will become reliable historical data. Therefore, a proper dataset for LCC and LCA should be prepared in conjunction with the improvement of current fragmented refurbishment processes. Currently, there are various software packages that can calculate the LCA in the market as listed in the Table 14 (AIA, 2010).

Table 14. LCA Software List

Name	Developer	Remark	Country
LCAidTM	University of Western Australia	LCA Evaluation Tool among Design Options	Australia
Eco-Quantum	Interfaculty Environmental Science Department (IVAM), University of Amsterdam	LCA Evaluation Tool for Residential Building	Netherlands
Envest	BRE	Environmental and Financial Tradeoffs among Design Options	UK
SimaPro	Pre consultants	LCA calculation process in this software can be edited and expanded	Netherlands
GaBi	IKP University of Stuttgart with PE Product Engineering	LCA calculation process is user-defined and not fixed. Mainly used for the automobile industry	German
VE/IMPACT	BRE with Integrated Environmental Solution (IES)	LCC and LCA Tradeoffs Calculation based on various Construction Materials	UK

Most software is designed to study the LCA of a building depending on the LCA dataset of the software developers' country. The LCA dataset should be carefully selected because the LCA study can indicate different outcomes with the same construction materials based on a specific location and the appropriate climate (Sartori and Hestnes 2007). For example, the UK and Sweden are located north of Spain and France where the climate is colder and where, as a result, a house uses fewer and lighter construction materials, such as insulation materials, depending on the climate. The Envest and VE/IMPACT (Virtual Environment/Integrated Material Profile And Costing Tool) have been developed by the BRE, a UK based organization, and they are suitable for this research since they consider LCC and LCA simultaneously. In particular, the BRE developed the VE/IMPACT software that has a capability to calculate LCC and LCA simultaneously in partnership with the IES and Technology Strategy Board based on the Envest, which use the specific database developed for LCC and LCA calculation in the UK construction environment. Furthermore, the use of VE/IMPACT is encouraged by the BREEAM assessment manual since the use of IES VE/IMPACT can get additional BREEAM credits. Currently, the GaBi and SimaPro are well-known LCA calculation tools in the industry (AIA, 2010); however there are potential issues to calculate the LCA outcomes because both software packages enable a user to customize and redefine the LCA calculation processes. As a result, the LCA outcomes can be different depending on the user. Therefore, the IES VE/IMPACT will be adopted in this research to formulate the LCC and LCA of a refurbishment solution.

3.7 Sustainable Housing Refurbishment Process

Currently, there is a lack of research has been done to develop a standardized refurbishment process to manage refurbishment projects in a sustainable way by integrating of LCC and LCA information simultaneously (Cooper et al. 2005; Leblanc et al., 2010a; Stafford et al., 2011; Burton, 2012). Although there were several refurbishment process models proposed, the models consider only one information of LCC or LCA. Researchers claim the current fragmented and unstandardised refurbishment process cannot provide a holistic approach to determine the best refurbishment solution financially and environmentally (Doran et al., 2009; Ma et al., 2012). In particular, Doran et al. (2009) pointed out that little research has been done on the planning and control processes for refurbishment. Furthermore, Cheng and Steemers (2011) pointed out the absence of an integrated decision-making model for construction professionals to estimate the financial and environmental impact of a refurbishment solution from the early design stage.

Indeed, the current refurbishment processes generate refurbishment solutions at the design phase, and this practice limits the opportunity for customers to be involved in decision making process from the outset of a project (Schlueter and Thesseling, 2009; Ma et al, 2012; Thuvander et al., 2012). As shown in Figure 3.15, the customers' involvement occurs at the end of Phase III before a refurbishment solution is finalized. Furthermore, current ineffective refurbishment project processes hinder the seamless integration of information among project stakeholders. As a result, housing refurbishment projects have become difficult to be carried out in sustainable manner, and challenging to determine whether a refurbishment solution is financially and environmentally viable based on LCC and LCA.

Figure 3.15 Refurbishment Process (Ma et al, 2012)

There are different refurbishment project phases and work stages proposed by different researchers and construction organizations as shown Table 15.

Table 15. Refurbishment Project Phase Comparison Table

<table>
<tr><th colspan="8">Project Phases and Work Stages</th><th>Ref.</th></tr>
<tr><td colspan="2">Assessment</td><td colspan="4">Design</td><td>Construction</td><td>Handover and Evaluation</td><td>A</td></tr>
<tr><td>Strategic Definition</td><td>Preparation and Brief</td><td>Concept Design</td><td colspan="2">Developed Design</td><td>Technical Design</td><td>Construction</td><td>Use</td><td>B</td></tr>
<tr><td colspan="2">Pre-project</td><td colspan="4">Pre-refurbishment</td><td>Refurbishment</td><td>Post-Refurbishment</td><td>C</td></tr>
<tr><td colspan="2">Pre-Investigation and Pre-design</td><td colspan="4">Design</td><td>Construction</td><td>Use</td><td>D</td></tr>
<tr><td colspan="2">Project Setup and Pre-Retrofit Survey</td><td colspan="2">Energy Auditing and Performance Assessment</td><td colspan="2">Identification of Retrofit Option</td><td>Site Implementation and Commissioning</td><td>Validation and Verification</td><td>E</td></tr>
</table>

*References: A - Institute for Sustainability, 2011; B - RIBA, 2013; C - Anumba et al., 2006; D - Thuvander et al., 2012; E - Ma et al., 2012

Currently, The RIBA (Royal Institute of British Architects) have outlined a plan of work (2013) that has been widely adopted in the construction industry as a generic construction phase, and recently, the Institute for Sustainability, which has a partnership with the Technology Strategy Board (TSB), published a series of documents named ‘Low Carbon Domestic Retrofit’ to provide a proper sustainable refurbishment guide to the specific construction professionals engaged in housing refurbishment projects (Institute for Sustainability, 2011). In particular, the TSB is a UK public body operated by the Department for Business, Innovation and Skills (BIS), and currently coordinates ‘The Retrofit for the Future’ program that adopt the whole-house refurbishment approach. The TSB officially encourage construction professionals to follow the guidance for proper whole-house refurbishments known as the ‘Low Carbon Domestic Retrofit Guides’. The refurbishment phases proposed by researchers share the common meanings using different terms with the RIBA and the Institute for Sustainability, and the terms are not popular amongst construction professionals compared to the RIBA and the Institute for Sustainability. Therefore, this research will adopt the refurbishment project phases provided by the Institute for Sustainability.

Poor decision making at the early design phase results in significant changes in the time and cost of a project which leads to reworks (Schlueter and Thesseling, 2009), and the cost for reworks and changes become five times larger as changes occur at later phases (Doran et al., 2009). Furthermore, various researchers emphasize that a significant portion of embodied CO_2 reduction is determined by decisions made in the early design phase, and thus construction professionals should focus on a considered selection of construction materials with low embodied energy at that stage (Konstantinoua and Knaack, 2013; Basbagill et al., 2013; Cuéllar-Franca and Azapagic, 2012;

Ellis et al, 2008). Current process models proposed for sustainable construction or refurbishment are summarized in Table 16.

Table 16. Sustainable refurbishment process model

Researcher	Model Name	Description	Remarks
Kagioglou et al, 2000	Generic Design and Construction Process (GDCPP) Protocol	A framework facilitates more effective collaboration among project stakeholders, and aligns the design and construction phases.	This framework is developed to facilitate effective collaboration and communication. This process is too generic to apply to housing refurbishment projects.
Khalfan et al., 2002	Sustainability Management Activity Zone (SMAZ)	A framework supports construction professionals to consider sustainability aspects at each construction project phase.	This framework considers sustainability aspects throughout the project life cycle, and researchers mentioned the potential use for refurbishment. However, the complexity and uncertainty of refurbishment projects are overlooked, and also LCC and LCA are not considered.
Anumba et al., 2006	Refurbishment Process Model (RPM)	A process model defines main and sub activities at each stage of the refurbishment process.	This model is specifically developed for structural demolition and refurbishment with a focus on the health and safety of the refurbishment works. This is too specified to use for housing refurbishment.
Carter and Fortune, 2008	Conceptual Sustainability (ConSus) Model	A web-based decision supporting tool to come to consensus about sustainability requirements at each project phase.	This tool is specifically developed to obtain consensus from project stakeholders on sustainability aspects at each stage of the project process. This tool requires time and effort from all project participants, and could result in time consuming works.
Juan et al., 2009	GA-based decision support system for refurbishment strategy	A genetic web-based algorithm-based decision supporting system.	This system starts with active customers' involvement to clarify their requirement, and refurbishment options are to be selected based on LCC. This system is relevant to housing refurbishment projects, although LCA is not considered.
Jenkins, 2010	Technology Assessment for Radically improving the Built Asset baSE	A model provides typical housing refurbishment variants such as fabric, service and renewable energy	This model is developed to adopt a whole-house approach, and consider all the possible refurbishment measures, while mainly focusing on CO_2

	(TARBASE) domestic model	systems to identify the most sustainable refurbishment solution.	reduction. However LCC is not considered.
Yin et al., 2011	Decision Support Model for Renovation Strategy	A flow diagram supports project stakeholders to determine financially feasible options.	This model provides a building component based payback period and energy saving analysis. However LCC and LCA are not considered.
Rysanek and Choudhary, 2012	Whole-building simulation model for refurbishment option	A model use computational tool (MATLAB/TRANSYS) to select the best option for energy and CO_2 reduction.	This model provides an exhaustive list of building refurbishment measures that mainly focus on building service and energy systems. However, the LCC and LCA are not considered.
Konstantinoua and Knaack, 2013	Toolbox Approach	A tool provides best practice for a designer to consider all possible refurbishment measures from the outset of a project.	This toolbox provides a holistic approach to the selection of refurbishment measures, and specifically aims at the whole-house refurbishment. However, the LCC and LCA are not considered.

Juan et al. (2009) argue that housing refurbishment requires a complex decision making process, and a refurbishment solution should be produced by considering all the possible refurbishment measures as a whole-house refurbishment approach does. They proposed a generic on-line algorithm-based decision supporting model for selecting refurbishment solutions based on various criteria, especially the priority of home occupants. They prioritized home occupants' requirements regarding quality using the Analytic Hierarchy Process (AHP), and calculated the trade-off relationship between refurbishment costs and quality. This model confirmed the conclusion in section 3.5.2 that the most feasible refurbishment solution should be proposed based on home occupants' preferences and economically viable cost.

Jenkins (2010; et al., 2012) proposed a step-by-step refurbishment measure adoption strategy named the TARBASE (Technology Assessment for Radically improving the Built Asset baSE) domestic model. The researcher argues that a whole-house refurbishment solution must be tailored since the same refurbishment solution results in entirely different outcomes in terms of project costs and CO_2 reduction depending on the characteristics of a house. Researchers argue that there is no universal refurbishment solution for the UK housing stock, and multiple variants such as fabric, service and renewable energy systems must be combined with considerate CO_2 reduction analysis.

Konstantinoua and Knaack (2013) suggested a toolbox approach that has the list of refurbishment measures in the shape of matrix as shown in Figure 3.16.

Building envelope					Installations	
Exterior wall	Windows	Balcony	Roof	Basement ceiling	Ventilation	Heat source
no insulation	single glazing	continuous slab no insulation	flat roof slab no insulation	no insulation	natural ventilation	gas boiler for each apartment
little/outdated insulation	double uncoated	separate slab no/little insulation	pitched roof no insulation	no insulation, basement heated space	controlled mechanical exhaust	gas boiler per block
exterior insulation, ventilated facade	upgraded existing window (glass, fittings, etc.)	insulation of the balcony slabs	insulation on the top floor	insulation on top of the basement ceiling slab	ventilation system with heat recovery (HR)	CHP installation
interior insulation	"box window"	cut out and replace balcony with thermal break	pitched roof insulation	insulation under the basement ceiling slab		air-water heat pump
exterior thermal insulation	window replacement 2ble glazing	non-insulated glass envelope / winter garden	flat roof insulation	VIP panels under the basement ceiling slab		solar collectors
double skin facade	window replacement 3ple glazing	integrated balconies in the thermal envelope	green roofs			geothermal heat pump
Photovoltaic (PE factor 0) *	shading internal	enlarged balconies	Photovoltaic (PE factor 0) *			district/ community heating
addition to exisitng building	shading external		additional floor			
one lift for one block (access via gallery)	"French windows"					

Building envelope					Installations	
Exterior wall	Windows	Balcony	Roof	Basement ceiling	Ventilation	Heat source
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Photovoltaic (PE factor 0) *	shading internal	enlarged balconies	Photovoltaic (PE factor 0) *			district/ community heating
addition to exisitng building	shading external		additional floor			
one lift for one block (access via gallery)	"French windows"					

Figure 3.16 The toolbox matrix (Konstantinoua and Knaack, 2013)

A designer can propose a whole-house refurbishment solution to customers by integrating various individual refurbishment measures listed in the toolbox, and this toolbox approach can tailor a refurbishment solution to a specific house condition. The strong point of this approach is that all the potential refurbishment measures are examined at the early design phase prior to determining a final refurbishment solution. Indeed, Thuvander et al. (2012) argue the necessity of a decision-making tool that can conduct a brief comparison between potential refurbishment measures to prune unfeasible refurbishment solutions at the early design stage. This suggested tool can enable construction professionals to focus more on feasible refurbishment measures and develop refurbishment solutions further without considering unnecessary measures. In this sense, although this toolbox does not consider LCC and LCA, it can provide an effective way of comparing the financial and environmental impacts among various combinations of refurbishment measures at the early design phase.

Through the literature review, it is identified that various researchers commonly emphasize the importance of proper decision-making at the early design phase, and the necessity of using proper tools - whether software is used or not - that can support construction professionals considering various refurbishment solutions (Rysanek and Choudhary, 2012; Christensen et al., 2006; Ellis et al., 2006; Horowitz et al., 2008). Currently, many researchers argue the potentials of BIM for formulating LCC and LCA simultaneously at the early design stage (Ma et al., 2012; Monteiro and Freire, 2012; Basbagill et al., 2013). Although there have already been various tools to calculate LCC and LCA, BIM has distinct merits in that it can analyse the cost and energy performance of refurbishment measures based on 3D models. Since BIM can perform a comparative analysis among possible refurbishment solutions, designers can make an informed decision about refurbishment measures while considering LCC and LCA simultaneously at the early design stages (Tobias and Vavaroutsos, 2009; Basbagill et al., 2013).

3.8 Conclusion

It has been widely recognized that an 80% CO_2 reduction by 2050 is impossible based on the uptake rate of refurbishment measures. In particular, the whole-house refurbishment approach is advised among researchers and practitioners for 80% reduction. However, there are three major barriers to increasing the uptake of whole-house refurbishment as follows.

1) Lack of understanding about homeowners' preferences

2) Ineffective integration of LCC and LCA.

3) Unorganized and ineffective refurbishment process

Through the literature review, it can be seen that these three major barriers could be resolved, and it would be possible to develop proper refurbishment processes that integrate LCC and LCA effectively. In addition, the refurbishment process should consider the active involvement of homeowners' preference from the early design phase. In order to improve the refurbishment process and decision-making throughout a refurbishment project life cycle, many researchers, practitioners and the government consider the use of BIM for better management of refurbishment project process and effective integration of LCC and LCA information. BIM will be further discussed in the following chapter.

Chapter 4 Building Information Modelling and Housing Sector

4.1 Introduction

This chapter develops the contextual background of Building Information Modelling (BIM), and ascertains whether BIM is suitable for sustainable whole-house refurbishment projects. This chapter is comprised of four main sub-chapters:

1) Background information about BIM
2) Definition of BIM
3) Current status of BIM in the UK
4) Current status of BIM implementation in the housing sector
5) Conclusion

As BIM is an emerging research field, the following literature review includes technical reports of software companies, the UK government's reports and other construction professional bodies, reflecting the latest developments in BIM. This chapter will provide an understanding of the benefits and barriers of using BIM for housing refurbishment, and finally explore how to use BIM for formulating an affordable housing refurbishment.

4.2 Background

It has been a central issue for construction customers to maximise value, lower cost and achieve sustainability in an industry that has been criticised for its inefficiency and lack of productivity. Sebastian et al. (2009) revealed that a 10-25% loss of efficiency occurs in each project due to unplanned redesigns and *ad hoc* modifications during the construction phase. This inefficiency results in delays in the project schedule, budget and scope, and eventually causes a quality-compromised product with a higher price (HZ, 2007). According to the National Institute of Standards and Technology (2004), $15.8 billion per annum is estimated to be spent due to inadequate interoperability among project stakeholders based on different software systems in the capital facilities sector of the US construction industry. This inadequate interoperability among stakeholders is caused by inefficient management during the design and construction phase and poor communication and maintenance of as-built data. Despite the current inefficiency in the construction industry, recent customers' design requirements have become more irregular and bespoke. These are difficult to present in a two-dimensional manner, and require more productive ways to manage the clients' design needs from the outset of a construction project. In particular, sustainable approaches to construction projects such as high energy performance with low environmental impacts are increasingly becoming one of the major considerations in the construction industry. As a result, relevant construction information has increased and become more specialized, and it has become crucial to manage and integrate the massive amount of information among project stakeholders throughout a project life cycle (Clough et al., 2008; Hooper and Ekholm, 2010). In order to achieve sustainability in the construction sector, diverse construction information such as the designs of a building, structure and services should be coordinated effectively among project participants, and integrated and updated throughout a project life cycle as changes occur. However, in the situation where changes occur in a design, current construction practice results in unproductive laborious work to integrate all the changes into various separate designs and to generate the necessary drawings. Traditionally, design development and project information management have relied on manual 2D drawings and documents, and this practice has caused many human errors and miscommunication due to misinterpretations of designs and construction documents (Cohen, 2010). As construction projects, in particular construction project information, have become more complicated to manage, current fragmented management practices cause reworks more frequently throughout a project life cycle (Smith and Tardif, 2009). Love et al. (2009) revealed that reworks cost about 11% of the original contract cost, and redesigns are the major causes of schedule delays and quality defects (Goodrum et al., 2008; Lopez et al., 2010; Sun and Meng, 2009). As sustainable housing refurbishment requires more considerate planning than a new build project for developing a proper refurbishment solution, it requires collaborative and integrated construction practice among various project stakeholders by using effective and efficient management supporting tools to formulate an affordable housing refurbishment solution.

As a response to the increasing complexity of construction projects, information and communication technology such as Building Information Modelling (BIM) has been introduced to manage, as well as achieve, sustainability in projects (Taxén and Lilliesköld, 2008; Gaith et al, 2012). BIM is currently recognized as an enabler to facilitate collaborative efforts among project participants, and to improve fragmented construction practice and productivity within the Architecture, Engineering, Construction (AEC) and Facility Management industry (Eastman et al, 2011; Bernstein, 2005; CWIC, 2004; Hampson and Brandon, 2004). Currently, BIM is regarded as a major paradigm shift in the construction industry as it is a catalyst for changes of process and culture that requires more integrated approach than before (Hannele et al., 2012; HM Government, 2012; Ibrahim et al., 2004; Succar, 2009). Furthermore, the UK government has introduced and promoted BIM in the construction industry, and BIM is mandated to be used for all public projects (HM Government, 2012).

4.3 Definition of Building Information Modelling (BIM)

This research studied the definition of BIM not only to clearly understand what it means, but also to investigate whether BIM has suitable characteristics for use in housing refurbishment. Currently, there are various definitions of BIM based on research as shown in Table 17.

Table 17. Definitions of BIM

Organization/ Researcher	Definition
NHBC, 2013	Building Information Modelling (or 'management', more appropriately) is about identifying the important information or data that is used throughout the design, construction and operation of buildings, or any other built asset, and managing it so as to make it useful to all those involved.
Jung and Gibson, 1999	Integration of corporate strategy, management, computer systems, and information technology throughout the project's entire life cycle and across different business functions
Krygiel and Nies, 2008	A creation and use of coordinated, internally consistent, computable information about a building project in design and construction
Langdon, 2012	The ability to use and manipulate objects that can have extensive data on a variety of properties associated with them (geometry, connections to other objects, thermal performance, cost, delivery, life expectancy, etc). BIM so powerful, and allows designers to produce accurate, coordinated, buildable and robust designs that can be tested in virtual 3D space before they are built
Eastman et al., 2011	A "generic technology" that in principle allows many benefits, like more efficiency in construction, less mistakes, more accurate and up-to-date information, more illustrative and accessible exposition of the building and its characteristics to all project stakeholders
National Institute of Building Sciences, 2007	A digital representation of the geometric and non-geometric data of a facility
Succar, 2009	A set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life cycle
Hardin, 2009	A revolutionary technology and process that has transformed the way buildings are designed, analysed, constructed and managed
Kymmell, 2008	A tool helping project teams to achieve the project goals through more transparent management process based on a three-dimensional (3D) model
Weygant, 2011	A technology that allows relevant graphical and topical information related to the built environment to be stored in a relational database for access and management
Graphisoft, 2003	A computer model database of building design information, which may also contain information about building's construction, management, operations and maintenance

Autodesk, 2008	An innovative new approach to building design, construction, and management that is characterized by the continuous and immediate availability of project design scope, schedule, and cost information that is high- quality, consistent and reliable.
London et al., 2008	An information technology enabled approach to managing design data in the AEC/FM (Architecture, Engineering and Construction/ Facilities Management) industry.
AIA, 2008	A digital representation of the physical and functional characteristics of the a single model or multiple models elements, and the process and technology used to create the model
HM Government, 2012	A collaborative way of working, underpinned by the digital technologies which unlock more efficient methods of designing, creating and maintaining our assets
CPIC, 2012	A digital representation of physical and functional characteristics of a facility creating a shared knowledge resource of information about it, forming a reliable basis for decisions during its life cycle from earliest conception to demolition
Penttila, 2006	A methodology for managing the essential building design and project data in digital format throughout the building life cycle
Ilozor and Kelly, 2012	A myriad of computer software applications that can be utilized by design and construction professionals alike to plan, layout, estimate, detail and fabricate various components of a building

Based on this literature review, it is identified that there are the three important common characteristics in BIM:

1. 3D Digital Representation of a building using 3D objects with geometric and non-geometric attributes based on parametric design.

2. Integration and management of construction project Information throughout the entire project life cycle.

3. Effective communication and collaboration among project stakeholders.

First of all, BIM develops a building model using 3D BIM objects such as walls, roofs, windows and doors that have built-in geometric and non-geometric attributes, while the 2D CAD (Computer Aided Design) builds a model with a 2D-based system using dots, lines, symbols and faces that do not have any parametric information. There is also a 3D CAD which builds a model in 3D manner, however it only can present a building in a 3D manner without any geometric and non-geometric attributes. Therefore, 2D and 3D CAD are completely different system with BIM.

More importantly, BIM adopts parametric design technology where all the objects represented within a building have relationships with each other regarding their geometric and non-geometric data. Thus, when any changes occur in a building object, the changes are reflected in all the related objects, and finally, the whole geometric and non-geometric information about a building can be reconfigured (Eastman et al., 2011; Cerovsek, 2011). For example, when a window placed in a wall is replaced with a larger one, the size of the void created in the wall will be automatically recalculated and construction costs for the wall would be updated automatically.

Secondly, project stakeholders are able to integrate and manage construction information more effectively throughout a project life cycle because a BIM-based construction project process has become non-linear and use a single data source about a building as shown in Figure 4.1 (WBDG, 2010). In a traditional construction project, as more changes occur in designs, more risks related to the integrity of design occur. There could be other changes as well related to the constructability of buildings. Since all these changes are communicated based on paper drawings, communication between architect and engineers or constructors is challenging, especially tracking all the information exchanges from multiple data sources. With BIM project stakeholders can exchange information and feedbacks immediately when there are any changes in a project, based on a single data source. This enables informed decisions in a timely manner by providing more accurate and quickly-updated information regarding design and material quantities, volume, cost of materials and other construction information throughout a project life cycle.

Illustration removed for copyright restrictions

Figure 4.1 BIM based construction project process (WBDG, 2010)

Indeed, 3D parametric representation is a fundamentally distinctive capability of BIM. However there are different uses of BIM in a construction project such as 3D, 4D, 5D and 6D BIM (Eastman, et al., 2011) as shown in Table 18.

Table 18. nD BIM and description

BIM	Capability	Description
3D BIM	3D Model	Project visualization, Model walkthroughs (Virtual mock-up models), Clash detection, Prefabrication
4D BIM	3D + Time	Schedule visualization, Construction Planning and Management
5D BIM	4D (3D + Time) + Cost	Quantity Take-offs, Real Time Cost Estimating
6D BIM	5D (3D + Time + Cost) + Facility Management	Life cycle management, Data Capturing and Monitoring (Actual Data of energy efficiency and building's life cycle costs)

Finally, BIM minimises effort and laborious works that are required for a 2D-designed traditional construction project to reproduce reports and designs, and coordinate the changed and updated information among project stakeholders when any changes occur in a project. As a result, more effective and efficient communication and collaboration among project stakeholders, and diverse construction information can be managed productively throughout a project life cycle. Furthermore, BIM has become a catalyst for the changes of process and culture in the construction industry due to this characteristic (Hannele et al., 2012).

Consequently, BIM is defined in this research as:

An information management system to integrate and manage various construction information throughout the entire construction project life cycle based on a 3D parametric design to facilitate effective communication among project stakeholders to achieve a project goal(s) in a collaborative manner.

New definition of BIM is provided to establish the common understanding about BIM and to enunciate the important characteristics of BIM that this research adopts. In particular, this research considers that the most important characteristic of BIM is an information management system as an information platform for various stakeholders to collaborate each other throughout an entire project lfe cycle to deliver a required outcome to customers. Therefore, it is required to suggest new definition of BIM to expand viewpoint of BIM and clearly indicate how this research considers BIM.

4.3.1 Benefits of BIM

BIM is being increasingly adopted in the construction industry due to various benefits that can be utilized for sustainable housing refurbishment (NBS, 2013; HM Government, 2012). In the literature, various benefits of BIM are identified as shown in Table 19, and this research focuses on three major benefits commonly mentioned in the literature: 1) Design Quality Improvement, 2)

Productivity Improvement (Effective and Efficient Project Information Management) and 3) Sustainability Enhancement.

Table 19. The Benefits of BIM

Authors	Benefits of BIM
Li et al. ,2009	1) Inspiration of novel design; 2) Design error detection; 3) Construction plan optimization; 4) Detection of unsafe areas; 5) Construction site management; 6) Improved communication; 7) Project information and knowledge management
Kaner et al., 2008	1) Improved engineering design quality; 2) Improved labor productivity
Sacks et al., 2004	1) Saved project cost for precast concrete companies; 2) Elimination of 50% of design errors
Suermann and Raja, 2009	1) Improved quality; 2) On time completion
Azhar et al., 2008	Saved cost and potential delays
CIFE, 2007, Liang et al., 2013	1) Elimination of unbudgeted change; 2) Increased cost estimation accuracy; 3) Reduced time for cost estimation; 4) Saving contract value; 5) Reduction of Project Schedule
Redmond et al., 2012	1) Total project costs reduction; 2) Reduction of delays and reworks; 3) Faster decision making
Grilo and Jardim-Goncalves, 2010	1) Information Management throughout building life cycle; 2) Better understanding of customers' needs; 3) Better analysis of building design and energy performance
BSI, 2010	50% less effort on information exchange

1) Design Quality Improvement: BIM enables design professionals to develop multiple design alternatives, and study these design options regarding cost, time and sustainability (Autodesk, 2008). Since BIM use a single data source built into a 3D model based on a parametric design, architects, engineers, constructors and other project stakeholders are able to exchange instant feedback on designs and construction methods. This capability can achieve continuous improvement on designs throughout a project life cycle. As all information can be stored and retrieved based on single-source data, improved consistency and integrity in building designs can be achieved, and design conflicts and clash can be detected before the construction phase. Thus, building designs can be developed and tested virtually before the constructors actually build on site, and better quality of designs can be achieved (Froese, 2010).

b) Productivity Improvement (Effective and Efficient Project Information Management):There is considerably less scope for misinterpretation and consequential changes, disruption and reworks (Langdon, 2012; London et al, 2008) as BIM provides a holistic view of building designs, costs, structures and sustainability issues simultaneously based on a single data source. Construction professionals, in particular facility managers and maintenance teams, can use BIM to manage a building throughout its operational life by providing and retrieving necessary information about maintenance and repair for future use (NHBC, 2013; Eastman, et al., 2011). In addition, researchers (Bryde et al., 2012) studied 20 construction project cases by specifically focusing on the benefits of BIM form the viewpoint of project management. The research revealed that BIM can provide various benefits: cost and time reduction or control, communication and coordination improvement, and quality increase/control. Thus, a building can be built twice, virtually and actually, which will reduce unnecessary reworks and improve productivity in the construction industry (NHBC, 2013; CIC, 2013a). As a result, BIM can achieve cost reductions of between 15% and 20% (NHBC, 2013) because it can reduce reworks and unnecessary costs by integrating various pieces of information regarding sustainable attributes, and through updating the information as the design changes effectively and efficiently.

c) Sustainability Enhancement: BIM supports informed decisions regarding sustainability issues such as energy performance and embodied CO_2 of a building at the early design phase by assessing the energy performance and the embodied CO_2 of a building where most of the level of sustainability is determined (Redmond et al., 2012; Krygiel and Nies, 2008). However, in a traditional way, it is challenging to secure sustainable attributes of a building from the early design phase because essential information regarding the construction materials that determine embodied CO2 is not readily available. In addition, it is challenging to exchange and integrate essential information amongst project stakeholders, in particular between design and construction professionals due to the fragmented nature of the construction industry. In addition, BIM can achieve sustainability in the construction supply chain by making construction and procurement processes more effective and efficient, and construction waste materials throughout a project life cycle can be reduced (HM Government, 2012; Crosbie et al., 2011; McGraw-Hill, 2010b)

As previously described in Chapter 3, the whole-house refurbishment approach requires a well-integrated design and plan to develop a refurbishment solution. It needs to utilize a proper tool to support effective communication and informed decisions among project stakeholders. According to CIC (2013a), all of these requirements for whole-house refurbishment can be fulfilled by adopting BIM, and BIM can provide the opportunity for homeowners or potential home buyers to customize their homes as they wish using the 3D visualization that does not require an in-depth knowledge of 2D drawings.

4.3.2 Barriers of BIM

Given the qualitative and quantitative benefits of BIM, it is evident that the construction industry should take advantage of implementing BIM. However, according to a BIM survey (NBS, 2013), the current adoption rate in the UK is only 39%, although the UK government has required the public sector to adopt BIM for construction projects from 2016. Bernstein and Pittman (2004) identified that there are the three main barriers to adopting BIM: Business, technical and human problems. Kiviniemi et al. (2008) researched the business problem further, and expanded that category to become the business and legal problem. The three major barriers and descriptions are identified in the literature as shown in Table 20.

Table 20. Three main barriers to adopt BIM

Barrier Categories	Description	References
Business and Legal Problem	- Lack of standards - Lack of clarity on roles and responsibilities - Lack of clients/market demands - Ambiguity in data ownership and legal risks - High investment cost and low incentives	c,f,g,h,i,j,k,m,q
Technical Problem	- Lack of standards - Interoperability - BIM Library/Dataset	c,f,j,n,o,p
Human/Organizational Problem	- Resistance to changing current practices - Lack of knowledge/skills - Lack of initiative and training	c,d,e,f,g,l,n

References: a) Allen Consulting Group, 2010; b) Azhar et al., 2008; c) Bernstein and Pittman 2004; d) BSI, 2010; e) Campbell 2007; f) Eastman et al., 2011; g) Forns-Samso et al., 2011; h) Hannele et al., 2012; i) Holzer 2007; j) Howard and Bjork, 2008; k) Ilozor and Kelly, 2012; l) Ibrahim et al 2004; m) Johnson and Laepple 2003; n) London et al, 2008; o) Manning and Messner, 2008; p) Succar, 2009; q) Weygant, 2011

a) Business and Legal Problem: Successful BIM adoption requires integration of construction information from the outset of a construction project and effective collaboration among project stakeholders. In order to tackle the current fragmented practice in the construction supply chain, project delivery methods, which are specifically developed for the early collaboration of project participants and front loaded efforts at the early design phase as shown in Figure 4.2, have been introduced to the industry such as Integrated Project Delivery (AIA, 2008), Soft Landing (BSRIA, 2010) and Integrated Design and Delivery Solution (CIB, 2010). In particular, the Soft Landing approach is also recommended for successful whole-house refurbishment solutions as previously explained in sub-section 3.5.2.

Figure 4.2 The time-effort distribution between BIM-enabled and traditional AEC processes (McLeamy, 2004)

However, as there is no universal BIM standard at present, construction project stakeholders have their own customized BIM standards, and they are unclear what types of information with what level of details need to be exchanged with other stakeholders (Langdon, 2012). As a result, the roles and responsibility of BIM-enabled work, which has been clearly defined in conventional construction projects, is not clearly defined among project stakeholders (Hannele et al., 2012; Ilozor and Kelly, 2012) and, as a result, there are legal/contract issues related to risks in construction projects. Furthermore, it is unclear who is responsible for the defects in a BIM model identified throughout a project life cycle, in particular during the construction phase (Langdon, 2012). Leung (2013) revealed that design professionals are reluctant to accept defects in a BIM model unless there are clear roles and responsibilities already set up from the outset of a project. In addition, there is no clear legal ownership for a BIM model as intellectual property (Bernstein and Pittman 2004, Holzer 2007, Johnson and Laepple 2003). The construction industry does not see the clear return on investment out of BIM implementation at present and, as a result, the demands of BIM use for construction projects among customers and the construction industry are low (Lee et al., 2012). This is despite the facts that, according to a recent study (Lee et al., 2012), the return of investment of BIM implementation has been analysed as reducing cost due to design errors by 63%.

b) Technical Problem: One of the important characteristics in BIM is the capability to coordinate and integrate a large volume of construction information. In order to achieve seamless integration across project teams, various BIM software needs to be utilized. However, the current prevalent data exchange format, which is known as International Foundation Class (IFC), is not able to transfer all the construction data between different software platforms without data loss or distortion (Redmond et al, 2012). In fact, the IFC format does not, and is not intended, to store and carry all relevant data throughout the entire construction project life cycle (Fuchas et al., 2010). There is another prevalent data format known as Green Building XML (gbXML) which is mainly used for energy simulation data exchanges, and this format also has the same data transfer problems (Dong et al., 2007). As a result, various geometric and non-geometric errors have been identified in data exchanges among different software, and construction professionals have recognized the use of IFC as cumbersome (Plume et al., 2007; Jeong et al., 2009; Sacks et al, 2010). Even, suppliers and constructors have their own data format instead of using the IFC format (Hecht, 2008).

c) Human/Organizational Problem: Researchers have argued that the human/organizational problem is derived from the other two barriers that hinder BIM adoption, a problem that this is inherited from the fragmented practice of the construction industry (Eastman et al, 2011; Hardin, 2009; Banahene and Tuuli, 2013). BIM adoption requires cultural changes and more integrated and collaborative construction practices throughout a project life cycle (Succar, 2009; Hannele et al., 2012). However, the construction industry and personnel are reluctant to embrace the changes inherent in adopting BIM because BIM adoption requires costs for setting up BIM system and training, and changes in a way of work with other stakeholders. Langdon (2012) asserts that the construction industry has to adopt BIM and develop a BIM implementation strategy based on collective efforts through the supply chains in order to improve productivity and reduce construction costs. However, the current uptake of BIM amongst customers is low in the construction industry in general (NBS, 2013).

4.4 Current BIM status in the UK

Global investment in capital projects is projected to grow by 67% globally by 2020, but productivity in the construction industry has decreased over the last two decades (Betts et al., 2011). In order to improve productivity and attain economic growth, many countries in the world such as the USA, France, Germany, South Korea, China and the UK have developed BIM adoption and implementation strategies (McGraw Hill, 2014).

In particular, the UK Cabinet Office released the Government Construction Strategy known as the

‘Push and Pull’ approach to improve productivity in the entire UK construction industry. For the ‘Push’ side of the strategy, the UK government has mandated the public sector adopt BIM for construction projects from 2016, and for the Pull side of the strategy the construction industry will adopt BIM progressively by following a maturity level from Level 0 to Level 3. Level 2 maturity is equivalent to the required BIM adoption level by 2016 as shown in Figure 4.3, and each level of BIM adoption maturity is defined as shown in Table 21. In particular, Level 2 BIM maturity has a significant meaning because this level is equivalent to the 3D parametric objective based BIM practice (Succar, 2008), and this is one major step that must be embraced in the UK construction industry to achieve the Level 3 maturity, which is fully integrated and open BIM practice.

Figure 4.3 BIM Maturity Model (Government Construction Client Group, 2011)

Table 21. BIM Maturity Level Definition (Government Construction Client Group, 2011)

The UK Cabinet Office has prepared this BIM adoption strategy to be implemented over a five year period to 2016, and it is expected that the UK will become a world leader in BIM-enabled construction projects, along with the substantial improvement of the efficiency of the UK construction industry (Cabinet Office, 2011). As the importance of BIM increases, various construction professional organizations in the UK have released standards and protocols for effective construction information management and integration as shown in Table 22.

Table 22. UK BIM Standards/Protocols

Organizations	BIM Standards/Protocols	References
BSI	a) PAS 1192-2:2013, Specification for information management for the capital/delivery phase of construction projects using building information modelling	a) BSI, 2013
	b) PAS 1192-3:2014, Specification for information management for the operational phase of assets using building information modelling	b) BSI, 2014
CIC	BIM Protocol, Standard Protocol for use in projects using Building Information Models	CIC, 2013b
RIBA	a) BIM Overlay to the RIBA Plan of Work	a) RIBA, 2012
	b) RIBA plan of Work 2013	b) RIBA, 2013
BIM Task Group	Construction Operations Building Information Exchange (COBie) UK 2012	BIM Task Group, 2012
AEC (UK)	AEC (UK) BIM Protocol, Implementing UK BIM Standards for the Architectural, Engineering and Construction industry	AEC (UK), 2012

The Construction Industry Council (CIC, 2013a) proposed several programmes to promote BIM adoption: a) Engagement with a number of professional and trade bodies to ensure that BIM can be embraced by all communities within the construction sector, especially SMEs, b) Working with a number of private sector clients to ensure that the benefits of BIM are shared across the entire client base and where possible to create a consistent presentation of requirements to the supply chain and c) Establishing 'Regional BIM Hubs' to enable SME and smaller clients to get advice from local networks. The PAS 1192:2 is the British standard for BIM model management, which the construction industry will eventually adopt and follow. The BIM Overlay to the RIBA Plan of Work (2012) is a well-organized process for BIM enabled construction projects. Therefore, in this research, the PAS 1192:2 and the BIM Overlay to the RIBA Plan of Work are used as a basis for developing a BIM framework for whole-house refurbishment in conjunction with the Low Carbon Domestic Retrofit Guides (See Section 3.5.4). The framework development will be further discussed Section 7.2 in Chapter 7.

Despite the current endeavour to adopt BIM, the BIM adoption in the entire UK construction industry is only 39% (NBS, 2013). Although the overall BIM adoption rate has been increased by 39%, BIM has been mainly implemented into large-scale new build projects (Allen Consulting Group, 2010; Arayici et al., 2011). Currently, small and medium sized enterprises (SME) with less than 9 employees contribute 92% (250,000 firms) to the total construction industry employment (ONS, 2011), and the BIM adoption in SMEs was identified as only 13% as of 2010 (Hamil, 2010). The use of BIM in SMEs is limited and far less than the overall BIM adoption rate because there are no practical standards to utilize BIM, and the investment in BIM systems is not economically feasible (Sebastian et al., 2009).

The NHBC foundation (NHBC foundation, 2013) released a report providing the current status of BIM penetration in the UK housing sector. Currently, BIM is regarded as being feasible for large scale and complex housing projects rather than small scale ones. Furthermore, eight major house builders that account for about 48% of all new house supply (Tinker, 2013) consider that BIM adoption for housing projects is not relevant to current construction practices in the UK. Although this survey was conducted with the eight major house builders, this result can provide the current BIM adoption status since they contribute almost 50% of the output of the housing sector. Currently, the BIM adoption rate in the housing industry is only 25%, which is lower than the BIM adoption rate in the overall UK construction industry as shown Figure 4.4.

Figure 4.4 BIM Adoption in the UK Housing Industry (NHBC foundation, 2013)

Small and medium size local house builders seem unlikely to adopt a BIM system like major house builders due to present economic conditions and technical reasons (see Section 4.3.2). However, as the major house builders currently adopt BIM due to the government's mandate for public projects, the uptake of BIM will increase eventually in the housing sector. The more new build housing utilizes BIM, the more BIM data will be accumulated and enriched throughout the operation and maintenance phase. Finally, The use of BIM in existing housing refurbishment projects could contribute to achieving sustainable whole-house refurbishment as a construction information and process management tool. In order to increase the uptake of BIM in the housing sector, the NHBC foundation (2013) recommends proper training and customized guidelines for the housing sector, although currently most of BIM strategy, standards and protocols mainly focus on new build construction projects.

4.5 Current Status of BIM implementation in the Housing Sector

In this section, current efforts to adopt BIM in the housing sector, and recent researches conducted to tackle the three major barriers to adopt BIM - business, technical and human - will now be explored, particularly focusing on the housing sector.

4.5.1 Business Barriers

Sebastian et al. (2009) implemented BIM for a small-scale housing development as a pilot case study to confirm that the integration capability of BIM can provide practical benefits for SMEs. This research revealed that BIM utilization provides basic benefits such as clash detections and better understanding of designs among project stakeholders. More importantly, BIM facilitates proactive early collaboration among project stakeholders, and in particular, the earlier engagement of constructors in the design phase adds value to more accurate informed decisions about construction methods and materials. However, the identified benefits are limited and basic because of fragmented construction practice, data exchange issues and unclear roles in a BIM-enabled project. As each project stakeholder uses different software, proper data exchange without information loss is a challenging task, and there are a legal contract issues across the supply chains to establish integrated and collaborative practice. As a result, researchers have emphasized that collaborative construction practice among project stakeholders is necessary in order to achieve further benefits from BIM adoption, and in order to establish the collaborative practice an open protocol based on a BIM library is needed.

As identified in Section 4.3.2, the current barriers to adopting BIM are a lack of standards and unclear roles and responsibility, which are also revealed the above research (Sebastian et al., 2009). In response to these barriers, Hjelseth (2010) proposed a construction project information management framework for a BIM-based project that has been developed based on the life cycle stage of ISO 22263:2008 as shown in Table 23. This framework matches the roles of key project participants throughout a project life cycle to define the primary and secondary roles for each level of a BIM model. However, this framework is too generic to apply to a specific construction sector without customizing roles and project life cycle stages. The important finding of this research is that clear roles among key project stakeholders for specific information exchange points should be developed first to utilize BIM effectively.

Table 23. A synchronized framework for a BIM based project built on ISO 22263:2008

BIM Orders	Roles	Phases	Life Cycle Stages
Demand BIM	Owner (Primary) Architect (Secondary) Engineers (Secondary) Contractor (Secondary)	Pre-project	0. Portfolio requirements 1. Conception of need 2. Outline feasibility 3. Substantive feasibility
Draft Model	Architect (Primary) Engineers (Secondary) Contractor (Secondary)	Pre-construction	4. Outline conceptual design 5. Full conceptual design 6. Coordinated design (and procurement)
Detail Model	Contractor (Primary) Engineers (Secondary)	Construction	7. Production information 8. Construction
As-built Model	Contractor (Primary) Engineers (Secondary)	Post-construction	9. Operation
Facility Management	Facility Manager	Hand-over and Use	9. Maintenance 10. Disposal

In addition, Hannele et al. (2012) and Ilozor and Kelly (2012) argue that heavy workloads have been allocated to design professionals such as architects and engineers because of the unclear roles and responsibility they have when building a BIM model. As design professionals are required to collaborate with other project stakeholders from the early design phase to examine possible design alternatives in a BIM environment, exchanges of diverse construction information are essential. Thus, the unclear roles and responsibilities regarding who provides what kind of information generate unnecessary and overlapping workloads. Hooper and Ekholm (2010) implemented a BIM Project Execution Planning (BEP) guide developed by the Pennsylvania State University to tackle the problems associated with roles and responsibilities and the unstandardised processes in 9 residential buildings developments as shown in Figure 4.5, since there is no universal standard accepted for BIM based project.

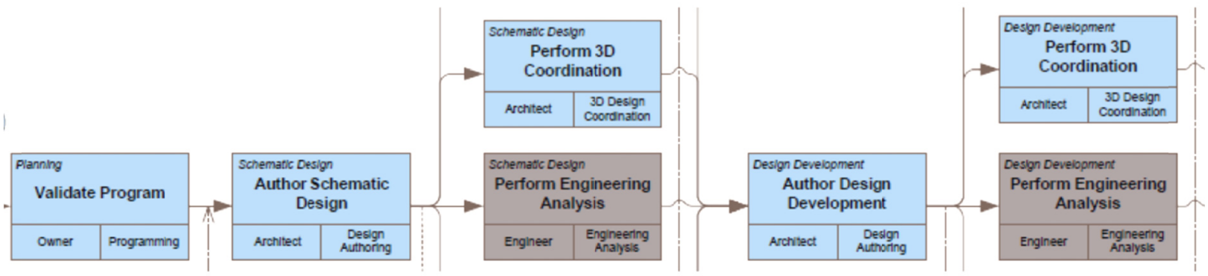

Figure 4.5 A Partial Part of BIM Execution Process Map for BIM Execution Planning

The implemented of a BIM-enabled project process provides model check-up points, known as

Design Authoring, throughout the design phase to establish if there is any flaws in the model. This authoring process maintains a BIM model containing a proper level of detailed construction information, and proactively detects errors and problems from the early design phase before it is further developed. In addition, this BEP sets out clear roles and responsibilities among project stakeholders to develop a BIM model at the design phase. As a result, the researchers recognized that the BEP guide is a feasible standard specifically for the design phase of residential building projects, although this research does not confirm if the BEP guide is feasible for the housing refurbishment. However, the important message from this research is that there should be a gate keeper to check building designs as they develop. This process should be applied in the case of housing refurbishment projects due to the various and complex decision making processes that are required to generate an affordable refurbishment solution.

Some researchers have pointed out that design authoring requires additional time for construction professionals to modify and update a BIM model based on individuals' level of competence in BIM (Leung, 2013; Bazjanac et al., 2011). Bazjanac et al. (2011) pointed out that currently any correction of a BIM model is manually carried out and the entire process requires extra time and cost. The efficiency of the authoring process is entirely dependent upon the experiences of designers, and this process can cause risks in project schedule, budget and quality because the whole BIM modelling processes will be delayed when the authoring process is delayed (Leung, 2013).

While some researchers focus on the design phase, Banahene and Tuuli (2013) investigated the briefing process at the conceptual design phase where key project stakeholders' requirements and final goals are identified. Researchers argue that the briefing process should capture sufficient information from project stakeholders to develop a BIM model with sufficient information that enables designers to determine how to develop and manage a BIM model further as shown in Figure 4.6. However, the early involvements of constructors and suppliers have been limited by the current fragmented practice, and this practice prevents design professionals from obtaining sufficient information to create an information enriched BIM model in terms of costs and environmental impacts.

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Figure 4.6 Framework for Briefing for BIM-enabled Projects (Banahene and Tuuli, 2013)

Eventually, a BIM enabled project cannot provide any improvement and advantages compared to traditional construction projects (Succar, 2009), and even more works are required to develop and correct a BIM model. Thus, researchers proposed a framework to improve the briefing process for a BIM-enabled project. This framework integrates the RIBA Plan of Work and BIM processes, and is very similar to the BIM Overlay to the RIBA Plan of Work as shown in Figure 4.6. This framework is unique because the required information and the responsibilities of project stakeholders at each stage have been identified while the BIM Overlay to the RIBA Plan of Work mainly focuses on core activities at each stage. Thus, this framework could be more useful to use in conjunction with the BIM Overlay to the RIBA Plan of Work since both frameworks have been built based on the RIBA Plan of Work.

In contrast with Banahene and Tuuli (2013), Crosbie et al. (2011) pointed out the occurrence of a broken feedback loop after the design phase. In general, a BIM model is not updated by incorporating feedback from any changes made during the construction phase (O'Donnell, 2004), and researchers argue that the energy performance of a building in the use phase can only be improved by conducting an energy performance simulation based on the actual building operation information. However, the current construction practice cannot manage knowledge gained throughout a project life cycle, and often the lessons learned from previous projects are not used for future projects (Lindner and Wald, 2011).

Figure 4.7 IntUBE BIM Data Repository Model (Crosbie et al., 2011)

To provide more accurate energy performance simulation results for a BIM model, researchers proposed the IntUBE (Intelligent Use of Buildings' Energy Information) system as shown in Figure

4.7. This system is designed to obtain actual building information throughout a building life cycle, and the restored data will be used to improve building design, energy performance and refurbishment in the future. This system has the capability to restore various information regarding building attributes and actual building performance, allowing design professionals to generate more realistic BIM design alternatives. It enables clients to make informed decisions on design selection at the early design phase.

Due to the characteristics of this system, there is a potential for BIM to be used for whole-house refurbishment projects. Since there is a large variation of housing condition in the UK housing stock, and it is challenge to build a prototype model. As a result, careful assessment of housing conditions is essential and currently, a 3D laser scanner has been used for this (CIC, 2013a). Thus, as described in Figure 4.7, if a BIM model is built based on actual housing attributes retrieved from actual housing conditions and energy performance, a whole-house refurbishment solution will be more realistic and feasible, and customers can make better decisions. Furthermore, the BIM model used for housing refurbishment will continue to retrieve actual maintenance and operation information throughout a housing life cycle, and eventually the restored data will be utilized when another refurbishment is required in the future. Jung and Joo (2011) also argue the same point regarding a BIM data repository, that practical BIM implementation requires proper BIM data in conjunction with a clear framework. Researchers emphasized that the importance of data properties embedded in a BIM object or model is essential for a BIM-enabled project. Based on the geometric and non-geometric data in a BIM's objectives, a BIM model can generate knowledge for an entire building in terms of project time, cost and sustainability. Researchers pointed out that once BIM is widely adopted in the construction industry, knowledge and lessons learned from construction projects will be restored as a historical database, and will be fully utilized for new build and retrofit projects.

As a new build housing project will secure the BIM model from the outset, an FM will provide the complete BIM model enriched with data and information about as-built housing. As FM utilizes this BIM model throughout the life cycle of a house, this will be the living and growing database for future refurbishment. BIM was not seen as relevant to work on existing buildings until recently when laser point-cloud surveying emerged as a rapid way to capture existing buildings and landforms into digital format. Currently, the importance of Big Data is getting increasing attention, and CIC (2013a) envisages its use, which is captured from the use phase of a building, for future construction and refurbishment projects. Therefore, the construction industry should establish a standard BIM library for BIM enabled projects to manage essential information exchange throughout a project life cycle.

4.5.2 Technical Barriers

Chung et al. (2013) implemented BIM for a 34-storey domestic building construction project which comprised 990 flats per building. In this research, the researchers explored the full capability of BIM such as 3D, 4D and 5D BIM, and established a BIM library including a standard modular flat as a preparatory work for enhancing flexibility and efficiency in building design process. This research revealed that benefits can be rendered based on different levels of BIM capability: 3D BIM is capable of checking constructability and sustainability, and 4D BIM supports better risk management by virtual planning for construction and equipment operation during the construction phase. As the construction sequences and equipment operation can be simulated in 3D, potential problems related to various construction works can be rearranged and/or removed at the early planning stage before actual construction begins. However, the benefits of 5D BIM have not been clearly identified because there is a lack of standards for BIM modelling and standardised methods for quantity measurement. In this research, it was strongly emphasized that the preparation of a BIM library is the most critical work to achieve the full benefits in terms of cost effectiveness and sustainability of a building. Other researchers (Cerovsek, 2011; Sebastian et al., 2009; Bazjanac et al., 2011; Jung and Joo, 2011) share the same viewpoint regarding the importance of a BIM library for making informed decisions and improving productivity at each phase of a construction project.

In particular, Cerovsek (2011) asserts that a lack of BIM libraries directly influence the absence of BIM standards to identify what types of information should be exchanged among project stakeholders at which project phases. Researchers emphasized that the BIM library should be established prior to developing a framework. They have used the following terms to provide a snapshot of BIM system: 'BIM model' and 'BIM Schema'. In order to effectively utilize BIM, a BIM model should have 'modelling granularity', which means various construction information such as building components, HVAC systems and other building systems. Based on the granularity of a BIM model, a BIM schema can produce more accurate information about a building, and can facilitate effective information management throughout a project life cycle. The importance of modelling granularity has been repeatedly emphasized in this research because a well-structured BIM dataset can be reused, and a BIM model itself also can be reused with proper modifications because the model is built based on the parametric design principle. However, Cavieres et al. (2011) criticized that current BIM practices among construction professionals reduces flexibility at the design phase since a BIM model must have a certain level of detailed information such as geometric and non-geometric data, which is challenging to obtain at the early design stage, in order to be developed further in designs.

As a solution for securing essential data for BIM model development, Cheung et al. (2012) proposed an objective library based on the parametric knowledge-based tool - the Low Impact Design Explorer (LIDX) - as shown in Figure 4.8. Researchers emphasized the importance of a BIM library and simultaneous design development at the early design phase because time delays are associated with feedback loops for design development and cost estimation as the design is being developed. The essential point of this proposed model is early cost estimation and environmental impacts assessment based on a BIM library from the early design stage, and more effective and efficient communication among project stakeholders. As a result, more financially and environmentally feasible designs can be determined based on a BIM model built based on a BIM library.

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Figure 4.8 Multi-dimensional design management (Cheung et al., 2012)

The uniqueness of this model is the use of various data sources for financial and environmental impacts assessment: NRM code and Building Price Book (BCIS, 2012) for financial analysis, and the Carbon Book (Franklin and Andrew, 2010) for environmental impact assessment. In order to utilize these data sources that are not readily available as a BIM dataset, researchers establish the cost and environmental impact database first. Through this research, it has been proven that it is possible to establish a BIM library for the full benefits of BIM as has been stated.

Another technical barrier is the interoperability among various project stakeholders using different software. As described in detail in section 4.3.2, collaboration with other project participants in a BIM enabled project is challenging because there is a limit to exchanging a BIM model without data loss (Redmond et al., 2012; Plume et al., 2007; Jeong et al., 2009; Sacks et al, 2010).

Howard and Björk (2008) addressed the interoperability issue regarding the use of the IFC as a medium among different BIM software. Researchers argued that the possible range of IFC use for data exchange between different BIM software is not clearly identified, and they pointed out that software companies should a provide clear level of interoperability between IFC and their BIM software. Researchers argue that the level of interoperability should be clearly identified first to establish a confident data exchange standard using IFC (London et al, 2008).

Cormier et al. (2011) argue that IFC can be utilized as a middleware between different BIM software to support effective data exchange regarding energy performance simulation. Researchers argue that this IFC based middleware can be successful only if the BIM dataset is interoperable between different BIM software via IFC as shown in Figure 4.9. Researchers pointed out that a time consuming processes occurred when a BIM model is transferred to energy performance analysis software. Due to limited interoperability, engineers need to re-enter the energy simulation data that has been lost in the process of transferring a BIM model between designers and engineers.

Figure 4.9 ThermalOpt Process (Cormier et al., 2011)

Although this proposed process requires a specific customized software set as shown in Figure 4.9, this research provides an important point that a BIM library dataset should be interoperable between different software via IFC. Thus, in addition to establishing a BIM library, the interoperability of a BIM library should be considered when the construction industry attempts to build a BIM library.

Bazjanac et al. (2011) also pointed out the importance of appropriate input data transformation from one software platform to another in order to achieve seamless data exchanges without distortion and loss of information as shown in Figure 4.10. However, researchers argue that the results of energy performance simulation have been more questionable and less reliable for decision-making due to poorly defined simulation models and inappropriately transformed data for energy simulation (Cormier et al., 2011). In particular, researchers (Bazjanac et al., 2011; Cormier et al., 2011) emphasized that IFC alone cannot effectively deliver all the required simulation data for accurate energy simulation, and recommend a Simulation Domain Model (SimModel) to utilize other supportive data formats such as gbXML to properly transfer BIM model and transform datasets as shown in Figure 4.10.

Figure 4.10 Simulation Domain Model (Bazjanac et al. ,2011)

In addition, the result of energy performance simulation through the SimModel proved that it is possible energy performance, not the exact performance of a building. Thus, the result of energy simulation should be carefully interpreted and used for decision making supporting tools at the design phase to develop design further in terms of shape and materials for a building.

Redmond et al. (2012) argue that a cloud-BIM, which is equivalent to Level 3 BIM maturity, will eventually resolve current interoperability problems as BIM maturity is being further developed in the construction industry. Currently, the UK government has called for Level 2 BIM maturity by 2016, and the Level 3 BIM maturity is an Open BIM or cloud-BIM, which is expected to resolve current interoperability issues and achieve a universal approach to collaborative design based upon open standards. All the project participants can collaborate and communicate in an open environment with IFC support regardless of what software platform or tools they are using. However, the current maturity level has not reached Level 2, and cloud-BIM also has data security and legal issues. In addition, as the data are open to anyone in project team, unnecessary changes on designs could occur unless clear roles and responsibilities of BIM data or models is defined, which is also one of the current barriers to adopting BIM.

Furthermore, Redmond et al. (2012) argue that the most important work in a cloud BIM environment is to decide what type of data exchange format or platform will be at the beginning of a project. In this research, it was pointed out that the COBie could be more effective for SMEs since the COBie is a MS Excel-based data exchange mechanism. Thus, the COBie can be easily adopted by SME and non-BIM users in conjunction with cloud-BIM. Furthermore, it could be an answer for those who are not ready to adopt BIM, but have to use BIM due to their jobs, such as a government contact construction workers who use BIM.

4.5.3 Human/Organizational Barriers

Ilozor and Kelly (2012) argue that BIM can only be successfully implemented when current project delivery methods are fundamentally changed in the supply chain. Indeed, Hardin (2009) argues that BIM is mostly ineffective in a design-bid-build contract environment. Researchers argue that the full benefits of BIM such as 4D and 5D capabilities can be rendered when project teams across the supply chain collaborate based on the Integrated Project Delivery (IPD) methodology as shown in Figure 4.11 (AIA, 2007).

Figure 4.11 Integrated Project Delivery (IPD) methodology (AIA, 2007)

IPD methodology was developed to integrate project stakeholders in the supply chain collaboratively and to increase value to the owner with maximizing efficiency throughout the entire project life cycle. Figure 4.11 illustrates how the IPD environment encourages project teams to work more collaboratively from the outset of a project compared to the silo approach in the separated traditional project delivery environment. However, the IPD is a relatively new concept to the construction industry and has not been accepted widely, and researchers identified four major barriers in the construction industry to adopting the IPD approach (Wickersham, 2009):

a) Legal issues with appropriate contracts
b) Financial issues with risk sharing and compensation
c) Cultural Issues with trust building and cohesive teamwork
d) Technological issues with interoperability among project stakeholders

Above findings are echoed with the current barriers to adopting BIM, and indeed, these issues need to be resolved to fully utilize BIM and improve productivity in the construction industry. Howard and Bjork (2008) argue that it is a challenging task to transform the current construction industry radically to a BIM-enabled collaborative project environment. Researchers identified a common misconception that the entire construction practice should be changed at once to adopt BIM practice. Although the full benefits of BIM adoption will be achieved through the entire change of a construction practice, BIM-enabled practice can be tailored to a certain phase of the entire project life cycle (Hjelseth, 2010; Cerovsek, 2011). According to survey results (Khemlani, 2007; Howard and Bjork, 2008) collaboration among project stakeholders is still carried out based on exchange of 2D drawings, although stakeholders understand the importance and benefits of BIM-enabled environment.

As a response to the issue identified by Howard and Bjork (2008), London et al. (2008) proposed a contractor-led BIM project framework as shown in Figure 4.12. This framework emphasizes the systematic assessment of the current capability of adopting BIM in a company or organization. Researchers recommend identifying internal work processes and their relationships with external stakeholders to develop a BIM framework that synchronizes with current work processes as shown in Figure 4.12. This framework provides an important point that BIM should be adopted based on the existing work processes, and thus it is not recommend to introduce a whole new work environment with new processes designed for BIM. Therefore, development of a BIM framework designed for a certain work environment is essential in order to adopt BIM efficiently, and furthermore, this research will develop a BIM framework for housing refurbishment based on current existing standards and guides.

Figure 4.12 BIM-enabled Design Process Roadmap (London et al., 2008)

Furthermore, Porwal and Hewage (2013) argue that the current procurement method for public construction projects limits the capability of BIM because the design and construction phases are carried out separately, and generally contractors are allowed to be involved in a project after a building design is finalized. In order to tackle the current fragmented practice, researchers proposed an “Early BIM Partnering” approach as shown in Figure 4.13.

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Figure 4.13 Early BIM partnering project delivery approach (Porwal and Hewage, 2013)

The uniqueness of this approach is that it is based on the fact that the construction industry is not fully ready to adopt BIM at present. Researchers argue that this approach should enable BIM to smoothly penetrate into the current public procurement environment because this approach recommends using 2D drawings, which are the most prevalent construction information exchange format at present, along with a 3D BIM model. Without lowering efficiency due to radical changes in adopting new procurement methodology, this approach enables contractors to be involved in the early design phase when accurate and reliable cost estimation and constructability assessment are required for a project's success (Ilozor and Kelly, 2012). In addition, Abbasnejad and Moud (2013) argue that parallel use of 2D practice with 3D BIM will render benefits because the period for adopting BIM and learning a new system can be shorten.

However, this parallel approach could cause more complications due to the combination of 2D and 3D approaches in the long-term view. The fundamental capability and benefit of BIM is a 3D digital representation of a building, enabling all project stakeholders to work on a single source of data; however, this approach could produce inefficient and unnecessary works in updating models and drawings from 2D to 3D for data exchanges. Although this approach has limitations in the long-term view, this is a realistic approach for the construction industry, in particular SMEs, to adopt for smooth transition between traditional and BIM enabled project environments.

4.6 Conclusion

Through the literature review, it was revealed that BIM has not been widely used for housing refurbishment projects. BIM has been used mainly for large and small new-build housing developments. However, BIM has the possibility to be utilized as an information and design management tool for whole-house refurbishment projects with its proven benefits:

a) Design Optimization
b) Efficiency Improvement (Effective Project Information Management)
c) Sustainability Enhancement

BIM could provide a better understanding of refurbishment in a 3D format to clients, and enables house builders to study various refurbishment options (Design Optimization). Then, based on this understanding, house builders can collaborate with each other in an integrated manner and coordinate construction information from the outset of a refurbishment project (Efficiency Improvement). Finally, as whole-house refurbishment design can be simulated and studied before actual construction starts, the sustainability of whole-house refurbishment can be improved in terms of energy performance and carbon reduction (Sustainability Improvement).

However, there are barriers to utilizing BIM, these are repeatedly addressed in the literature:

a) Lack of Standards and Frameworks
b) Lack of a BIM Library
c) Interoperability

Since BIM has been used mainly for new-build housing projects, the BIM model as a data library should be utilized for facility management throughout the building life cycle (CIC, 2013a). As a BIM model can be reused and requires various pieces of construction information at the early design phase, the issues related to the lack of a BIM library will be resolved as time goes on. As Cheung et al. (2012) proposed, it is possible to match up standards (RIBA Plan of work, NRM and Carbon Data) with refurbishment projects. In this way, the problems caused by a lack of standards and frameworks will be resolved. Yet, there are none developed for housing refurbishment projects. Thus, this thesis will develop a proper BIM framework for whole-house refurbishment projects to support key project stakeholders involved in a refurbishment project to efficiently collaborate with each other throughout a project life cycle. The interoperability will not be a scope of this thesis, however as many researchers and practitioners including software developers have put in effort to resolving interoperability issues, it is expected that a way can be found to overcome current technical problems in the near future.

Chapter 5 Methodology

5.1 Introduction

This chapter provides an overview of the research philosophy, strategies and approaches that have been adopted in this thesis to achieve the aims and objectives. This chapter comprises three main components:

1) Background information of research philosophies and approaches
2) Research Strategies
3) Research design
4) Conclusion

Based on the provided information, it will be ascertained if the research goal has been achieved through an appropriate research methodology and research design.

5.2 Research Philosophies and Approaches

A research philosophy, often called as paradigm is a belief and assumption taken by a researcher that provides guides how to carry out a research and influences researchers to interpret social reality (Denzin and Lincol, 1994; Creswell, 1998). The philosophy is important as it provides basis to choose relevant research methodology, strategy and develop a research design (Mertens, 2005). Philosophy can be understood as different viewpoints about social reality in a range from positivism to interpretivism (Guba and Lincoln, 1994).

Positivism focuses on scientific research assuming that society operates according to general laws like the physical world. It rejects to obtain any knowledge from intuitional attempts, and believes that valid knowledge is objectively given and can be measured by quantitative research approach (Kelly, 2004). As positivism researches are heavily relied upon quantitative studies, data generated from studies can be generalized easily and studies can be repeated by other researchers. However, disadvantage of this philosophy is that researchers have a chance to lose in-depth knowledge and insights about the subject that can be obtained from qualitative research.

On the other hand, interpretivism is a common philosophy in social research that believes reality is socially constructed by persons' experiences, and focuses on understanding the context of social reality based on human experience and background (Mertens, 2005; Creswell, 2003). This philosophy can have an in-depth knowledge and understanding about research subjects, however there is a large chance to generate bias by a researcher. Furthermore, research data cannot be generalized as positivism study since researches relies on personal viewpoint and experiences.

In addition, there is a philosophy named pragmatism that takes a middle stance between positivism and interpretivism, and this philosophy empowers researchers to use a variety of research methods to find answers for research questions. Pragmatism breaks the traditional viewpoints of social reality in a range of positivism and interpretivism, and guides researchers to focus on understanding what and how of the research questions in real life context (Creswell, 2003). As a result, mixed-methods approach is commonly associated with pragmatism that combines both qualitative and quantitative methods (Tashakkori and Teddlie 1998; Creswell 2007).

This research aims to develop a BIM framework for whole-house refurbishment based on the belief that there should be a systematic process to utilize BIM, which is related to positivism. Simultaneously, this research requires clear understanding about rationale how construction information flows and project stakeholders interact within a BIM system, which is related to interpretivism. Therefore, this research adopted pragmatism philosophy to develop a BIM framework that can provide a systematic way to utilize BIM based on in-depth understanding of information flow and interactions among diverse construction professionals. Based on pragmatism philosophy, this research can identify a practical way to develop a BIM framework and reveal current challenges in a BIM system to utilize BIM for housing refurbishment.

Once the research philosophy was determined, a research approach that provides a method of reasoning about research data was considered. There are two main research approaches - inductive and deductive approaches - which researchers can take as a method of reasoning (Trochim, 2006). In an inductive approach to research, a researcher begins with collecting data that is relevant to research topic. Then, researchers identify themes and patterns in the data, and they generalise the findings from specific data. Thus when researchers use an inductive approach, they move from a particular experience to a general idea. In contrast, a deductive researcher begins with a general information or social theory, and they move toward more specific information. Researchers typically begin with a theory, and then they narrow it down into more specific hypotheses that can be tested. Finally, researchers can confirm if the hypothesis is correct by testing it with specific data.

For this research, it is essential to obtain a holistic understating about how a BIM system integrates project stakeholders and construction project information, and it is also important to identify specific construction data such as essential inputs, activities and stakeholders for each process of a whole-house refurbishment project within a BIM system. Thus, this research adopted inductive approach to collect specific data required in a BIM system, and then develop a general BIM framework designed for a whole-house refurbishment.

There are two main types of research methods to collect data - quantitative and qualitative research method - which the former is typically associated with deductive approach and the latter is associated with inductive approach. As this research adopted an inductive approach, it is associated with qualitative method. However, this research needs to adopt qualitative method and also quantitative method. This is because a BIM framework can be developed inductively by quantitative data collection regarding BIM input variables such as key activities, essential input data and key project stakeholders for each process, which can be generalised. At the same time, rationale behind the framework such as the collaborations and construction information flows among key project stakeholders can be identified via qualitative data collected using interviews in order for in-depth understanding of a BIM system and further development of the developed framework in the future. Therefore, this research adopted mixed-methods which use both qualitative and quantitative methods for collecting data. Creswell et al. (2004) assert that the mixed-methods research approach is not just about applying quantitative and qualitative methods for data collection, but focuses on integration of data and theory and enrichment of explanations. Mixed-methods approach can reveal unidentified aspects of current problems, and result in a more holistic understanding of the research topic (Creswell et al., 2004; Anchin, 2008). In addition, Amaratunga et al., (2002) emphasize that mixed methods can be complementary approach as both methods can supplement its weakness and strength. Therefore, the mixed-methods approach is relevant to this research.

5.3 Research Strategies

Research strategy guides researchers to plan a process to conduct researches to answer the research questions (Saunders et. al, 2009, Bryman, 2008). There are various strategies available to researchers such as experiments, surveys, case study, grounded theory, action research, and ethnography (Yin, 2009; Creswell, 2007). Yin (2003) asserts that a researcher needs to consider three major aspects to select relevant research strategy - Form of research questions, Necessity of control of behavioural events, Focus on contemporary events (Yin, 2003) as summarised in Table 24.

Table 24. Relevant Situations for Different Research Strategies (Yin, 2003)

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This research requires no control over behavioural events as a researcher cannot intervene customers' preferences for housing refurbishment, and focuses on contemporary event which is a whole-house refurbishment using BIM in the UK. Interactions among project stakeholders and rationale behind a BIM framework can be identified by asking how and why. Thus, case study is the most relevant strategy for this research. However, this research also has to consider other four aspects – who, what, when and where - in conjunction with how and why because a BIM framework has to provide what kind of construction information needs to be required when and which phase, and who is responsible for the information and activities to generate information. In order to develop a general BIM framework based on the four aspects, this research adopted grounded theory because this strategy is a systematic approach to inductively generate theoretical frameworks from the collected data (Glaser & Strauss. 1967; Creswell, 1998). Its focus is to obtain analytical information related to a particular event (Creswell, 1998). Grounded theory can be applied on combination of data - qualitative and quantitative - to collect and analyze data for theoretical frameworks building (Glaser and Strauss 1967; Denzin and Lincoln, 1994). As aforementioned, BIM has been rarely studied for housing refurbishment and a BIM framework for housing refurbishment does not exist, other research strategies which require existing knowledge and data regarding BIM use for housing refurbishment such as survey and archival analysis strategy cannot be relevant and applied. Therefore, grounded theory is relevant for this research to develop a research plan, and also relevant to this research philosophy and approach.

Once the BIM framework is developed, a case study approach was used to investigate the framework to ascertain whether or not it is practical for housing refurbishment, and to highlight the limitations and issues in a framework. Case study as a strategy is used for an experimental theory or topic using set procedures (Fellows and Liu, 2003). The case study is well fitted into this research and grounded theory because a researcher can enhance understanding about a specific situation and it allows generalising understanding by combining the existing theoretical knowledge with new empirical insights (Yin 1994). The benefit of this strategy is that a researcher is able to evaluate or test particular theory or concept based on a consensus of the findings from quantitative and qualitative data (Mangen, 1999; Yin, 2003). The BIM framework proposed in this research may provide a basis for BIM use for housing refurbishment, and also it may have limitations and issues as the framework is a theoretical model. Therefore, a case study was used in order to test and the proposed framework, and to identify current limitations and issues in the framework.

In addition to these two strategy, a pilot study was conducted as an exploratory study because BIM is not widely adopted in the housing sector at present, and there have been a lack of research to utilize BIM for housing refurbishment projects. Exploratory study is used when a research problem has not been clearly defined, and when a researcher attempts to determine research direction based on the outcome of an exploratory study. An exploratory study was used in order to diagnose the feasibility of using BIM for housing refurbishment, and to further define and adjust the research direction of this thesis. This is because the feasibility of BIM for housing refurbishment has not been clearly defined and BIM has been rarely used for the housing refurbishment although its adoption is mandated by the government (See Section 4.4). Therefore, an exploratory study was required in order to clearly understand why BIM is not used and confirm if this research question and aim are worth pursuing. Therefore, this research adopted exploratory study, grounded theory (what, who, when and where) and case study (how and why) to achieve research aim.

5.4 Research Design

Figure 5.1 illustrates the research design of this thesis. Phases 1 and 2 were an inductive approach for collecting data to develop a BIM framework at phase 3. Then, the questionnaire survey results for homeowners' preferences at phase 2 were used as inputs for a case study to test the proposed BIM framework in phase 4. The homeowners' preferences were used as inputs because the housing refurbishment is a particular type of construction project where each homeowner has their own requirements, and the proposed framework is developed for the housing refurbishment specifically. Therefore, the framework was tested based on the research findings from actual homeowners to obtain more realistic test results. Then, the proposed framework was reviewed by construction professionals and academic researchers for validation purposes.

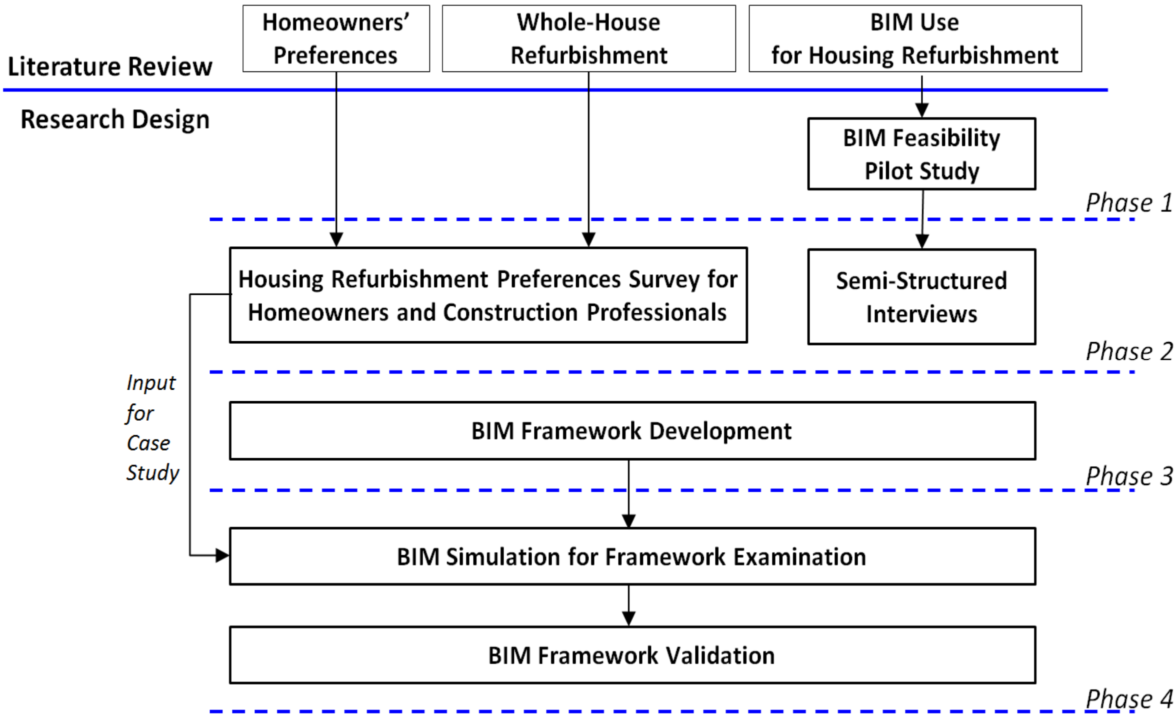

Figure 5.1 Research Design

In phase 1, a pilot study was conducted as an exploratory study to investigate BIM feasibility for housing refurbishment.

In phase 2, the questionnaire survey was conducted to reveal the housing refurbishment preferences for homeowners and construction professionals, and to identify any different preferences between them. Semi-structured interviews were conducted among construction professionals who were engaged in whole-house refurbishment using BIM to obtain more insights and knowledge for developing a BIM framework at the next phase.

In phase 3, a BIM framework for whole-house refurbishment was developed based on the collected data from the phases 1 and 2.

In phase 4, a BIM simulation was conducted to examine the developed framework though a hypothetical case study at phase 3, which was reviewed by two academic researchers and two practitioners to validate the framework, to see if it is worth using for whole-house refurbishment.

More detailed information about research methods adopted in this thesis will be provided in the following sub sections.

5.4.1 Phase 1 – BIM Feasibility Pilot Study

The questionnaire survey was conducted to ascertain BIM's suitability for housing refurbishment projects as an exploratory research, and to refine research direction.

In order to collect various viewpoints of construction professionals, the target for questionnaire survey was local authorities, architects and constructors, construction professional organizations, and BIM software developers as a focused group. Stratified random sampling (Teddlie and Yu, 2007) was used for the questionnaire survey which combines stratified sampling with random sampling. Sampling was purposeful (Maxwell, 2005) and randomly targeted 100 professionals who were actively involved in BIM adoption for their organization or practice because it was more likely to obtain meaningful information about challenges and benefits of BIM utilization that professionals encountered. 100 professionals were identified via construction professionals organization websites such as the Chartered Institute of Building (CIOB), the Royal Institution of Chartered Surveyors (RICS), Royal Institution of British Architects (RIBA), the Building Research Establishment (BRE) and personal contact information retrieved from the ICE retrofit solutions conference 2011 and 2012 such as the Birmingham City Council, the Sustainable Housing Action Partnership (SHAP) and other professionals.

The web-based questionnaire comprised 16 questions designed to explore the following four key areas of information about BIM: a) awareness and current status; b) benefits; c) challenges, and; d) feasibility of using BIM for housing refurbishment projects. The questionnaire consisted of multiple choice and rating questions in five sections (see Appendix 1), with each question being designed to ask respondents to explain why they selected the choices for the questions. The questions were benchmarked from previous similar research carried out by the National Building Specification (NBS, 2011).

Section 1 consists of two questions (Questions 1 and 2) asking respondents' years of experience and their discipline in order to ensure they were appropriate for the survey.

Section 2 comprises three questions (Questions 3, 4 and 5) asking the current awareness of BIM among respondents and their clients. In order to find out the potential use of BIM, it is important to identify if there is a demand and awareness of BIM among practitioner and clients.

Section 3 consists of three questions (Questions 6, 7 and 8) regarding the status of BIM use in respondents' fields. This question is designed to understand how BIM is currently used for which building type and project.

Section 4 consists of three questions (Questions 9, 10 and 11) regarding the potential use and benefits of BIM for housing refurbishment. This question is designed to reveal how construction professionals consider BIM at present, and to identify if they are aware of potential BIM use for housing refurbishment project.

Section 5 (Questions 12 – 16) regarded the feasibility of and barriers against adopting BIM for housing refurbishment projects. This section is the focal point of the questionnaire, and is designed to identify the required actions for adopting BIM.

5.4.2 Phase 2 – Preference Questionnaire Survey and Semi-structured Interviews

1) Housing Refurbishment Preferences Survey for Homeowners and Construction Professionals

The main goal of this study is to identify homeowners and construction professionals' preferences for housing refurbishment. This questionnaire survey is critical to examine a BIM framework at Phase 3 because the outcome regarding homeowners' preferences will be used as a hypothetical case study inputs.

A pilot questionnaire survey was conducted prior to the main questionnaire survey to eliminate misleading questions, ambiguity and any difficulty in responding (Evans and Mathur, 2005; Polit et al., 2001). In particular, the wording and structure of questionnaire was peer-reviewed by a professor in the social science sector, an editor of SuperHomes (housing refurbishment projects website) and three native-speaking colleagues. Since the main questionnaire targeted a wide range of respondents in terms of ages, family types and geographical locations, it was essential to receive professional feedbacks on questionnaire for delivering easy and understandable questionnaire to targeted respondents. After reviews and updates of the questionnaire, the pilot survey was conducted among five homeowners, who were introduced by an editor of SuperHomes, to confirm if there are any potential improvements needed in the questionnaire survey. As a result, the questionnaire was reviewed and updated (Appendix 2), and then the finalized version (Appendix 3) was used as the main questionnaire survey.

Random sampling was adopted because the total population is large and the purpose of the survey is to collect data regarding homeowners' preferences about housing refurbishment as diverse as possible to remove bias from selecting a certain group of people in terms of geographical locations, ages and types of occupier. If the research questions require a certain level of knowledge and experience about housing refurbishment, this sampling method could be ineffective. However, in this case, it does not require level of expertise in housing refurbishment, and therefore random sampling is relevant for this research.

In order to collect information from homeowners from various locations, the target population for a questionnaire survey was chosen from the three main geographical regions in England: the North, the Midlands and the South. 1,000 homeowners were targeted via local communities, refurbishment project-related websites such as SuperHomes, and personal contact information retrieved from local organizations such as churches and schools. In order to increase the response rate, the survey was conducted both face to face and a web-based survey with the focused group. A face-to-face survey using questionnaire has been used because it is effective to communicate with respondents and can help to obtain more enriched information from them while providing instant feedback/opinions about housing refurbishment.

The main questionnaire comprised nine questions designed to explore the following three key factors about the importance of decision-making priorities between homeowners and construction professionals: a) refurbishment priorities among elements of a house; b) the importance of refurbishment measures, and; c) the importance of refurbishment materials. The questions consisted of multiple choices and rating questions that obtained facts and inquires about personal opinions as a customer and subject matter experts. The questions mainly adopted a 5 point Likert scale in order to quantify the responses. The 5 point scale Likert scale is the most popular method among scientists and researchers (Knight and Ruddock, 2008; Chimi and Russell, 2009). More importantly, the ultimate goal of the questionnaire survey is to identify housing refurbishment preferences from homeowners, and the questionnaire is just a communication tool to facilitate that data collection. Thus, this research used the 5 point scale Likert scale for easy communication. The main questionnaire survey was structured in four major sections with nine questions.

Section 1 (Questions 1 and 2) regards respondents' home location, age, family types and home ownership. In order to categorize respondents based on their backgrounds, there were two questions asked.

Section 2 (Questions 3 and 4) regard the basic information about respondents' homes in terms of housing type, age and construction type. As the UK housing stock shown wide range of housing characteristics, it is essential to capture the information about respondents' houses.

Section 3 (Questions 5 and 6) regards the basic preference of respondents as to whether they would like to undertake housing refurbishment or not and prevents them from refurbishing their houses.

Section 4 –(Questions 7, 8 and 9) regard detailed information about how and where respondents want to refurbish for energy efficiency improvement. The main goal of this section is to identify where homeowners consider the most important component (housing fabric) to be refurbished, and decision-making factors for refurbishment measures and materials selection.

Question 7 asked respondents to rank their preference among house fabric elements such as roof/loft, wall (internal), wall (external), floor and window/door. The elements of house fabric were adopted from RdSAP 2009 (BRE, 2011). The first indicates the most important and the fifth is the least important. As identified in the literature review, there are conflicts between designers and customers regarding the priority about housing refurbishment measures. Based on the responses to this question, it was expected to reveal the homeowners' priority for housing refurbishment.

Question 8 asked respondents to rank the decision-making factors about refurbishment measures selection. Respondents were asked to indicate the decision-making factors in terms of "Very Important" to "Not considered". This question was further developed to identify the decision-making factors impacting selection of refurbishment measure related to the preference for house fabric components. The decision-making factors were identified and collected from the literature review.

Question 9 asked respondents to rank the importance of decision-making factors regarding the selection of construction materials. Respondents were asked to indicate the decision-making factors in terms of "Very Important" to "Not considered". This question was designed to identify the decision-making factors impacting selection of construction materials for housing refurbishment measures. The decision-making factors were identified and collected through following literature.

The decision-making factors for refurbishment measures and materials used in the questionnaire were from similar researches focused on homeowners' decision-making factors in the housing sector (See Section 3.5.2). The literature covers European countries such as: Germany (Achtnicht, 2011; Michelsen and Madlener, 2012), Sweden (Nair et al., 2010a; 2010b), the UK (Joseph Rowntree Foundation, 1998) and other countries - Belgium, Bulgaria, The Czech Republic, Denmark, France, Greece, Hungary, Norway, Portugal, and Romania (Mills and Schleich, 2012). In addition, the BREEAM domestic refurbishment assessment criteria (BRE, 2012) have been referred to in the questionnaire as it is the only sustainable housing refurbishment criteria in the UK, which is not mandatory.

The collected data from the questionnaire survey was checked using the Cronbach's Alpha test to confirm whether the questionnaire survey is structured in a reliable manner, and whether the survey result is acceptable as a relevant data set for statistical analysis (Gadermann et al., 2012; Polit and Benk 2009). After the reliability of data was confirmed, a weighted average was used to compare priorities between two groups regarding housing refurbishment such as refurbishment measures and construction materials. The Statistical Package for Social Scientists (SPSS Version 20) software was used for statistical analysis because the web-based survey tool used for the questionnaire survey has a function to export the received original data to SPSS. This is important as it can minimise human errors when coding and transferring data from the original source.

The same questionnaire survey was conducted among construction professionals to identify their preferences, and compare these with the homeowners' to see if there were any differences. The target for the questionnaire survey was chosen from local authorities, architects and construction professionals as a focused group. The survey targeted at professionals did not include the questions on housing or family information. It was sent via email with the web-based questionnaire link attached. Since whole-house refurbishment requires skills and experience for quality works, 100 qualified professionals were targeted via construction professional bodies such as the Green Deal qualified builders, the Energy Saving Trust recommended builders, the Building Research Establishment (BRE) recommended builders, the British Board of Agrément (BBA) qualified builders, the Centre of Refurbishment Excellence (CoRE) recommended and trained professionals, and personal contact information retrieved from Retro Expo 2012, Retrofit Roadshow 2012, EcoBuild 2012 and GreenBuild Expo 2013.

2) Semi-structured Interviews

Semi-structured interviews were undertaken to understand current BIM-enabled housing refurbishment project processes, and identify what kind of information is required to adopt BIM for housing refurbishment project, in particular solid wall housing refurbishment. Semi-structured interviews are flexible and allow for both interviewer and interviewee to explore and elaborate more in-depth discussions (Denscombe, 2010; Bryman, 2006). Furthermore, the interview has been used as a supportive method to communicate with construction professionals more closely in conjunction with the main questionnaire survey, not to generalise current practices or to induce common practices about BIM enabled housing refurbishment projects which are currently practiced. The interviews were transcribed by hand and the transcribed notes were confirmed by interviewees.

Open-ended questions were used since there has been no previous research, and they can facilitate discussions between interviewer and interviewee about this area of study. The interview questions were designed to obtain construction professionals' expert insights and opinions. The interview questionnaire was sent to interviewees three business days prior to the actual interview date to provide enough lead time for them to think more about the subjects. Purposive sampling was used to select interviewees because the interview requires specific level of expertise in BIM utilization in the housing refurbishment, and interviewee is required to be actively involved in BIM practice presently as well (Bernard et al. 1986; Bridges and Lau, 2006). Thus, sampling was purposive and the contacts acquired from BIM feasibility pilot study were reused to identify experienced and knowledgeable interviewees.

A one-hour interview was arranged with each of the interviewees - 50 minutes interview and 10 to 20 minutes discussion and follow-up questions to clarify their intention and viewpoints. Total four interviews were conducted , and the followings are 10 interview questions (Appendix 4).

Question 1 was designed to identify the background and experience of interviewees.

Question 2 was designed to identify the common process of refurbishment project and the expected impact from BIM use for refurbishment.

Question 3 was designed to identify the form of collaboration with other project team members for whole-house refurbishment project.

Question 4 was designed to identify the historic data about the homeowners' preferences.

Question 5 was designed to identify the barriers and challenges to adopt BIM for housing refurbishment.

Question 6 was designed to identify the economic feasibility of BIM for SME builders.

Question 7 was designed to identify the current use of COBie in conjunction with BIM

Question 8 was designed to identify the possible solution to use BIM for housing refurbishment.

Question 9 was designed to confirm the current refurbishment practices if it is actually used (closed-end question)

Question 10 was designed to identify the use of NRM 2 for cost estimating.

5.4.3 Phase 3 – BIM Framework Development for Housing Refurbishment

The main goal of this phase is to develop a theoretical BIM framework based on the collected data from the literature review and professional trainings based on the grounded theory by adopting a general procedure of theory-building (Wacker, 1998) as shown in Figure 5.2.

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Figure 5.2 General Procedure of Theory-building (Wacker, 1998)

In order to define the variables (Who and What) and identify processes (When and Where) for a BIM framework for whole-house refurbishment, the standards and guidelines identified at the Chapter 3 and Chapter 4 (See Section 3.5.4 and subchapter 4.4) – the RIBA Plan of Work (RIBA, 2013) and Low Carbon Domestic Retrofit (Institute for Sustainability, 2011), BIM overlay to the plan of work (RIBA, 2012) and PAS 1192-2:2013 (BSI, 2013) – were used.

Then, specific activities and required information for each phase were identified through the professional trainings and interview. Since the standards and guides cover general construction projects, in particular new build construction projects, professional trainings designed for specific whole-house refurbishment, which were provided by the Centre of Refurbishment Excellence (CoRE) and domestic retrofit workshop provided by Retrofit Roadshow, were used to identify specific information and key project stakeholder for whole-house refurbishment.

After identifying the project stakeholders, construction information and processes, all the defined variables and sequences of processes were integrated and combined leading to a framework. After developing the framework, semi-structured interviews were conducted in order to obtain a practical understanding of how construction professionals utilize BIM in the construction industry. Additionally, an interview was conducted with a BIM manager, who was engaged in a housing refurbishment project using BIM in York, and this interview provided in-depth understanding of current BIM use for housing refurbishment (See Expert 4 at Appendix 4).

5.4.4 Phase 4 – BIM Simulation for Framework Examination and Validation

In order to examine the developed BIM framework, a hypothetical case study was used. The BIM framework was explained in detail as a hypothetical case study was conducted following processes in the framework. The data collected from Phase 2, which is homeowners' preferences, was analysed, and the data were used for a BIM simulation as inputs. Typical solid wall houses –

Detached, Semi-Detached and Terraced– were used as a BIM simulation model. Detailed information about the BIM simulation and the case study will be provided in Chapter 7

In Chapter 8, after completing the case study, comparative analyses regarding life cycle cost and life cycle CO2 performance for three solid wall housing types - Detached, Semi-Detached and Terraced – were undertaken based on two different insulation materials and four different energy standards. Once the comparative analyses were completed, a BIM framework validation was conducted among subject matter experts – 2 academics and 2 construction professionals – to see whether the framework is suitable for housing refurbishment and whether the outcomes of the BIM framework is useful as a decision making criteria for determining the best refurbishment solution.

5.5 Conclusion

This chapter introduced the research methodology and design adopted to achieve the research goal. As the of use BIM for housing refurbishment has rarely been studied and its potentials not clearly identified, this research adopted exploratory and grounded theory strategies to develop a BIM framework for housing refurbishment based on realism philosophy. Housing refurbishment is specific kind of construction projects the qualitative research such as an interview was used in conjunction with quantitative research to obtain better understanding of BIM use for housing refurbishment. The following chapter will present the findings from each phase of the research design.

Chapter 6 BIM Feasibility Study and Housing Refurbishment Preferences

6.1 Introduction

This chapter presents and discusses the research results. It comprises two main components:

1) BIM Feasibility Study Results
2) Questionnaire Survey Results for Homeowners' Preferences

In this chapter, it will be confirmed that the research aims and objectives are fulfilled, and will be identified what the challenges and limitations are to close the research gaps.

6.2 BIM Feasibility Study

1. Profile of Respondents

100 professionals were selected for the questionnaire survey and the response rate was 51%. The average experience of respondents was 18 years with 60% (31 respondents) having more than 20 years of experience in the housing sector. The respondents' profile is shown in Table 25 shows the profile of the respondents and the corresponding numbers.

Table 25. Profile of Respondents (Number of Respondents)

Profile of Respondents	**Number of Respondents**	**Respondents' Profile**	**Number of Respondents**
Architect	19	Civil Engineer	4
Quantity Surveyor	8	Structural Engineer	4
Private Client	6	Facilities Management	4
Project Management	6	Specialist Contractor	3
BIM Consultant	6	Tier 1 Contractor	2
Public Client	4	Service Engineer	2
Building Surveyor	4	**Total**	51

2. Awareness and Current Status of BIM

Respondents were asked to indicate current use of BIM and awareness of the UK BIM strategy. 81%

of respondents were aware of UK BIM strategy (Level 0 to Level 3), yet their clients' demand for BIM was low (61%) as shown in Figure 6.1.

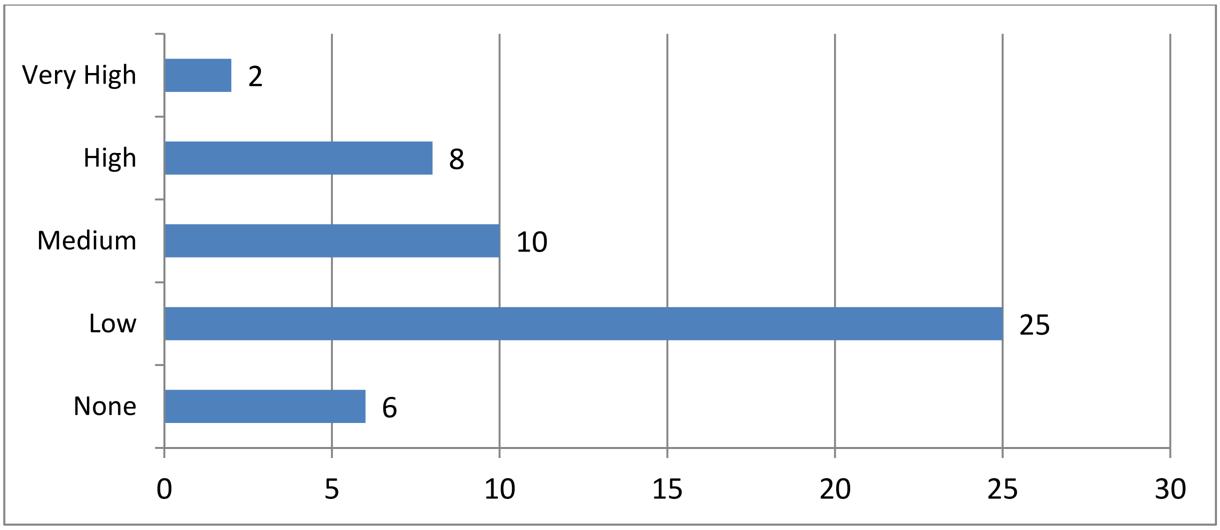


Figure 6.1 Awareness and Demand of BIM, Clients' Standpoint (X-axis is the number of respondents)

Respondents were asked to indicate their current use of BIM; the result is shown in Figure 6.2. About 60% of respondents said they were not engaged to use BIM, a result very similar to with the outcome of the NHBC survey (2013) which showed 64% non-BIM use.

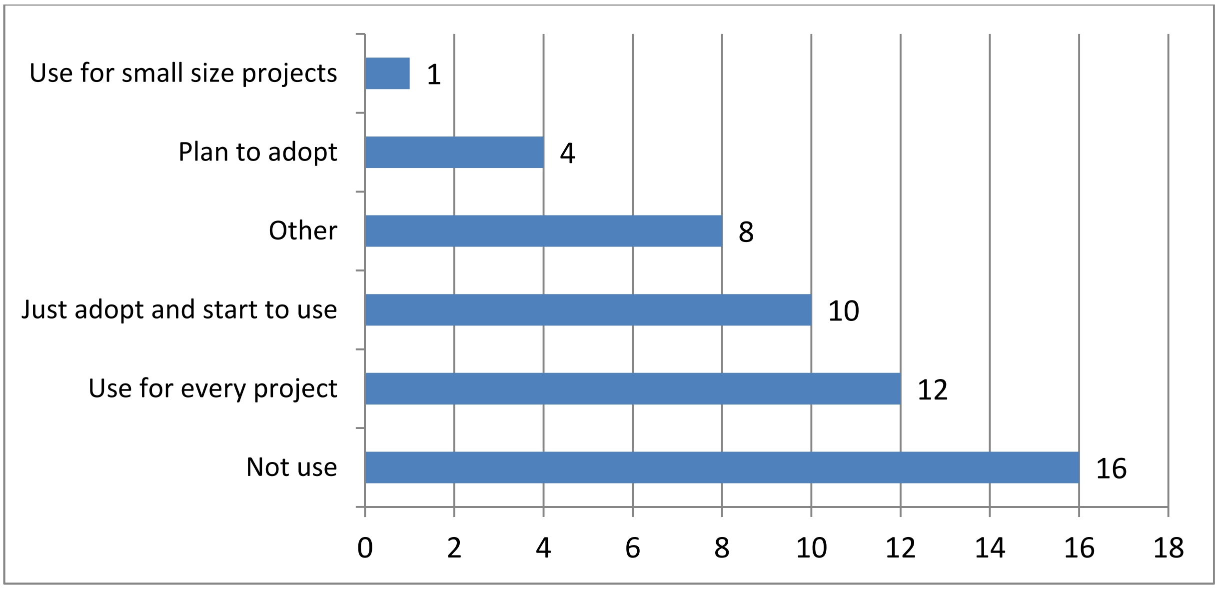


Figure 6.2 Current Status of BIM Use (X-axis is the number of respondents)

8 respondents indicated that they belonged to the 'Other' category as they are BIM software developers (2 respondents) and BIM education and consultants (6 respondents). Of the 12 respondents who use BIM for every project, 8 were architects, 2 were civil engineers and 2 were structural engineers. It could be assumed that architects are the dominant users of BIM at the design phase of a project. Respondents said that the main challenges of BIM adoption is the motivation of clients and their organizations.

Respondents were asked to indicate what kind of functions they use BIM for. The results are shown in Figure 6.3. Except those who are not engaged in BIM or currently adopting, most of the respondents (16 professionals) used BIM for 3D visualization to communicate with the project team and to present a design in 3D.

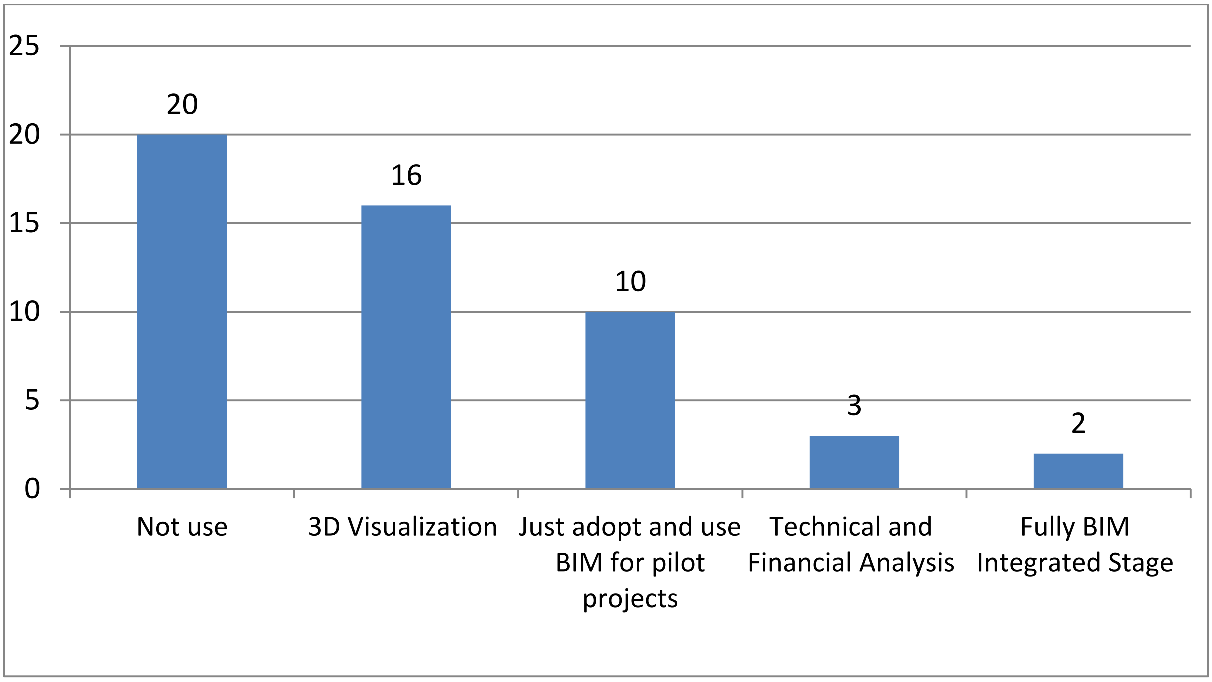


Figure 6.3 Purpose of BIM Use (Y-axis is the number of respondents)

Those who selected *Technical and financial analysis* utilized BIM for energy performance simulation and life cycle cost calculation for refurbishment measures and construction materials. Interestingly, two respondents indicated that they utilized the full extent of BIM up to 5D cost management. However, the validity of these answers is questionable since the definition of BIM is contentious among practitioners and researchers. Furthermore, two respondents are BIM consultants and the answers could reflect their own viewpoints.

Respondents highlighted the issue of having a reliable data source for construction materials, and the necessity of a BIM library to provide a quick and accurate standard model for refurbishment measures. They shared the same viewpoint that BIM adoption is not just switching or learning new software, it is about adopting a facilitator for changes in process and culture in the construction industry.

3. Benefits and challenges of BIM use for housing refurbishment

Respondents were asked to indicate the benefits of BIM. The results are shown in Figure 6.4. This question allowed multiple choices.

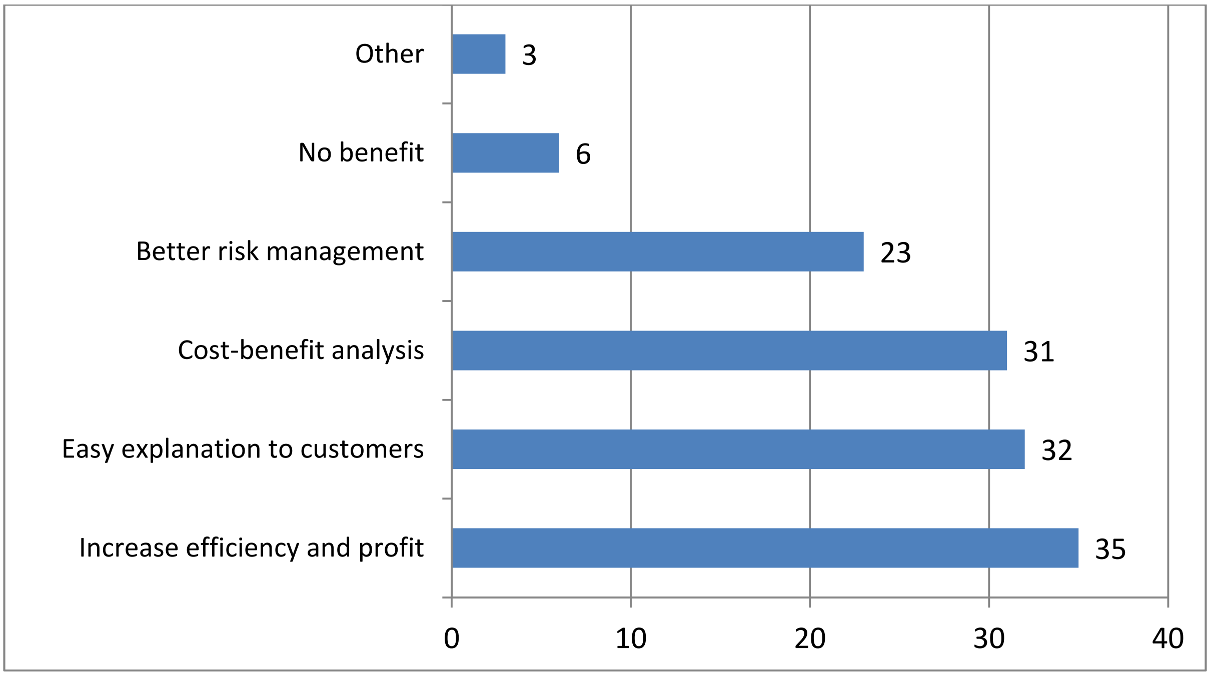


Figure 6.4 Benefits of BIM in housing refurbishment (X-axis is the number of respondents)

Respondents were well aware of the benefits of BIM even if they are not engaged in BIM currently. They mainly addressed the 3D modelling function that enables them to explain complicated designs effectively and easily in a 3D manner. As a result, customers and the project team understand better the refurbishment measures and can address their opinions more clearly. Furthermore, BIM has the capability to perform comparative cost-benefit analysis between various refurbishment measures. According to respondents, this comparative analysis can be done much quicker and more efficiently than with a 2D system. Six respondents who selected *No benefit* explained they did not know the benefits of BIM as they are not using BIM currently. There were three *Other* responses which included better asset management and effective management on bespoke design.

Respondents were asked to indicate the challenges of BIM adoption; the result is shown in Figure 6.5. This question allowed multiple choices.

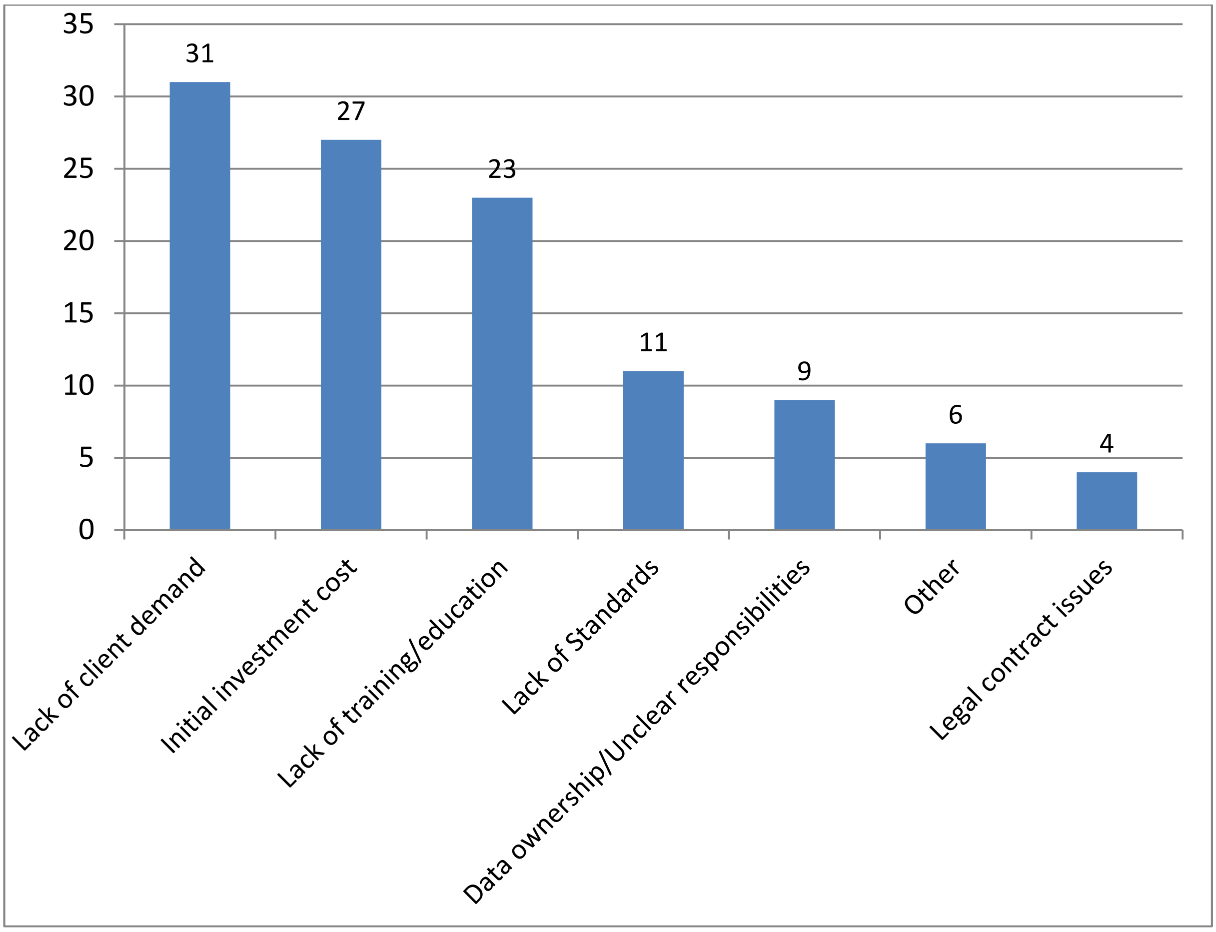


Figure 6.5 Challenges of BIM adoption in housing refurbishment

(Y-axis is the number of respondents)

The result revealed that *Initial investment cost* and *Lack of client demand* were the most challenging issues. *Lack of training/education* was the next highest response. Current demand and awareness of BIM among clients is low, and respondents were reluctant to invest in BIM although they were keenly aware of benefits of BIM based on the Figure 6.1 and Figure 6.5. In addition, since BIM facilitates a collaborative working environment, the ownership of BIM data is an issue. Furthermore, the lack of a standard for BIM for housing refurbishment project can lead to unclear roles and responsibilities among project team. There are other challenges addressed such as a lack of incentive to use BIM. One respondent said *"There is minimal additional incentives in this type of work and much higher costs in using BIM."* In addition, difficulty to transfer housing condition survey results to BIM and a lack of quality BIM families (BIM data/content) were raised.

4. Feasibility of BIM adoption in housing refurbishment

Respondents were asked to indicate the feasibility of BIM adoption in terms of timing, and the reason for their answer. The result is shown in Figure 6.6.

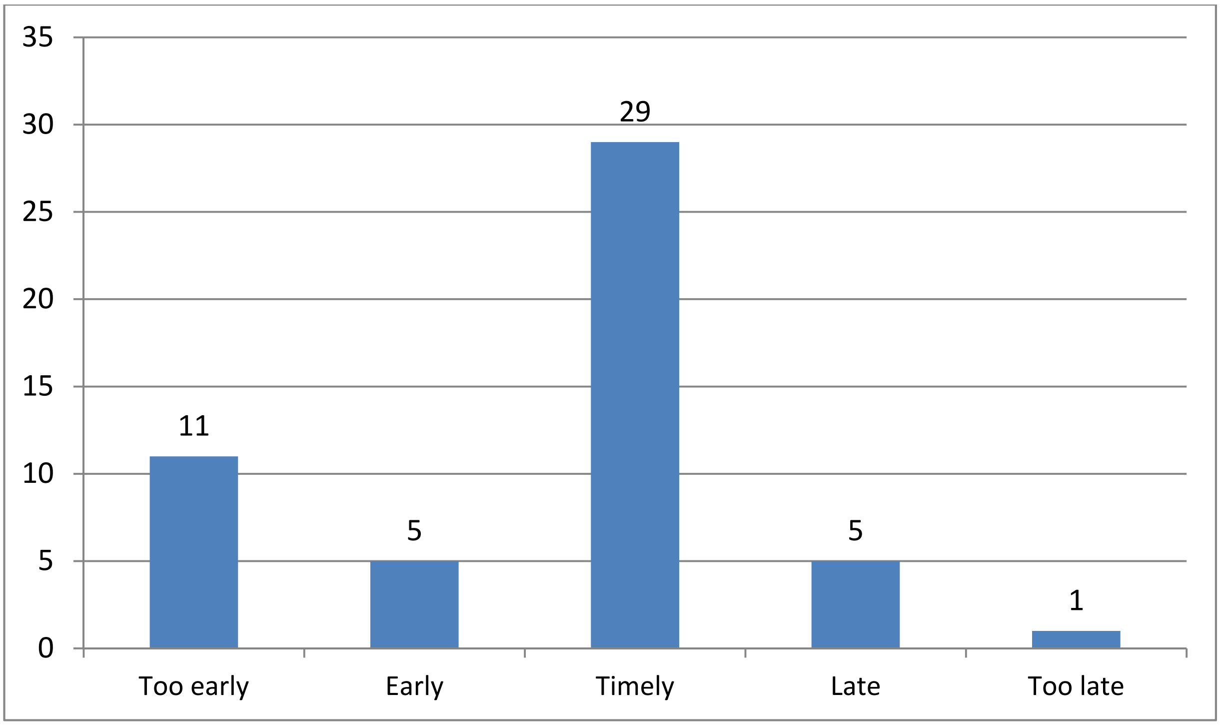


Figure 6.6 Feasibility of BIM adoption in housing refurbishment

(Y-axis is the number of respondents)

57% (29 respondents) indicated that BIM adoption is timely, while 22% indicated it was too early for adoption. 16 respondents who indicated *Early* or *Too early* mentioned the uniqueness (non-standardization) of the housing stock, which would require a lot of work to adopt BIM such as the establishment of a BIM standard and process, proper legal amendments in contracts and appropriate incentives.

In order to identify the critical steps for the housing sector to embrace BIM, respondents were asked to indicate what the critical steps should be undertaken. The results of the question are shown in Figure 6.7. This question allowed multiple choices.

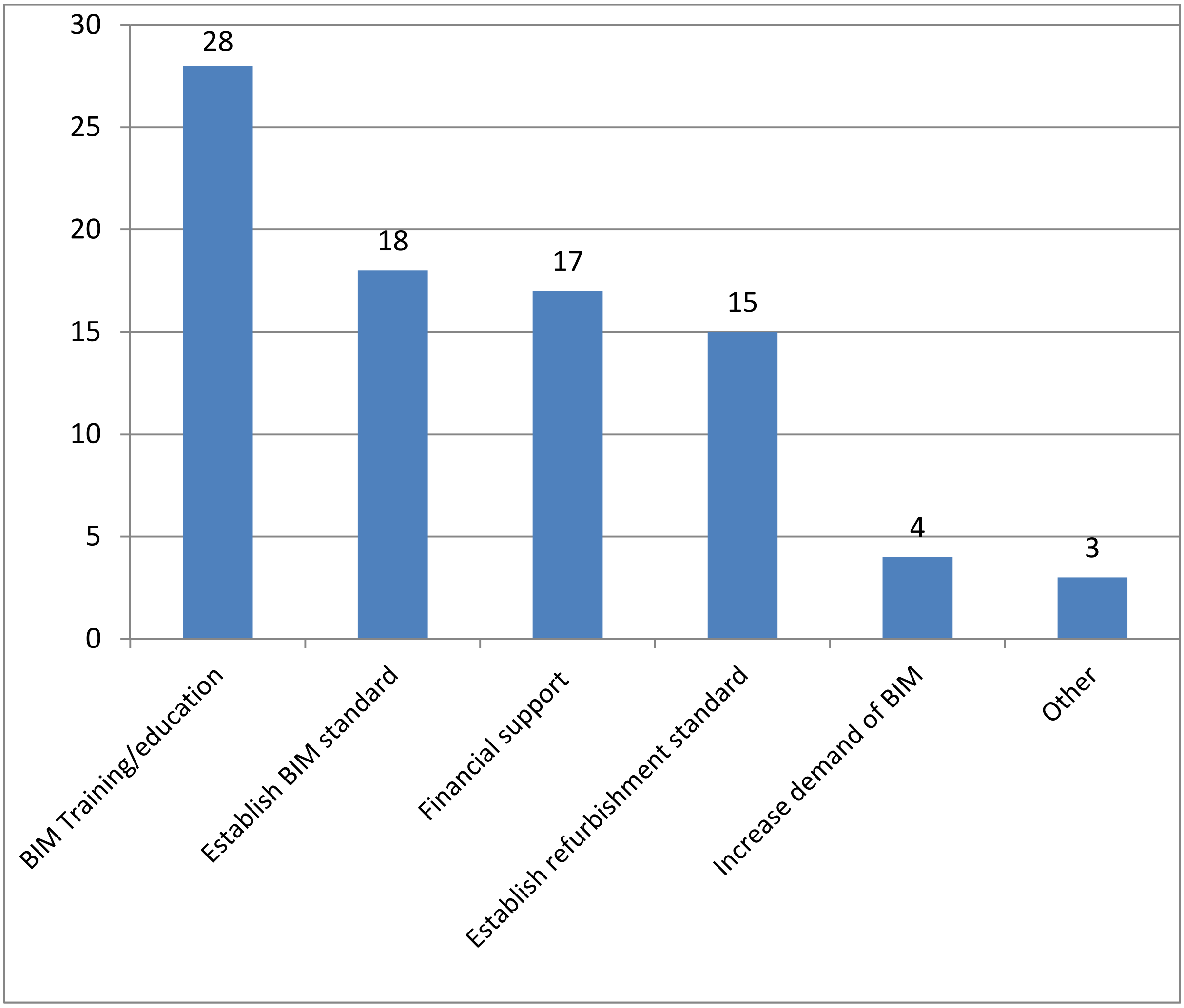


Figure 6.7 Critical steps for BIM adoption in housing refurbishment

(Y-axis is the number of respondents)

Respondents saw *BIM training/education* as being most critical to increase BIM adoption in the housing sector. They indicated if clients and organization clearly understood the benefits of BIM, and then demands for it would increase. In addition, *Establish BIM standard* and *Financial support* for initial BIM adoption were rated highly. *Increase demand of BIM* received four responses. This could occur naturally if enough BIM education is supplied to the housing sector.

Through the survey, it was revealed that the housing sector was relatively insensitive to BIM adoption. Respondents indicated that housing is deeply related with households, and they are more interested in quick and easy installation such as window replacements and voltage regulators. Furthermore, it was revealed that currently there are no financial incentives or rewards when construction professionals use BIM for housing refurbishment projects.

The findings revealed that BIM adoption for housing refurbishment projects is feasible and timely, although the clients' demand and BIM penetration in the housing sector is low. In order to encourage adoption, BIM education/training and BIM standard establishment are the most critical steps that need to be undertaken along with Financial support. The survey results showed that the benefits of BIM adoption should be clearly understood by clients and the project team if BIM awareness and demand is to increase. It was found that the construction professionals were aware of the benefits of BIM whether or not they were engaged in BIM. Therefore, the BIM adoption for housing refurbishment project is feasible with proper BIM education/training support and BIM standard.

6.3 Housing Refurbishment Preferences Survey

6.3.1 Questionnaire Survey Response Rate

The response rate of the questionnaire survey was 32% as shown in Table 26. 1,000 targeted respondents were asked to answer the online questionnaire and face-to-face questionnaire survey; a total of 322 people responded.

Table 26. Response Rate

Location	Targeted Number	Responses	Response Rate
Local Community	100	81	81%
Schools (Primary and Middle)	100	51	51%
Direct Emails	800	152	19%
SNS (LinkedIn)	N/A	38	N/A
Total	1,000	322	32.2%

Since there are good relationships established among the committee members of local communities such as the church/cathedral and schools, the response rate from the local community was as high - 81% and 51% respectively. Prior to the questionnaire survey, it was announced that the questionnaire survey would be conducted for academic research purposes. The questionnaire survey was conducted through a face-to-face meeting using printed questionnaire survey form. The survey was also conducted in the SNS community "Affordable Housing Network" where people living in the UK gather to share housing refurbishment information.

6.3.2 Reliability Check – Cronbach's Alpha Test

Cronbach's Alpha test was undertaken to confirm that this survey was structured in a reliable manner and the survey result data is acceptable as a relevant data set as a Likert scale has been adopted in the questionnaire (Maidabino and Zainab, 2011). As shown in Table 27, when the Cronbach's alpha is between 0.8 and 0.7, it is considered that the reliability is good.

Table 27. Cronbach Alpha and Level of Consistency (DeVellis, 2003)

Aston University

Illustration removed for copyright restrictions

The Cronbach's Alpha test indicated that the survey results of homeowners' preferences are reliable enough to use as a dataset for statistical analysis with 0.7 for refurbishment measures and 0.8 for refurbishment materials as shown in Tables 32 and 35. The priorities among elements of a house did not adopt the Cronbach's Alpha test since the survey result was shown as a ranked order (ordinal) data, not on a Likert Scale. Weighted average was used to compare the survey results between homeowners and construction professionals.

6.3.3 Result of Questionnaire Survey

6.3.3.1 Result of Section 1 and Section 2

As shown in Figure 6.8, the 322 respondents comprised 240 homeowners (75%) and 82 tenants (25%). 74% of homeowners responded that they would like to refurbish their homes, and actually have a plan to do so soon. Most of the respondents who plan to refurbishment their homes addressed a great need for additional space for their children. They also showed great concern about energy costs. While they have a plan for refurbishment, they highlighted the fact that the initial cost for refurbishment will be a financial burden for them. At the same time, they had concerns about the uncertain outcomes of refurbishment carried out by local builders. 26% of owners responded that they have no plan to refurbish their homes since they had already done so or they did not see it as necessary. The majority of refurbishment measures installed in respondents' homes were cavity wall insulation and new boiler installation.

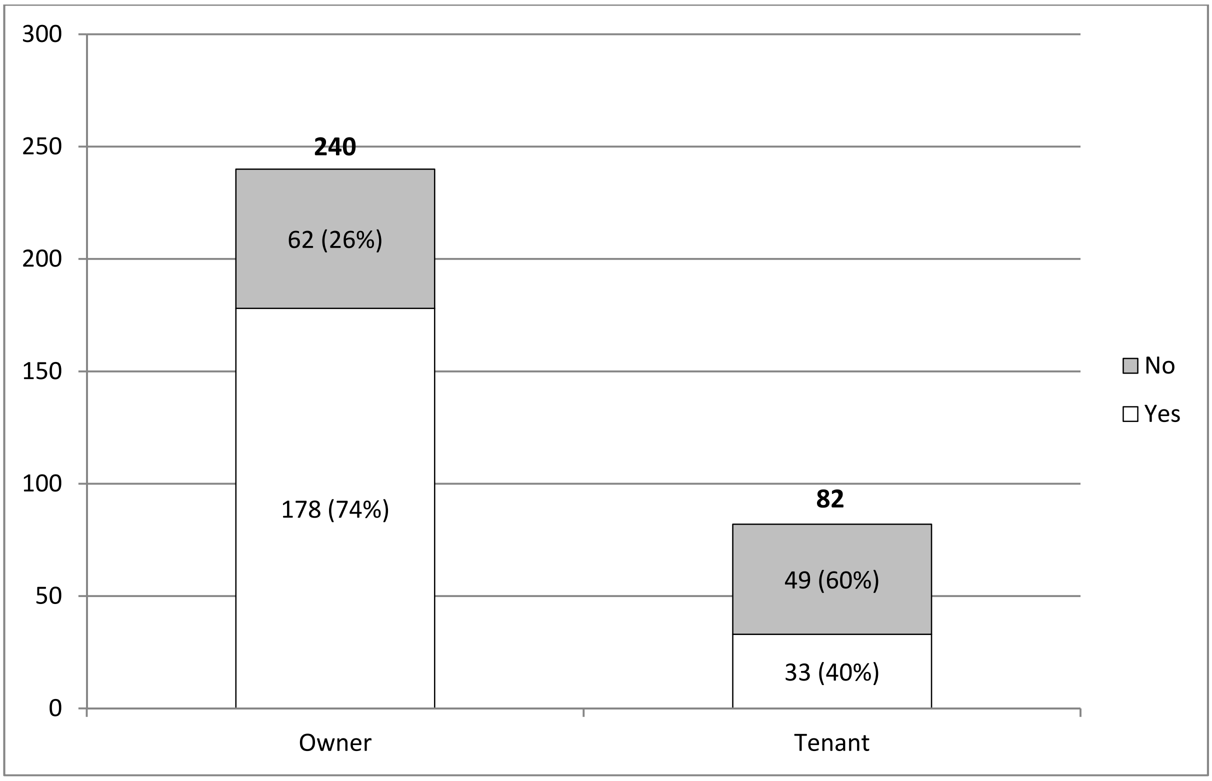


Figure 6.8 Refurbishment Yes and No Composition

40% of tenant respondents indicated that they would refurbish their homes for better thermal comfort and low energy bill if the house was owned by them. While 60% of tenants respondents said they have no interest in refurbishment since the house is not owned by them. From this result, it was revealed that owners and tenants share the common concerns about the high energy cost.

Privately-owned solid wall housing stock has the greatest potentials to reduce CO_2 and improve energy efficiency (See Chapter 2 and 3). This questionnaire survey was distributed to a wide range of households (owners and tenants) and housing characteristics (housing type, year built and construction type), not just to those with solid wall housing. Thus, the analysis of this survey result was mainly focused on those homeowners' with solid wall housing. As a result, the final respondents were a total of 112 people, and the final outcome of survey result is explained from this section forward after sorting out irrelevant respondents (tenants and other housing type except solid wall housing). A summary of Section 1 and Section 2 of the Questionnaire is indicated in the Table 28 (Appendix 6). Occupier specifications were adopted from the EST (2011).

Table 28. Result of Questionnaire Section 1 and Section 2 Summary (Total respondents = 112)

Question	Response Categories	Survey Result (Number of Respondents)	Proportion (%)
Respondents' Location	Northern Region	17	15%
	Midlands	66	59%
	Southern Region	29	26%
Age	20s	9	8%
	30s	34	30%
	40s	32	29%
	50s	28	25%
	60+	9	8%
Occupier	Singles	19	17%
	Young Couples	16	14%
	Families with young children	44	39%
	Families with older (16+) children	13	12%
	Empty Nesters, whose children had moved on	20	18%
	Other	None	0%
Housing Type	Terraced	38	34%
	Semi-Detached	49	44%
	Detached	21	19%
	Don't Know	4	4%
Year Built	Pre 1919	53	47%
	1919-44	34	30%
	1945-64	9	8%
	1965-80	3	3%
	1981-90	6	5%
	Post 1990	6	5%
	Don't Know	1	1%
Orientation	North	19	17%
	East	18	16%
	South	37	33%
	West	15	13%
	Don't Know	23	21%

Number of Bedroom	One	2	2%
	Two	20	18%
	Three	56	50%
	Four	19	17%
	Five+	15	13%
Wall	Solid Wall	112	100%
Floor	Suspended Timber Frame	63	56%
	Solid Concrete Floor	32	29%
	Don't Know	17	15%
Roof	Pitched Roof	106	95%
	Flat Roof	4	4%
	Don't Know	2	2%
Window	Double Glazing	97	87%
	Single Glazing	15	13%
	Don't Know	0	0%

Note: Northern Region – North East, North West, Yorkshire and Humberside
Midlands – East Midlands, West Midlands
Southern Region – East of London, London, South East, South West

As shown in Figure 6.9, more than 50% of respondents were located in the Midlands since this research was mainly conducted in the West Midlands, and the three regions were further divided as shown in Fig 6.9. According to the survey result as shown in Table 27, 77% (87 respondents) indicated that their homes were built before 1945 when solid wall construction was prevalent and the Building Regulations Part L was practiced in the housing sector. The result of this survey echoed the literature review (See Section 2.3) with solid wall housing being the dominant building type pre 1919 and between 1919 and 1944. Thus, this result identified that homeowners dwelling on old housing stock have more interest in housing refurbishment for energy performance improvement than relatively new and high energy standard housing. The 62 respondents who are not included said they had no interest in housing refurbishment since they live in good energy performance housing built post 1980. Interestingly, some of respondents were not fully aware of the basic information about their houses such as housing type, year built and orientation. Therefore, construction professionals should provide enough information for homeowners to understand their homes, and support them to make informed decision based on that.

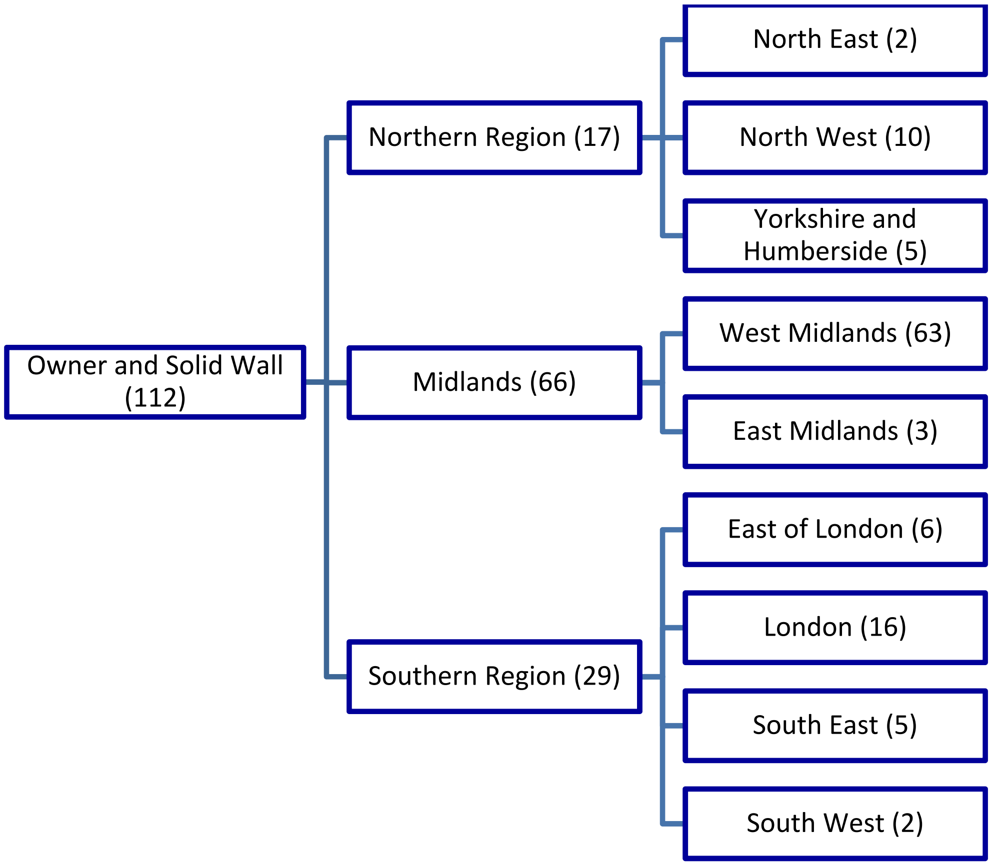


Figure 6.9 Owner and Solid Wall Housing by region

From the questionnaire section 1 and 2, basic background information about respondents and housing characteristics were identified.

6.3.3.2 Result of Section 3

84 (75%) homeowners said they would refurbish their homes, 28 (25%) said they would not. 4 respondents indicated that they had never thought about refurbishment so they did not answer the question. 2 respondents indicated that they already refurbished their homes.

Figure 6.10 shows that respondents care about the aesthetic and energy cost and see them as the most important factors in the refurbishment of their houses. The next two factors were associated with energy costs. *Thermal comfort* can be achieved by proper energy efficiency improvement as a refurbishment measure, and the *Energy efficiency* improvement can result in *Energy cost saving*. CO_2 *reduction* had a relatively low impact on decision-making for refurbishment. This factor shows the very different priorities between construction professionals and householders, their customers.

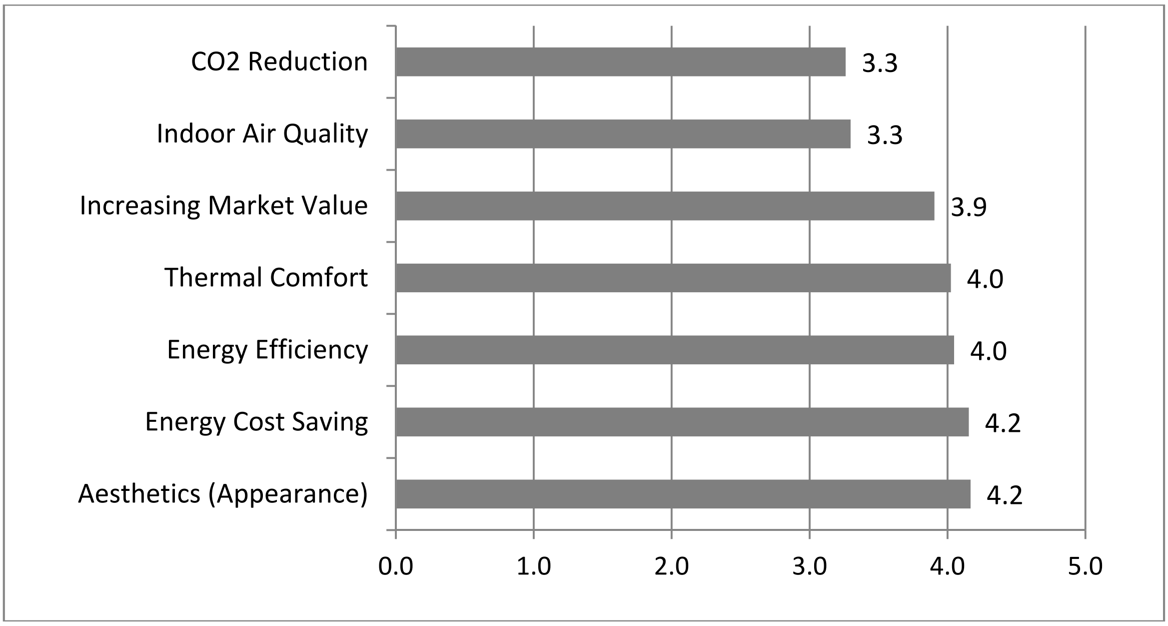


Figure 6.10 Reasons for Refurbishing Houses
Note: x-axis is Likert Scale (0.0 is Not considered to 5.0 is Very Important)

As shown in Figure 6.11, respondents were unanimous in *No Need* being the most important reason for the not undertaking refurbishment. As a result, the weighted average of the Likert scale shows 5. Apart from *No Need*, the primary barrier for adoption of refurbishment is the *Initial cost* followed by the *Disruption caused by refurbishment*. There is a relatively large gap between *Initial cost* and *disruption*. Respondents showed less concern when they were determined to refurbish their homes. *Mistrust of builders* came next, a barrier already mentioned by respondents that they do not have confidence about the outcome of any refurbishment carried out by local builders.

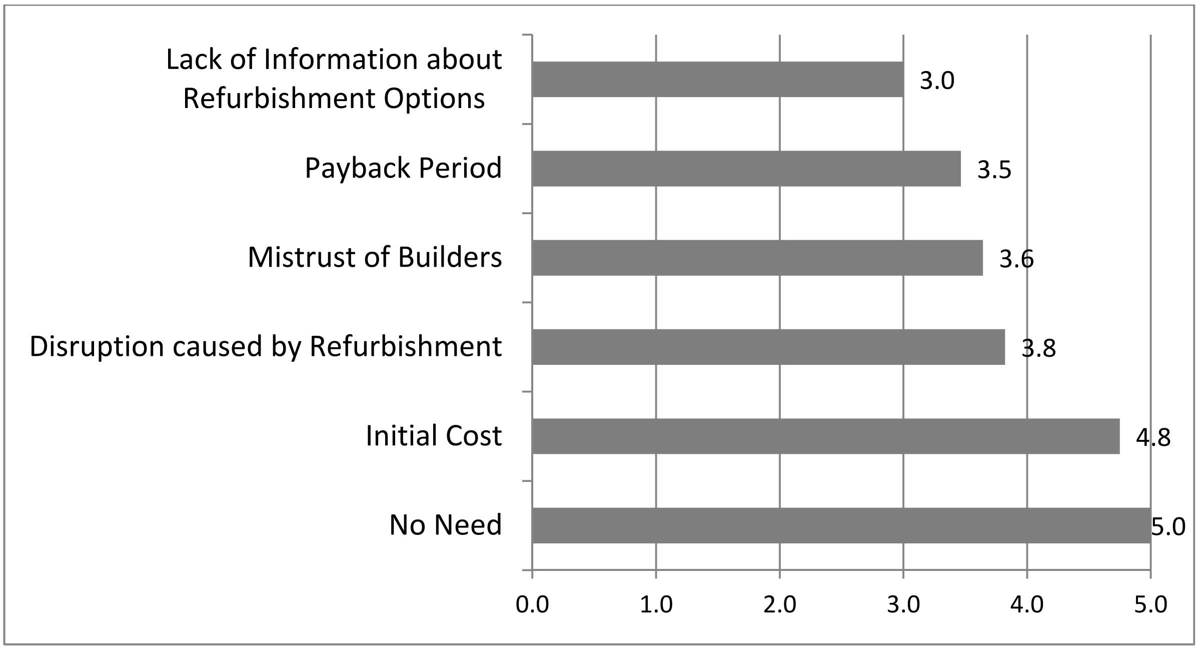


Figure 6.11 Reasons for Not Refurbishing Houses
Note: x-axis is Likert Scale (0.0 is Not considered to 5.0 is Very Important)

6.3.3.3 Result of Section 4 – Comparative Analysis between Homeowners and Construction Professionals

The 100 targeted construction professionals were asked to answer the questionnaire via an online questionnaire survey, to which a total of 39 professionals responded - a response rate of 39%. The average years of experience is 18 years, and over 50% of respondents have more than 21 years of experience in housing refurbishment projects as shown in Table 29 (Appendix 7).

Table 29. Construction professionals' profile

Years of Experience	Number of Respondents	%
Less than 5 years	5	13%
5-10 years	6	15%
11-15 years	4	10%
16-20 years	4	10%
21-25 years	3	8%
26+ years	17	44%
Total	**39**	**100%**

AT	MB	BS	CO	PP	QS	PM	SC	LA	PrM	Total
7	7	6	5	5	3	2	2	1	1	39

* AT: Architect, MB: Master Builder, BS: Building Surveyor, CO: Contractors, PP: Private Practice, QS: Quantity Surveyor, PM: Project Management, SC: Special Contractor, LA: Local Authority, PrM: Property Management

The Cronbach Alpha test for the survey result among construction professionals indicated 0.3 for refurbishment measures and 0.6 for refurbishment materials. Although the collected data from this survey could be problematic to be used as a dataset for statistical analysis, this should not be dismissed or ignored because the results can provide various viewpoints of construction professionals on how they think about housing refurbishment. The Cronbach Alpha test result could be calculated with a lower score when the sample data is not sufficient enough to draw a statistical trend from the collected data, while low numbers of survey respondents shows a large variation in their opinions (Tavakol and Dennick, 2011). Indeed, the sample size was limited to only 39 construction professionals, although 100 construction professionals were targeted for this survey. This is because most construction professionals are involved in partial refurbishment projects such as wall or loft insulation, and they therefore declined to respond to this survey. Furthermore, respondents have different viewpoints because they are a heterogeneous group with different positions. For example, someone have ownership or decision-making authority from customers about projects, while others do not. Thus, this research used the survey results only for comparing preferences between homeowners and construction professionals, not to draw any definitive conclusions.

Refurbishment Priorities among Elements of House

Respondents were asked to indicate the refurbishment priorities for the elements of a house. The priorities between the two groups are compared using weights from 5 for 1st priority to 0 for 5th priority. The elements listed in Table 30 have been adopted from RdSAP 2009 as a default fabric of a typical house (See sub section 5.4.2). Regardless of the locations and year built, the survey results have shown very similar priorities on preferable refurbishment elements, measure and materials; for example, roofs and windows are 1st and 2nd priorities to refurbish although the weighted averages on an element of roof for the Northern and Southern Regions are a slightly higher weighted average with 4.1 and 4.2 respectively. 87 respondents living in a house built before 1945 (See Table 28) indicates the completely same priorities with Table 32, while 19 homeowners out of 25 living in a house built after 1945 responded differently as *Window* is the first priority and *Roof* is the second.

Table 30. Homeowners' Preferences for House Elements

Rank (Weight)	1st	2nd	3rd	4th	5th
Roof	56	28	12	6	5
Wall (Internal)	12	23	37	19	19
Wall (External)	11	18	28	28	25
Floor	6	17	19	32	33
Window/Door	48	29	12	10	13

Note: The number in the table is the frequency for each rank

Table 31. Construction Professionals' Preferences for House Elements

Rank (Weight)	1st	2nd	3rd	4th	5th
Roof	35	3	1	0	0
Wall (Internal)	1	8	13	10	7
Wall (External)	20	9	4	3	3
Floor	2	1	3	14	19
Window/Door	7	19	6	4	3

Note: The number in the table is the frequency for each rank

Table 32. Comparative Analysis of Refurbishment Priorities between Homeowners and Construction Professionals

Priorities	Homeowners		Construction Professionals	
	Elements	**Weighted Average**	**Elements**	**Weighted Average**
1st	Roof	4.0	Roof	4.9
2nd	Window	3.8	Wall (External)	4.0
3rd	Wall (Internal)	2.9	Window	3.6
4th	Wall (External)	2.6	Wall (Internal)	2.6
5th	Floor	2.3	Floor	1.8

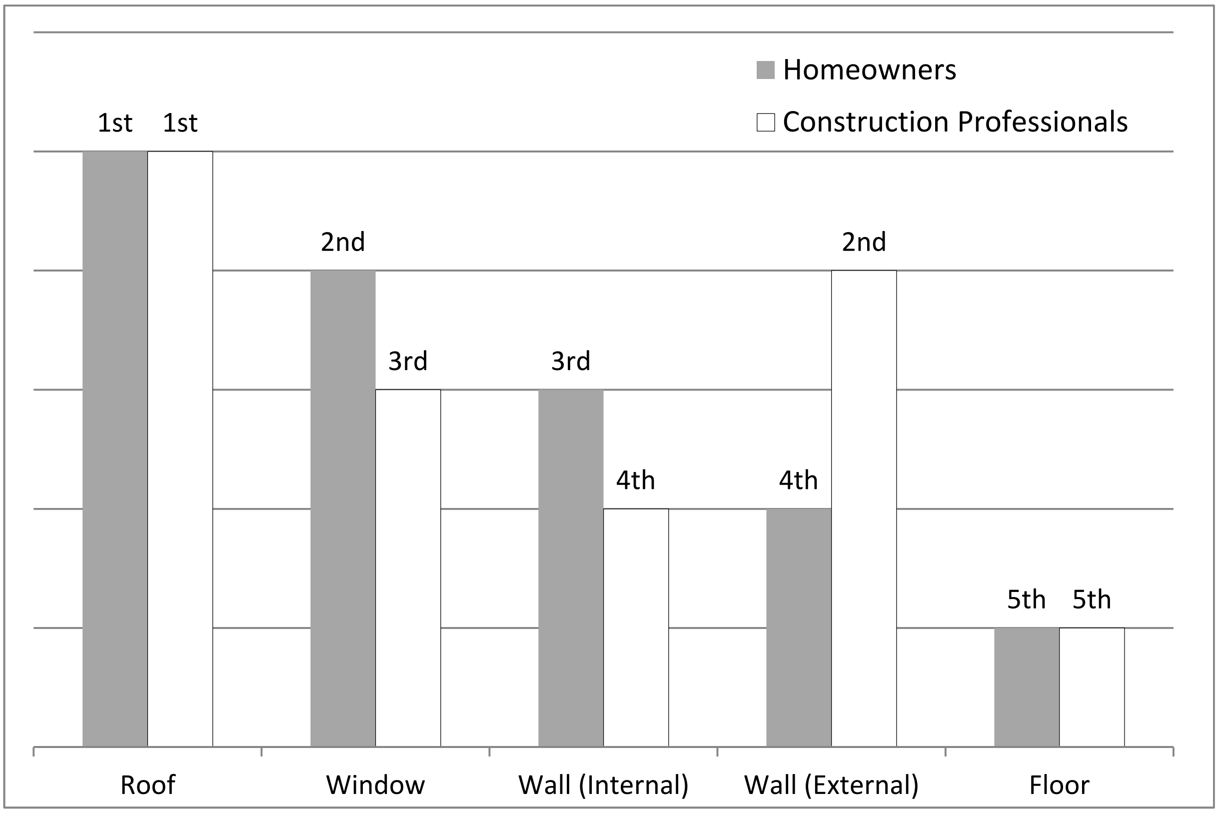


Figure 6.12 Refurbishment Priorities for Elements of a House

Homeowners and construction professionals indicated the same priorities for Roof and Floor refurbishment as shown in Figure 6.12. Both groups agreed that roof refurbishment usually means loft insulation with top-up insulation material on the ceiling joist. Homeowners prefer this measure since it is financially affordable, less disruptive and has a quick installation. Construction professionals prefer this measure because there is high chance of receiving the government incentives and the duration for installation is short. The priorities for window and wall were identified differently between homeowners and construction professionals as shown in Figure 58. The external wall refurbishment particularly showed the largest difference in priorities.

Homeowners do not prefer the external wall insulation as it is expensive and the external appearance of their houses will be altered. In contrast, construction professionals prefer the external wall insulation to internal insulation because it is an effective measure for energy efficiency improvement, and causes fewer risks related to moss and fungal growth. As a result, construction professionals indicated the internal insulation as the 4th priority, and further commented that internal insulation causes disruption to homeowners.

Similarly, homeowners do not prefer internal insulation (3rd priority) as they may need to vacate their home until the insulation is completed. Homeowners commented that they prefer to change windows because of the support from government funding and easy installation. Most homeowners believed that windows are the largest heat-loss element in their homes although, in reality, walls lose the greatest heat. This implied that there is a lack of knowledge about housing energy performance among homeowners. Overall, these results provide important insights that there are conflicts of priorities between homeowners and construction professionals, and these results echoed with the current construction professionals oriented design practice which renders low customer satisfaction in the housing sector.

6.3.4 Importance of Refurbishment Measures

Respondents were asked to indicate the importance of decision-making factors about refurbishment measures on a Likert Scale of 'Very Important' to 'Not Considered'. The priorities between the two groups are compared using weights from 5 for 'Very Important' to 0 for 'Not Considered'. The decision-making factors listed in Table 33 have been adopted from a similar research focusing on homeowners (See Section 5.4.2).

Table 33. Homeowners: Importance of the Decision-Making Factors for Refurbishment Measures Response Frequency

Decision Making Factors	Very Important	Important	Neutral	Unimportant	Not Considered
CO_2 Reduction	5	33	38	15	21
Disruption caused by Refurbishment	3	51	47	5	5
Initial Cost	45	47	13	2	1
Low Maintenance (Durability)	39	56	7	4	1
Payback Period (Energy Cost Saving)	34	42	22	8	3
Thermal Performance	41	50	12	3	5

Note: The number in the table is the frequency for each importance

Table 34. Construction Professionals: Importance of the Decision-Making Factors for Refurbishment Measures Response Frequency

Decision Making Factors	Very Important	Important	Neutral	Unimportant	Not Considered
CO_2 Reduction	5	18	8	5	2
Disruption caused by Refurbishment	7	17	9	4	1
Initial Cost	17	20	2	0	0
Low Maintenance (Durability)	10	19	7	0	0
Payback Period (Energy Cost Saving)	18	18	3	0	0
Thermal Performance	28	8	2	0	0

Note: The number in the table is the frequency for each importance

Table 35. Importance Comparison Table between Homeowners and Construction Professionals

Decision Making Factors	Homeowners		Construction Professionals	
	Level of Importance	Weighted Average	Level of Importance	Weighted Average
Initial Cost	1st	4.1	3rd	4.4
Thermal Performance	2nd	4.0	1st	4.6
Low Maintenance	2nd	4.0	4th	3.8
Payback Period	4th	3.8	2nd	4.4
Disruption	5th	3.3	5th	3.6
CO_2 Reduction	6th	2.8	6th	3.4

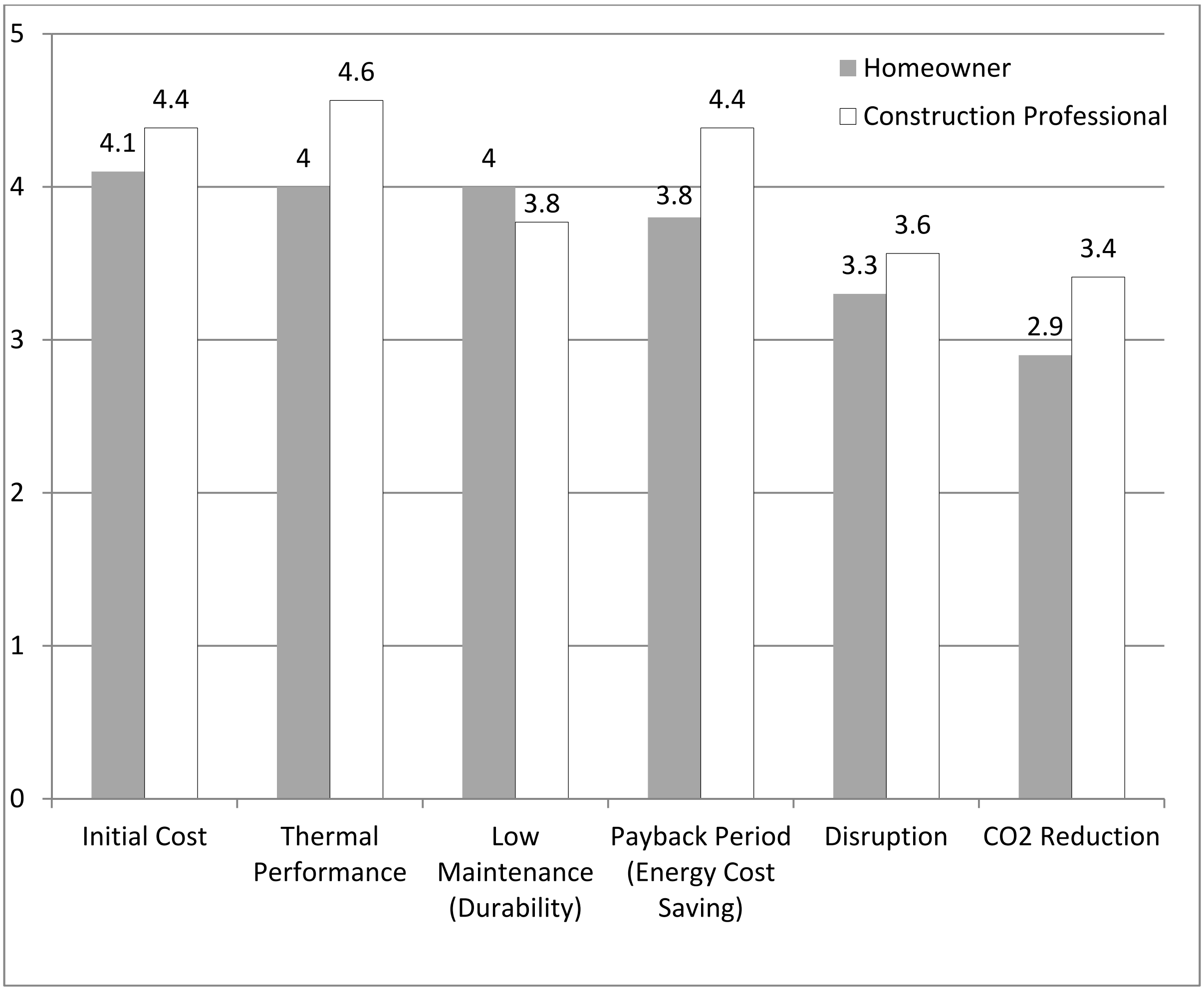


Figure 6.13 Decision Making Factors for Refurbishment Measure
Note: y-axis is Likert Scale (0.0 is Not considered to 5.0 is Very Important)

Surprisingly, both homeowners and construction professionals indicated the lowest importance as being CO_2 reduction when they selected a refurbishment measure, whereas both groups indicated high importance of initial cost for refurbishment measures (as shown in Table 35). Overall, two groups have shown similar preferences on the decision-making factors of initial cost, thermal performance, low maintenance and payback period as shown in Figure 6.13. The most interesting result from this question is that homeowners care relatively less about disruption caused by refurbishment although many researchers assert that the disruption is one of the most significant barriers that prevents homeowners from doing housing refurbishment. Many homeowners commented that the initial cost is the most important since refurbishment cannot be carried out if the cost is over budget for them. They also commented that the disruption can be tolerated once they are determined to refurbish their homes, and the benefits from refurbishment are clearly understood. Therefore, it is important to convince homeowners of affordable and proper refurbishment solutions by adequately visualizing processes and providing relevant and necessary information for a better understanding of the benefits of housing refurbishment.

6.3.5 Importance of Refurbishment Materials

Respondents were asked to indicate the importance of decision-making factors about refurbishment materials in the Likert Scale from 'Very Important' to 'Not Considered'. The priorities between the two groups are compared using weights from 5 for 'Very Important' to 0 for 'Not Considered'. The decision making factors listed in Table 36 have been adopted from the similar research focusing on homeowners (See Section 5.4.2).

Table 36. Homeowners: Importance of the Decision-Making Factors for Refurbishment Materials Response Frequency

Decision-Making Factors	Very Important	Important	Neutral	Unimportant	Not Considered
Aesthetic (Finished Look)	58	43	8	2	0
Low Maintenance (Durability)	46	53	10	0	0
Health and Safety (Non-toxic Materials)	56	38	16	0	0
Initial Cost	45	47	13	1	1
Life Cycle Cost	31	48	16	5	6
Manufacturers' Reputation	28	46	25	6	1
Recycled Materials (CO_2 Reduction)	6	38	46	10	6
Thermal Performance	41	51	13	2	2

Table 37. Construction Professionals: Importance of the Decision-Making Factors for Refurbishment Materials Response Frequency

Decision-Making Factors	Very Important	Important	Neutral	Unimportant	Not Considered
Aesthetic (Finished Look)	14	19	5	0	0
Low Maintenance (Durability)	17	19	2	0	0
Health and Safety (Non-toxic Materials)	17	16	4	1	0
Initial Cost	12	22	4	0	0
Life Cycle Cost	17	13	6	2	0
Manufacturers' Reputation	8	16	9	3	0
Recycled Materials (CO_2 Reduction)	4	11	15	7	1
Thermal Performance	24	14	0	0	0

Table 38. Importance Comparison Table between Homeowners and Construction Professionals

Decision Making Factors	Homeowners		Construction Professionals	
	Level of Importance	Weighted Average	Level of Importance	Weighted Average
Aesthetic (Finished look)	1st	4.4	3rd	4.1
Health and Safety	2nd	4.3	4th	4.2
Low Maintenance (Durability)	3rd	4.2	2nd	4.3
Initial Cost	4th	4.1	6th	4.1
Thermal Performance	5th	4.1	1st	4.5
Manufacturers' Reputation	6th	3.7	7th	3.5
Life Cycle Cost	7th	3.7	5th	4.1
Recycled Materials	8th	3.1	8th	3.2

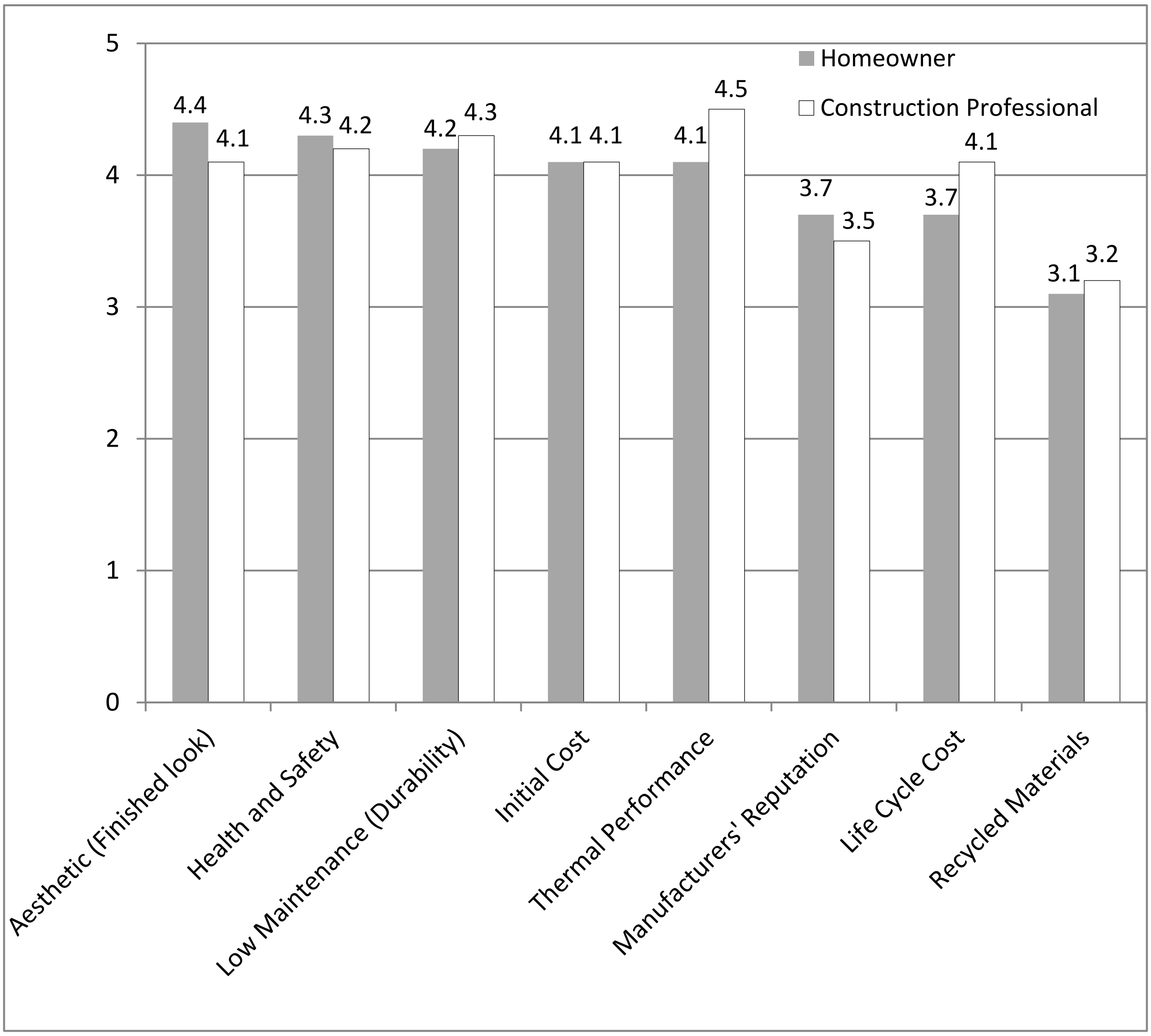


Figure 6.14 Decision-Making Factors for Refurbishment Materials
Note: y-axis is Likert Scale (0.0 is Not considered to 5.0 is Very Important)

As shown in Table 38, the manufacturer's reputation and recycled materials shows low importance for both groups. The majority of homeowners commented that they are not aware of the manufacturers, and that they are more interested in the finish of refurbishment materials such as colors, shapes and designs. As a consequence, *Aesthetic* was identified as the most important decision-making factor in the selection of refurbishment materials while the most important factor for construction professionals is the *Thermal performance* of refurbishment materials as shown in Figure 6.14. This result echoes the previous results of survey questions about the priority of elements and the importance of refurbishment measures. These results show that the construction professionals consistently indicate that their priorities of housing refurbishment are on thermal performance and effectiveness of refurbishment outcomes, whereas homeowners indicate that their priorities are on the initial cost and their own interests such as the aesthetics.

6.4 Conclusion

From the pilot study that investigated the feasibility of BIM use for housing refurbishment, it was revealed that it is feasible to use BIM for housing refurbishment, and that it is timely to do so. Most of the construction professionals who responded to the pilot survey were well aware of the benefits of BIM, and indicated that a lack of demand from customers, the investment costs for BIM adoption, and a lack of BIM standards and education are the most critical barriers in the use of BIM for housing refurbishment at present. The first two barriers are not in the scope of this research and cannot be resolved by an individual researcher. It requires collective efforts through the entire construction industry and the government. However, the third barrier related to standards is in the scope of this research, which confirms the need for a BIM framework for housing refurbishment, and is the aim of this research. Therefore, this research moved on to Phase 2, which is researching homeowners' preferences for housing refurbishment

From the questionnaire survey, it was revealed that there were differences in priorities and preferences between customers and construction professionals. In addition, both groups give little attention to CO_2 reduction, and mainly focus on initial costs and thermal performance of refurbishment. This research outcome is echoed in the literature review (See Section 3.5.1). Although a larger sample size from various regions such as northern and southern would provide a more general pattern of homeowners' preferences, the results have consistently shown similar refurbishment priorities for the elements of a house and preferences on the decision making factors such as initial cost in particular, regardless of the profiles of homeowners and their homes. Respondents were randomly selected and the limited numbers of homeowners in the northern and southern regions were involved in the preference survey due to a lack of contact information compared to the Midlands.

Therefore, BIM is a feasible tool for housing refurbishment and a BIM framework that can integrate construction information, such as the initial cost and thermal performance, which homeowners consider the most important, is needed. The following chapter will discuss how a BIM framework is developed and how the proposed framework is examined.

Chapter 7 Housing Information Modelling Framework

7.1 Introduction

This chapter explains how a BIM framework for housing refurbishment – the Housing Information Modelling Framework - was developed, and how it is examined through a hypothetical case study using the homeowners' preferences and typical housing models such as detached, semi-detached and terraced houses.

7.2 Housing Information Modelling Framework Development

This research developed a theoretical BIM framework for whole-house refurbishment by following a general procedure of theory-building (See Section 5.3.4) based on standards and guides which are identified through a literature review;

a) the RIBA Outline Plan of Work 2013 (RIBA, 2013)
b) the Low Carbon Domestic Retrofit Guides (Institute for Sustainability, 2011)
c) the BIM Overlay to the RIBA Outline Plan of Work (RIBA, 2012)
d) the PAS 1192-2: 2013 (BSI, 2013).

The RIBA Outline Plan of Work 2013 and the Low Carbon Domestic Retrofit Guides were used for establishing phases and work stages for a housing refurbishment project; and the BIM Overlay to the RIBA Outline Plan of Work and the PAS 1192-2: 2013 were used for developing processes and identifying essential refurbishment information and BIM data for each work stage to formulate an affordable refurbishment solution as shown in Table 38. In addition, key project stakeholders who have essential construction information for each stage were identified through professional trainings and literature review. The proposed work stages and sub-work stages of this research are marked in grey as shown in Table 39.

As a result, the final proposed BIM framework - the Housing Information Modelling Framework – was illustrated as shown in Figure 7.1. Detailed explanation about the BIM framework and processes will be provided in Section 7.4.

Table 39. BIM Framework for Whole-house Refurbishment Development

References	**Phase or Work Stage Name**				
Refurbishment Phases *	**Assessment Phase**		**Design Phase**		
Work Stages (RIBA, 2013)	Stage 0: Strategic Definition	Stage 1: Preparation and Brief	Stage 2: Concept Design	Stage 3: Developed Design	Stage 4: Technical Design
Work Stages Proposed by this research	Stage R0: Assess Housing Condition	Stage R1: Prepare Refurbishment Plan	Stage R2: Develop a Refurbishment Design	Stage R3: Perform Energy Simulation	Stage R4: Constructability Check
Work Sub-stages Proposed by this research (R#-# is the name of sub-stages)	No Sub-stage	R1-1: Identify Customers' Preferences	R2-1: Develop Refurbishment Design Alternatives	R3-1: Perform Energy Simulation	Stage R4: Constructability Check
		R1-2: Develop an Initial Refurbishment Plan	R2-2: Develop LCC and LCA Information (Cradle to Site)	R3-2: Perform Comparative Analysis among Design Alternatives	Stage R4: Constructability Check
		R1-3: Develop a BIM Model			
Core BIM Activities recommended by BIM Overlay to the RIBA Outline Plan of Work (RIBA, 2012)	- Advise client on purpose of BIM including benefits and implications. - Agree level and extent of BIM including 4D (time), 5D (cost) and 6D (FM) following software assessment. - Advise client on Integrated Team scope of service in totality and for each designer including requirements for specialists and appointment of a BIM Model Manager. - Define long-term responsibilities, including ownership of model. - Define BIM Inputs and Outputs and scope of post-occupancy evaluation (Soft		- BIM pre-start meeting. - Initial model sharing with Design Team for strategic analysis and options appraisal. - Environmental performance and area analysis. - Identify key model elements (e.g. prefabricated component) and create concept level parametric objects for all major elements. - Enable design team access to BIM data.	- Data sharing and integration for design co-ordination and detailed analysis including data links between models. - Integration/development of generic/bespoke design components. - BIM data used for environmental performance and area analysis. - Data sharing for design co-ordination, technical analysis and addition of specification data. - Export data for Planning Application. - 4D and/or 5D assessment.	

	Landings). - Identify scope of and commission BIM surveys and investigation reports.	- Agree extent of performance specified work.		
Core BIM Activities recommended by PAS 1192-2: 2013 (BSI, 2013)	- Model information communicating the brief, performance requirements, performance benchmarks and site constraints	- Models which communicate the initial response to the brief, aesthetic intent and outline performance requirements. - The model can be used for early design development, analysis and co-ordination. - Model content is not fixed and may be subject to further design development. - The model can be used for co-ordination, sequencing and estimating purposes	- A dimensionally correct and coordinated model which communicate the response to the brief, aesthetic intent and some performance information that can be used for analysis, design development and early contractor engagement. - The model can be used for co-ordination, sequencing and estimating purposes including the agreement of a first stage target price	- A dimensionally correct and coordinated model that can be used to verify compliance with regulatory requirements. - The model can be used as the start point for the incorporation of specialist contractor design models and can include information that can be used for fabrication, co-ordination, sequencing and estimating purposes, including the agreement of a target price/guaranteed maximum price
Important Refurbishment Activities identified by Professional Trainings	-Contact Qualified Energy Assessors -Secure Occupant Engagement	-Adopt Fabric First Approach -Secure Continuity of Insulation -Contact Trained Professionals (CoRE and RIBA Qualified) for Installation - Risk Assessment (Cold Bridging and Ventilation)		
Project Stakeholders identified by literature (Hjelseth, 2010) and Professional Trainings	Owner/Customer, Energy Assessor/Surveyor, Architect, Master Builder, BIM Professional, 3D Laser Scanning Service Provider	Customer, Architect, Quantity Surveyor, Manufacturer/Supplier	Customer, Engineers, Architect, Contractor	Contractor, Architect, Engineer

Note: * referred to the Low Carbon Domestic Retrofit Guides Institute for Sustainability (2011)

References: RIBA Outline Plan of Work 2013 (RIBA, 2013), the BIM Overlay to the RIBA Outline Plan of Work (RIBA, 2012) and the PAS 1192-2: 2013 (BSI, 2013)

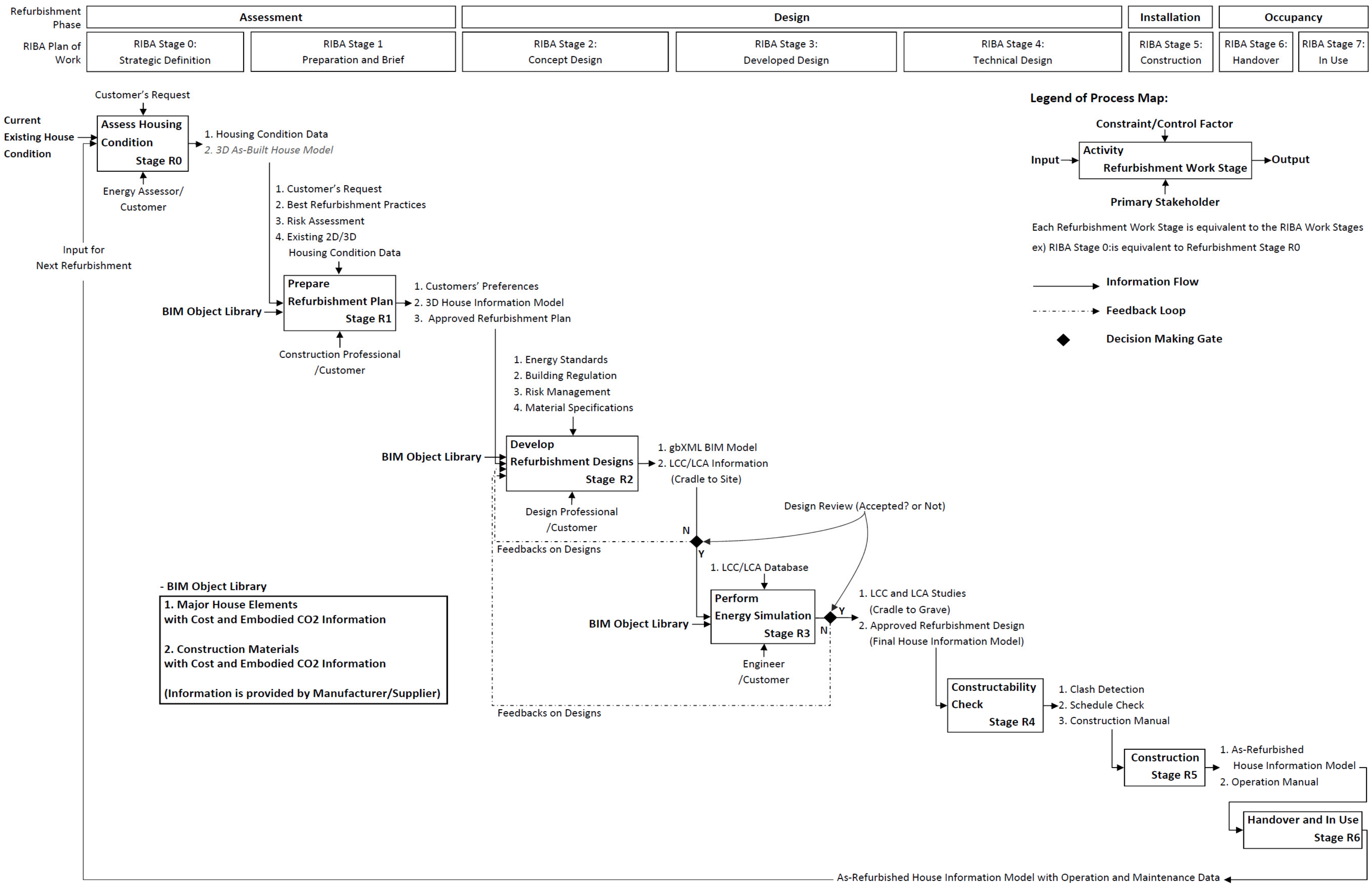


Figure 7.1 A BIM Framework for Whole-house Refurbishment (Developed from the RIBA Outline Plan of Work 2013 (RIBA, 2013), the Low Carbon Domestic Retrofit Guides (Institute for Sustainability, 2011), the BIM Overlay to the RIBA Outline Plan of Work (RIBA, 2012) and the PAS 1192-2: 2013 (BSI, 2013))

7.3 Essential Input Data and Assumptions for Housing Information Modelling Framework Case Study

This research adopts a simulation approach to examine housing information modelling framework utilizing software tools to formulate LCC and LCA of housing refurbishment alternatives. The following BIM software is the main simulation tool:

- Autodesk Revit 2013 – Basic Housing Model Development for Simulation
- IES VE/IMPACT – LCC and LCA calculation

Autodesk Revit was selected for this research because it is one of the most widely used BIM tools for architectural design, and it is comparable with AutoCAD platform which is the most prevalent tool in the construction industry (NBS, 2014). Thus it is easy to exchange data between Autodesk products. The IES VE/IMPACT was selected for formulating the LCC and LCA (See Section 3.6). Compared to other available software tools, in IES VE/IMPACT is more capable of dealing with all possible building simulations such as building fabric, ventilation, daylighting and solar, air Infiltration, HVAC systems/components and renewable energy systems (Crawley et al., 2008). In addition, there have been a number of research projects carried out for energy simulation for refurbishment or retrofit using IES VE (Murray et al., 2012). Furthermore, IES VE/IMPACT is the only tool that is compatible with BIM software such as Autodesk Revit. This can significantly reduce human errors, time and effort to exchange data between BIM software and life cycle impact calculation software.

Various data sources are required to formulate LCC and LCA for housing refurbishment alternatives. The following data sources have been used in conjunction with BIM software:

- Basic Simulation Model – A Detached Solid Wall House
- LCC and LCA – IES IMPACT dataset provided by BRE (BRE, 2013) in partnership with a Major Construction Company (Willmott Dixon)
- Cost for Materials and Labour – SMM7 Estimating Price Book 2013 (BCIS, 2012)
- Embodied CO_2 for Materials – University of Bath (Hammond and Jones, 2011)
- Embodied CO_2 for Construction Works – Black Book (Franklin and Andrews, 2010)

In order to generate more reliable information for LCC and LCA, data sources provided by well-known highly-rated construction organizations have been used as inputs at the beginning to avoid a situation known colloquially as ‘garbage in, garbage out’. Although BIM software has a built-in dataset such as basic dimensions, density and U-value of materials, these datasets are not sufficient to formulate LCC and LCA. Furthermore, BIM software such as Autodesk Revit uses a BIM object library, which is known as 'Family Library', and the library can be provided any third parties who have a capability to make a BIM objects. Thus, the dataset provided by third parties could be more biased than that provided by well-known construction organizations.

This research narrowed the scope of whole-house refurbishment down to the whole-house fabric refurbishment, as the fabric approach should be the first stepping stone to improve a whole-house and various researchers and construction professional organizations have argued that the whole-house fabric should be improved first rather than upgrade services or renewable energy systems (Rosa, 2012; Gupta and Chandiwala, 2010; National Refurbishment Centre, 2012; EST, 2010; Institute for sustainability, 2011, Zero Carbon Hub, 2012). Furthermore, the whole-house approach covers a wide range of refurbishment alternatives, which cannot be covered and understood by one individual researcher, and requires in-depth knowledge and skills to develop building services and renewable systems using BIM. Thus, this research adopted a whole-house fabric refurbishment for a hypothetical case study.

7.3.1 Basic Information for House Models

The general information about the three major housing types in the UK (See Subchapter 2.3) is provided in Tables 40 to 44, and Figures 7.2 to 7.4. The Gross Internal Floor Area (GIFA) was used for the calculation of LCC and LCA and energy performance simulation.

Table 40. General Information about a House for simulation

Information	Detached House	Semi-Detached House	Terraced House	References
Number of Bedrooms	4 Bedrooms	3 Bedrooms	2 Bedrooms	a
Number of Floors	2	2	2	b, c
Construction Type	Solid Brick Wall	Solid Brick Wall	Solid Brick Wall	d
Ventilation	Natural Ventilation	Natural Ventilation	Natural Ventilation	d
Heating (using water)	Radiator	Radiator	Radiator	a, d
Main Energy Source	Natural Gas	Natural Gas	Natural Gas	a
Household size (Number of people)	Single Family (2.3)	Single Family (2.3)	Single Family (2.3)	a
Indoor Temperature	19-23 °C	19-23 °C	19-23 °C	a, b
Usable Floor Area	130 m^2	90 m^2	60 m^2	b
Ceiling Heights (Ground and First Floor)	2.7m	2.7m	2.7m	c

References: a - Utley and Shorrock, 2011, b - Brinkley, 2008,c - Neufert, 2012, d - Riley and Cotgrave, 2008

Table 41. Detached house - Room and Space Information (Neufert, 2012; Brinkley, 2008)

Floor	Rooms	Description	Area (m^2)
Ground Floor	Room 1	Kitchen	16
	Room 2	Bathroom	3
	Room 3	Lobby	16
	Room 4	Living Room	15
	Room 5	Dining Room	14
First Floor	Room 6	Bedroom	12
	Room 7	Bedroom	12
	Room 8	Corridor	10
	Room 9	Bathroom	5
	Room 10	Bedroom	12
	Room 11	Bedroom	13
		Total Usable Floor Area	130

*Note: Roof (Loft) was not included into the usable floor area. All areas are measured by GIFA.

Table 42. Semi-Detached/End Terraced House

Floor	Rooms	Description	Area (m^2)
Ground Floor	Room 1	Kitchen	15
	Room 2	Bathroom	20
	Room 3	Lobby	8
	Room 4	Living Room	2
First Floor	Room 5	Dining Room	11
	Room 6	Bedroom	7
	Room 7	Bedroom	5
	Room 8	Corridor	7
	Room 9	Bathroom	15
		Total Usable Floor Area	90

*Note: All areas are measured by GIFA.

Table 43. Terraced House

Floor	Rooms	Description	Area (m^2)
Ground Floor	Room 1	Kitchen	5
	Room 2	Dining Room	9
	Room 3	Living Room	16

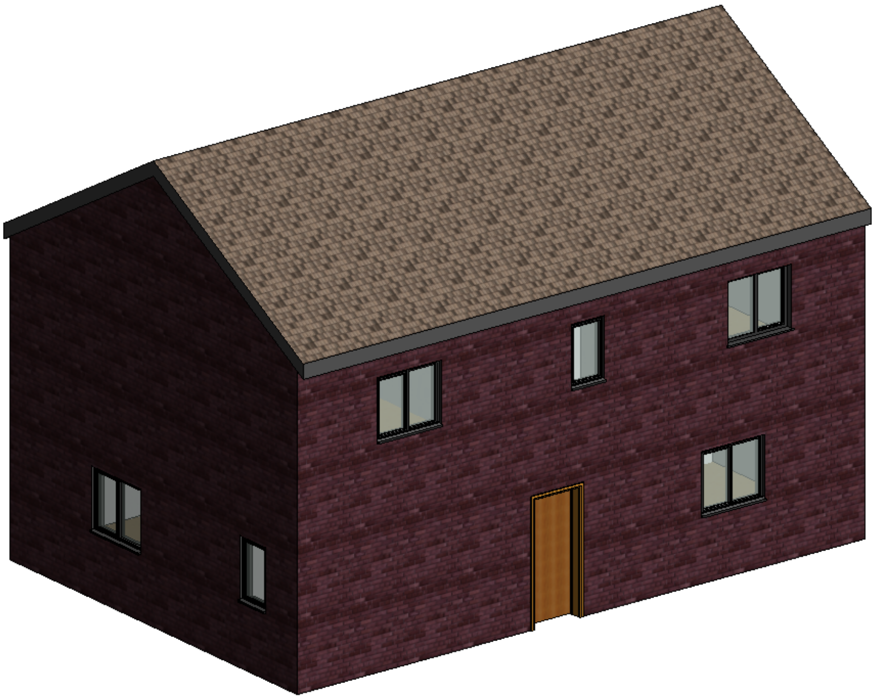
First Floor	Room 4	Bedroom	14
	Room 5	Corridor	4
	Room 6	Bathroom	4
	Room 7	Bedroom	8
		Total Usable Floor Area	60

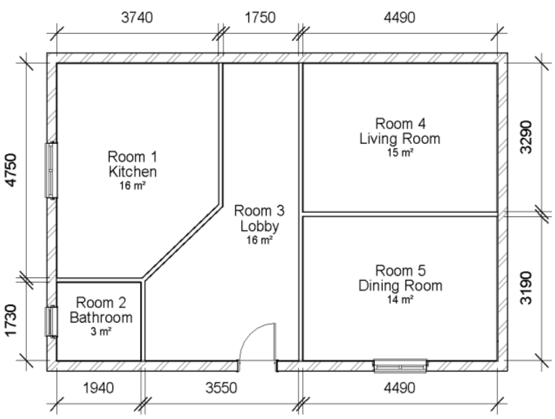
*Note: All areas are measured by GIFA.

Table 44. Construction Information

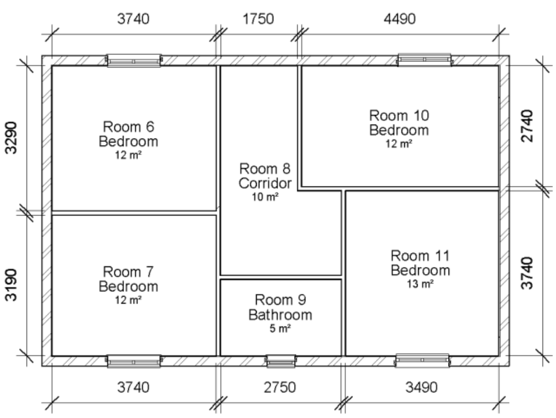
Element	Construction Type	Components	Thickness (mm)	U-Value (W/m2K)
Roof	Pitched Roof with Timber Joist and Rafter	Roofing Tile	25	0.8
		Wood (Batten)	25	
		Roofing Felt	5	
		Timber Structure	140	
		Total	218	
External Wall	Solid Brickwork Masonry Wall (Single Leaf)	Dense Gypsum Plaster Finish (External)	13	2.1
		Solid Brickwork	220	
		Total	233	
Party Wall	Timber Stud Partition Wall	Gypsum Wall Board	12.5	0
		Air Infiltration Barrier	75	
		Gypsum Wall Board	12.5	
Floors	Suspended Timber Floor	Timber Joist Structure	225	0.7
		Chipboard	25	
		Carpet	10	
		Total	260	
Ceiling	Generic Ceiling	Gypsum Wall Board	12.5	N/A
Windows	Double Glazing	Double Glazing, Timber Frame	6mm Glazing	2.0
Exterior Door	Wooden Door	Wooden Door	44	3.0

Note: U-Value and Thickness has referred to RdSAP 2009 (BRE, 2011). Party wall is only applied to semi-detached/end terraced and terraced house.



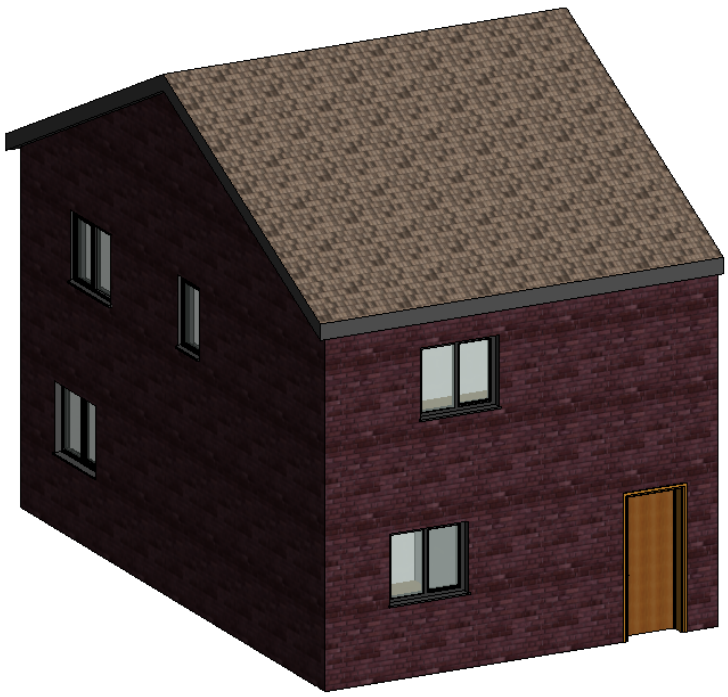


Ground Floor



First Floor

Figure 7.2 Floor Plan for a Typical/Average Detached House



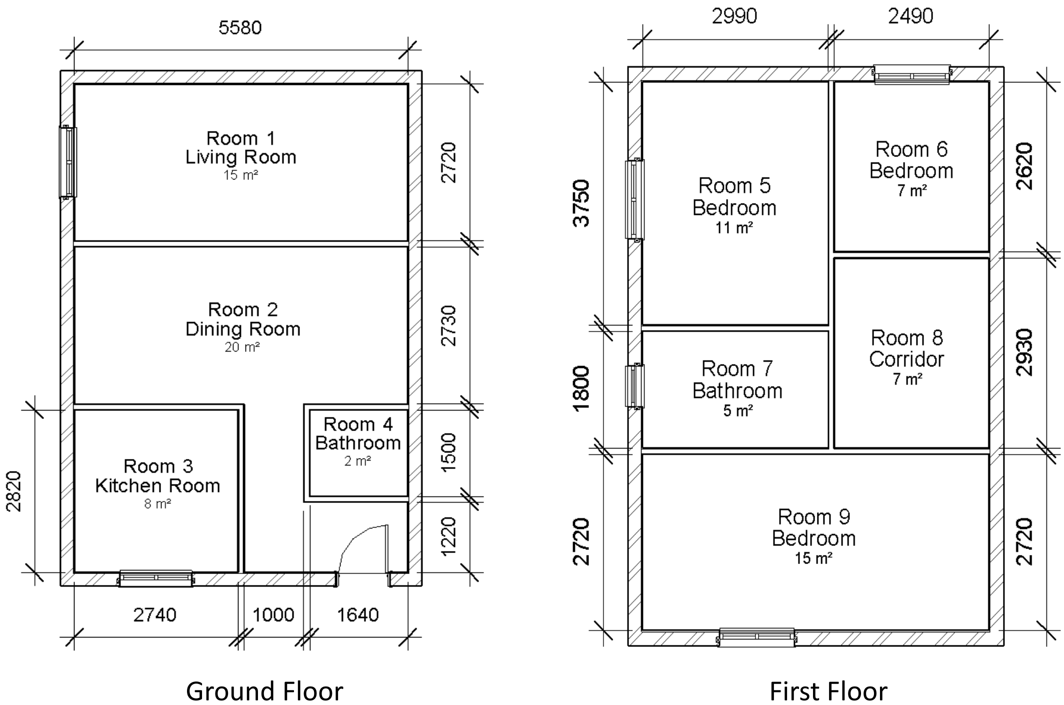
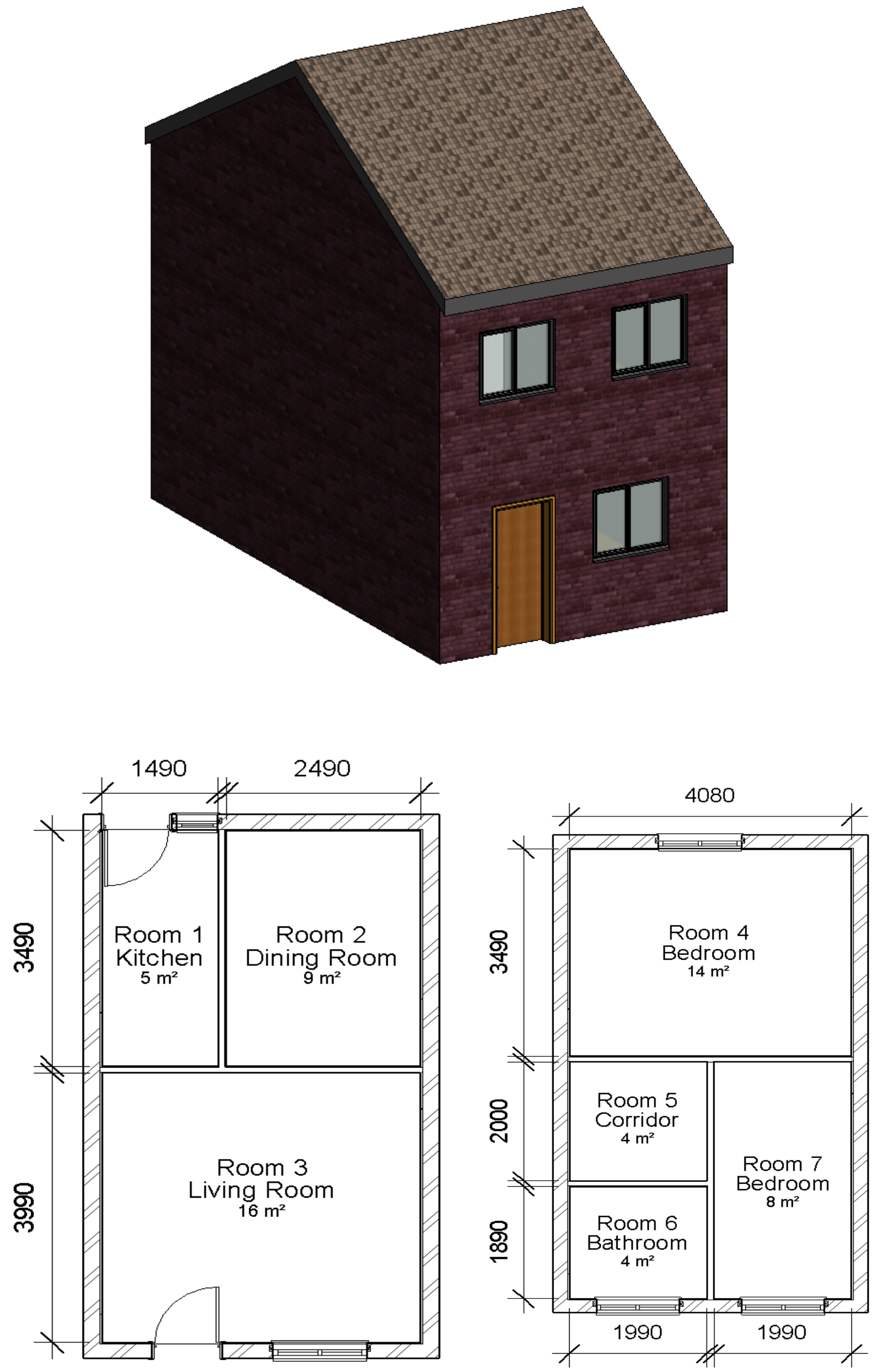


Figure 7.3 Floor Plan for a Typical/average Semi-detached/End-terrace House



Ground Floor First Floor

Figure 7.4 Floor Plan for a Typical/Average Terraced House

7.3.2 Whole-house Fabric Refurbishment Measures

The best current housing refurbishment measures, i.e. refurbishment best practices for whole-house refurbishment (Appendix 5) applied for solid wall housing, were identified as shown in Table 45, in order to implement refurbishment measures in a BIM simulation and develop a case study for developing/testing a framework. The current best practices of refurbishment measures were referred to in various construction organizations and actual refurbishment projects such as the Retrofit for the Future (EST, 2010; RIBA, 2013; Construction Products Association, 2014; Retrofit for Future).

Table 45. Current Best Refurbishment Practices for Whole-House Fabric Refurbishment

Elements	Construction Type	Best Refurbishment Measures	*Capital Cost	*Disruption	*Carbon Cost Effectiveness
Roof	Pitched Roof	Rafter insulation	£ 1,000 – £ 5,000	Low	£ 100 – £ 500/ 1 tonne CO_2
		Loft insulation	£ 100 – £ 1,000	Moderate	Repay more than initial capital cost
Wall	Solid Wall	External Wall Insulation	Over £ 10,000	Moderate	Repay more than initial capital cost
		Internal Wall Insulation	£ 5,000 – £ 10,000	Significant	Repay more than initial capital cost
Floor	Suspended Timber Floor	Underfloor Insulation (Insulation between joists)	£ 100 – £ 1,000	Significant	Repay more than initial capital cost
		Surface Insulation (Insulation over the floor board)	£ 100 – £ 1,000	Significant	Repay more than initial capital cost
Window	Single Glazing	Double Glazing	£ 1,000 – £ 5,000	Moderate	£ 100 – £ 500/ 1 tonne CO_2
		Triple Glazing	Over £ 10,000	Moderate	£ 100 – £ 500/ 1 tonne CO_2

Note: Insulation materials and its thickness can be varied depending on energy standards that will be applied for housing refurbishment. Information marked as * referred to Construction Products Association (2014)

7.3.3 Basic House Models for LCC, LCA and Energy Simulation

The basic house models for IES VE/IMPACT software are visualized as shown in Figures 7.5 to 7.7. These models were transferred from the Autodesk Revit models as described previously.

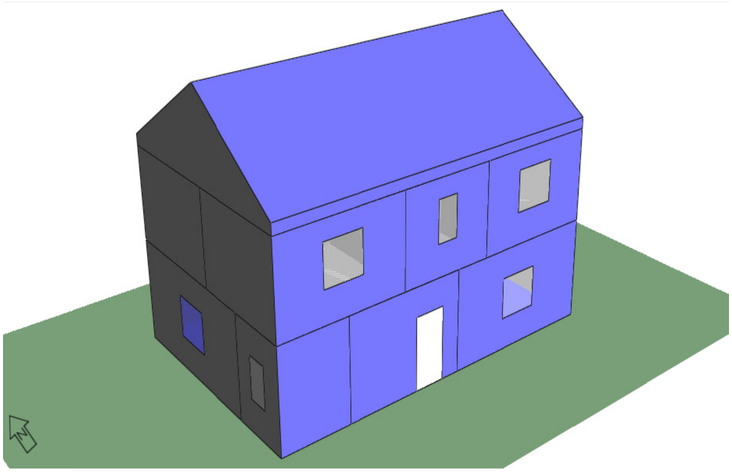


Figure 7.5 Detached House

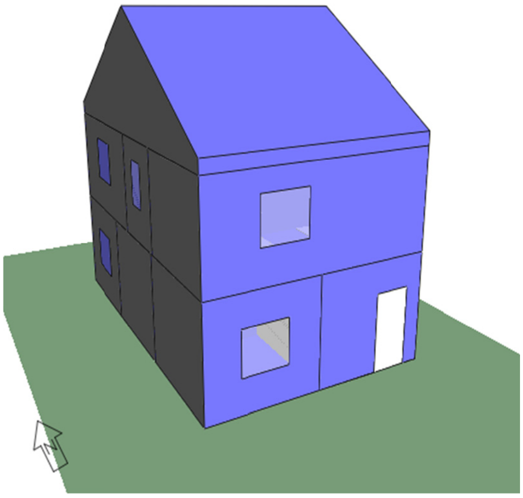


Figure 7.6 Semi-Detached House/End Terraced House

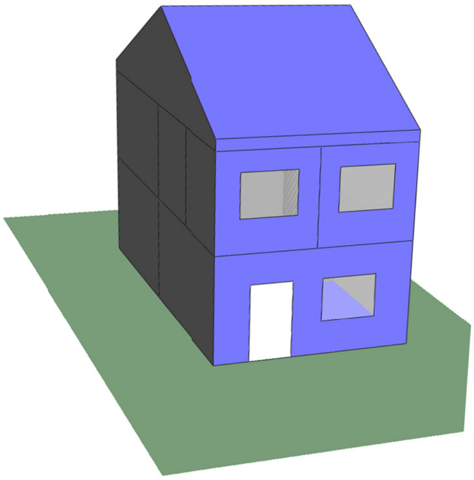


Figure 7.7 Terraced House

Ceilings were excluded from the energy simulation since this research focused on the whole-house fabric refurbishment. The information regarding air permeability and thermal bridging has been inherited from IES VE/IMPACT simulation software because this information cannot be generalised as a typical information since various housing condition exist. Furthermore, according to the BRE trust (2012), air permeability and thermal bridging can be improved as a partial result of the whole-house fabric insulation upgrade.

The energy simulation was conducted based on the weather dataset of the West Midlands because the majority of respondents were from that region (See Section 6.3.3). However, the differences in energy demand reduction based on the location – Edinburgh, Manchester, London – were not significant as the differences were located between 1% and 3%, when an 80% CO_2 reduction refurbishment scenario was adopted (Mohammadpourkarbasi and Sharples, 2013). Thus, the weather data based on the West Midlands was used, and there could be a minimal discrepancy in the outcomes of simulation.

7.3.4 Energy Performance Standard

Building Regulation Part L 2010, Building Regulation Part L 2013 and the Fabric Energy Efficiency Standard (FEES) will be adopted for energy simulations. The Building Regulation Part L 2010 and 2013 mandates the minimum energy efficiency standard for housing fabric as shown in Table 46 in the first column. In addition to the minimum standard, Building Regulation Part L 2010 and 2013 advise construction professionals to consider further energy efficiency by providing a notional energy efficiency standard aimed at a 25% CO_2 reduction as shown at the second and third columns. The U-values has been updated between 2010 and 2013.

Table 46. Current Energy Efficiency Standards (BR stands for Building Regulations Part L)

Housing Element	Energy Standards			
	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES
Wall	0.3	0.22	0.18	0.15
Floor	0.25	0.18	0.13	0.13
Roof	0.2	0.15	0.13	0.13
Window	2.0	1.4	1.4	1.2
Door	2.0	1.2	1.2	1.0

*Note: The standards stands for the U-value of each housing element

The Fabric Energy Efficiency Standard has been recently introduced to the Building Regulation Part L 2013 aimed at achieving zero carbon homes by 2016. These energy efficiency standards have been adopted because there is no energy efficiency standard for housing refurbishment and these are the most reliable standards at present. Furthermore, FEES has been introduced specifically for zero carbon in existing housing to achieve the required 80% CO2 reduction. This research will identify the most financially and environmentally feasible energy standard for the whole-house fabric refurbishment by comparing the different outcomes LCC and LCA based on these different energy standards.

7.3.5 Data Analysis for LCC and LCA

This research adopts Life Cycle Costing method and Life cycle assessment methods to compare possible housing refurbishment alternatives (see Section 3.5.3). This research has adopted a 60-year life cycle study because it was assumed that the life span for LCC and LCA studies was 60 years (ISO, 2008). The embodied CO_2 calculation adopted the cradle to site study (ISO, 2006). The life cycle costing includes various life cycle costs. This research has excluded the categories highlighted in grey in Table 47 because most of the categories are client definable costs and other categories such as administrative and overheads cost are excluded since no published data is available. More detail assumption about construction cost based on the NRM – Risk contingency and other costs are not included.

Table 47. Cost variables for LCC calculation

Life Cycle Cost Category		Assumption
Construction Cost	Construction works costs	Included
	Other construction related costs	Included
	Client definable costs	Excluded
Maintenance costs	Major replacement costs	Included
	Subsequent refurbishment and adaptation costs	Included
	Redecorations	Included
	Minor replacement, repairs and maintenance costs	Included
	Unscheduled replacement, repairs and maintenance costs	Included
	Grounds maintenance	Excluded
	Client definable costs	Excluded
Operation costs	Cleaning costs	Included
	Utilities costs (Fuel- Gas and Electricity)	Included
	Administrative costs	Excluded
	Overheads costs	Excluded
	Taxes (if applicable)	Excluded
	Client definable costs	Excluded
Occupancy costs	Water and Sewage costs	Included
End of life costs		Excluded

The LCA study adopts a Cradle to Grave approach with the exclusion of the recycle, reuse and/or disposal stage as this contributes minimal percentages of CO_2 impact throughout the entire life cycle of a house (Rosa, 2012). The purpose of this research leads to a greater focus on the quantified energy use and CO_2 emission in the use phase of a building after refurbishment.

In order to achieve the full benefit of BIM, the entire project life cycle should be covered by the framework and a BIM process map. However, this research focuses on the assessment and design phase because these phases, in particular the early design phase, are the most critical phases to decide the best refurbishment solution financially and environmentally (See Section 3.5, 3.6, 3.7 and Figure 4.2 at Subsection 4.3.2). Furthermore, the benefits of 5D (cost management), which is related with the construction phase, have not been clearly defined and practiced at present (See Section 4.5.2). Thus, this research will discuss the assessment and design phases of housing refurbishment only, and the following section will provide a detailed explanation about the BIM process map as shown in Figure 7.8 and how it can support construction professionals to formulate a refurbishment solution using a hypothetical case study.

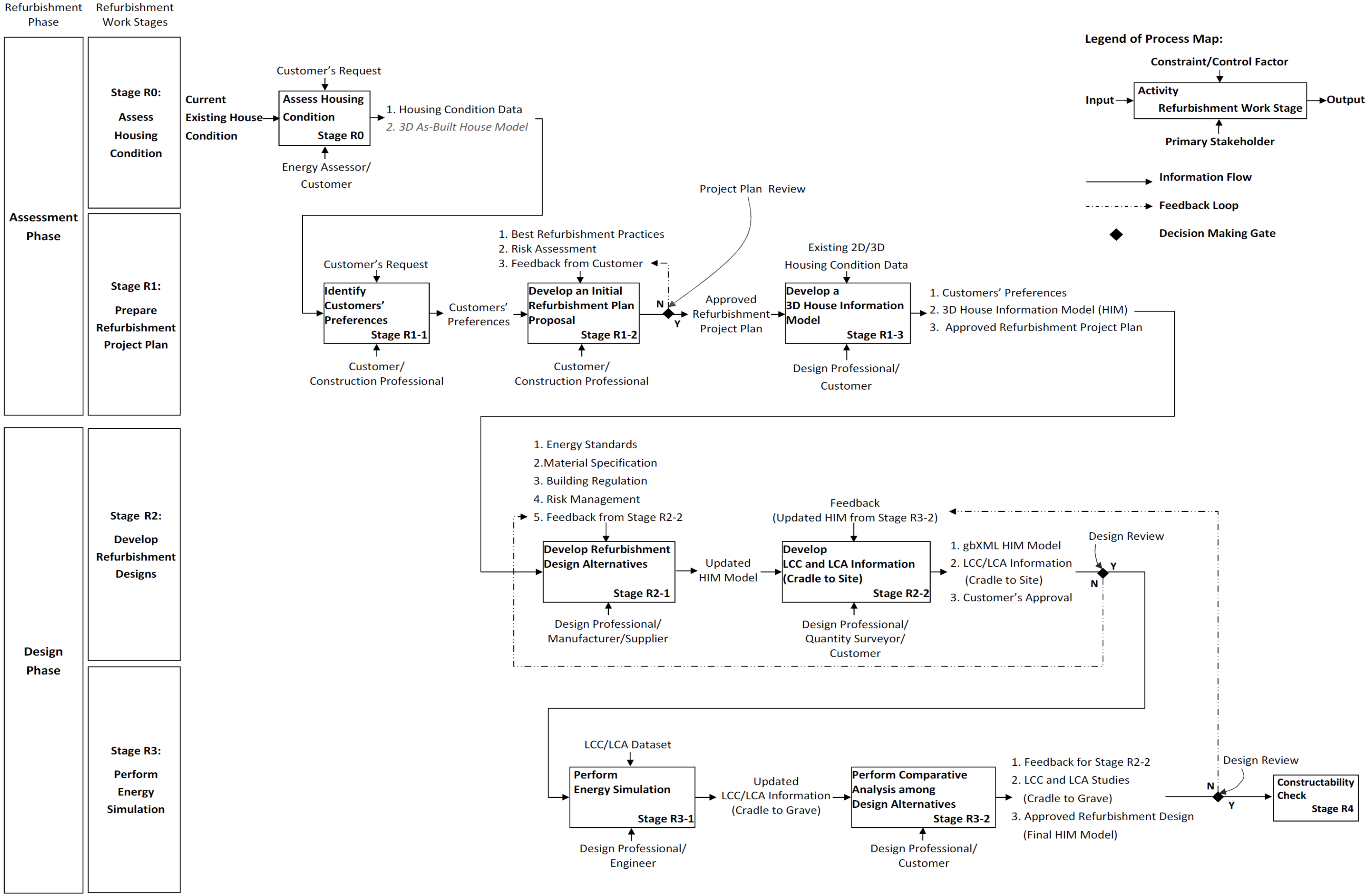


Figure 7.8 A BIM Process Map for Whole-house Refurbishment

7.4 Hypothetical Case Study for Housing Information Modelling Framework

7.4.1 Legend of Process Map for Housing Information Modelling Framework

The process map as shown in Figure 7.8 is adopted to explain details of a Housing Information Modelling framework. The framework and the process map have the unique opportunity to provide a substantial contribution to BIM use for housing refurbishment by supporting key project stakeholders to understand a big picture of refurbishment projects through a project life cycle. Also, various stakeholders responsible for formulating an affordable refurbishment solution can coordinate the right construction information at the right time with the right sequences based on this framework. As a result, construction professionals can suggest an affordable housing refurbishment solution to customers more productively without unnecessary future reworks.

The framework and the process map presents structured processes by decomposing and categorizing stages throughout a project life cycle as shown in Figure 7.9.

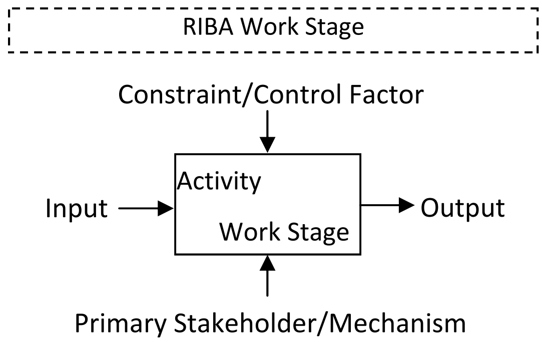


Figure 7.9 The Legend of Process Map

The detailed information about process map is defined by using the example as shown in Figure 7.11:

- RIBA Work Stage: The equivalent work stage with the proposed work stage
  e.g.) RIBA Stage 0: Strategic Definition is equivalent to Stage R0: Assess Housing Condition
- Activity: Works to convert inputs into outputs; e.g.) Assess Housing Condition
- Work Stage: Name of stage; e.g.) R0 is work stage name
- Input: Information that triggers the activity; e.g.) Current Condition of Existing House
- Output: Information resulting from the activity;
  e.g.) Housing Condition Data, 3D As-Built House Model
- Constraint: Factors influencing how to perform activity; e.g.) Customer's Request

- Primary Project Stakeholder: Stakeholder that is responsible for the activity;

  ex) Energy Surveyor/Assessor and 3d Laser Scanning Service

7.4.2 Assessment Phase – The Stage R0: Assess Housing Condition

The assessment phase consists of two stages, R0 and R1 as shown in Figure 7.10.

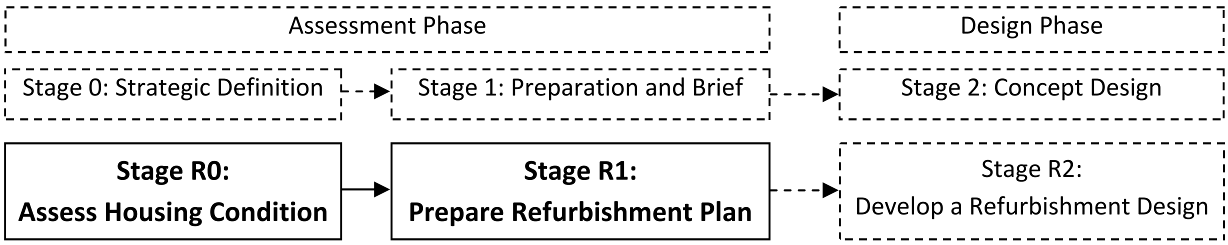


Figure 7.10 Two Stages of the Assessment Phase

The purpose of stage R0 is a thorough housing condition assessment to identify the current status of existing housing in terms of energy performance and its physical condition such as fabric and services, as shown in Figure 7.11. As a result of the assessment, a baseline for refurbishment such as energy consumption and CO_2 emissions is established this baseline information is then used as critical key inputs for the next stage (R1) to prepare a refurbishment plan.

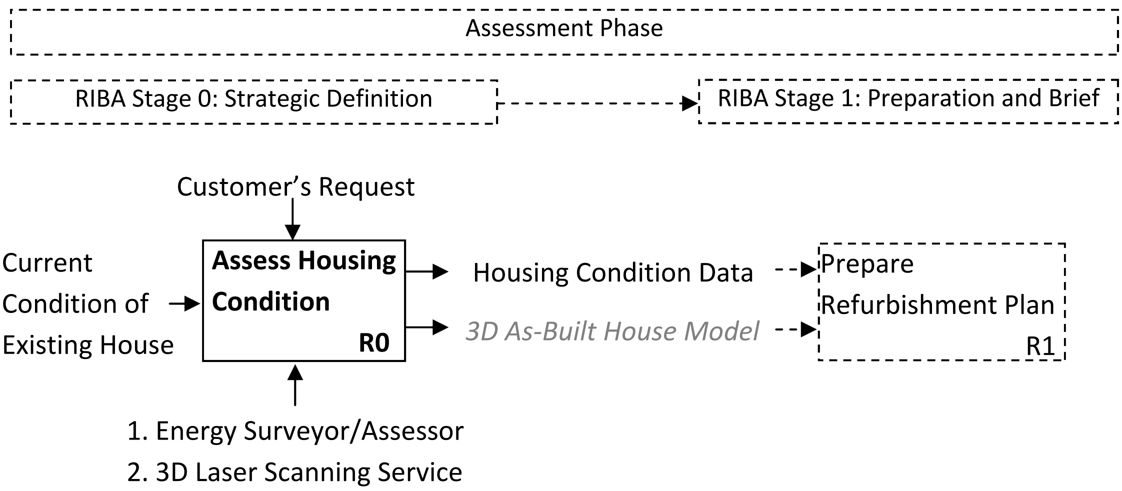


Figure 7.11 Stage R0 – Assess Housing Condition

When a customer requests an assessment of a house for energy performance improvement, an energy surveyor or assessor should survey the existing housing to generate a current housing condition data regarding energy use. Although the existing construction professionals such as building surveyors, quantity surveyors and house builders also perform the energy assessment for housing refurbishment, it is recommended that the services of a qualified energy surveyor or assessor are used to identify more proper refurbishment measures (Institute for Sustainability, 2011, DCLG, 2013b).

In addition to professional services, there is another option for assessment, which is a 3D laser scanning service. The 3D laser scanner can be adopted to generate a 3D as-built house model of existing buildings as an option. The CIC and the NHBC expect the 3D scanning service to be widely adopted in the housing sector in conjunction with BIM or cloud-BIM. When a 3D laser scanning service provider produces the 3D as-built model of an existing house, it can be more effective and efficient to develop a 3D house information model of a house, and the time and effort for developing a model can be reduced.

The input at stage R0 is an existing house, and the outputs are a wide range of characteristics in terms of housing types, ownerships and construction types as identified. These outputs are crucial to prepare and develop an affordable refurbishment solution and a refurbishment project plan, especially as homeowners are often not fully aware of the conditions of their homes (See Sub-section 6.3.3).

The housing condition data includes the following detailed information:

1. As-Built Data (Existing Housing Data) - To calculate thermal transmittances (U-values) and reveal current energy consumption via SAP rating.

- Housing Type and Year Built
- Dimensions;
  a) Floor areas (Floor Plan)
  b) Storey heights
  c) Areas of all fabric elements (wall, roof, floor, window and door)
- Construction Information
  a) All fabric elements construction types (wall, roof, floor)
  b) External window frames and glazing types
  c) External door types
- Further Information
  a) Extension or in-situ construction addition to the existing house
  b) Occupancy data (Internal temperature setting, heating timings)

As most solid wall housing in the UK uses natural ventilation and the scope of this research is to investigate the whole-house fabric refurbishment for solid wall housing, mechanical heating and cooling is not investigated.

2. SAP rating data – As the SAP rating is a standard energy performance assessment criteria mandated by the UK government, it is used as a reference point to set up a current energy use baseline and develop future expected energy use after refurbishment.

To identify affordable refurbishment solutions, the housing condition data need to be secured at stage R1. From this point forward in the thesis, a detached solid wall house is used as a hypothetical case study, and the following is an example of the housing condition data for a detached solid wall house (Table 48 to 50 and Figure 7.12).

Table 48. General Information about Typical UK Housing

Information	Detached House
Number of Bedrooms	4 Bedrooms
EPC Rating	F
Number of Floors	2
Construction Type	Solid Brick Wall
Ventilation	Natural Ventilation
Heating	Radiator (using water)
Main Energy Source	Natural Gas
Household size (Number of people)	Single Family (2.3)
Indoor Temperature	19-23 ^{o}C
Usable Floor Area	130 m^2
Heights (Ceiling Height of Ground and First Floor)	2.7m

Table 49. Detached Solid Wall House - Room and Space Information (Neufert, 2012; Brinkley, 2008)

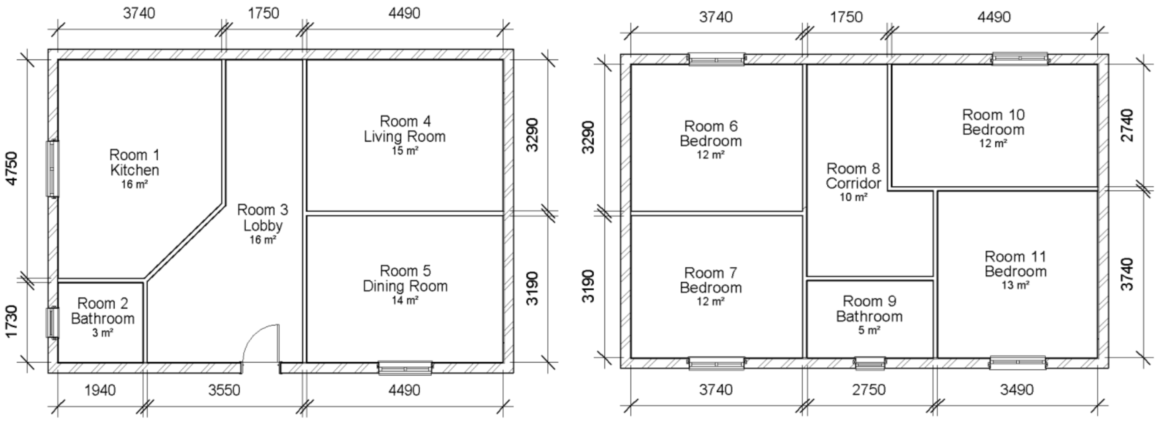
Floor	Rooms	Description	Area (m^2)
Ground Floor	Room 1	Kitchen	16
	Room 2	Bathroom	3
	Room 3	Lobby	16
	Room 4	Living Room	15
	Room 5	Dining Room	14
First Floor	Room 6	Bedroom	12

	Room 7	Bedroom	12
	Room 8	Corridor	10
	Room 9	Bathroom	5
	Room 10	Bedroom	12
	Room 11	Bedroom	13
		Total Usable Floor Area	130

*Note: Roof (Loft) was not included into usable floor area.

Table 50. Detailed Construction Information of Detached House

Element	Construction Type	Components	Thickness (mm)	U-Value (W/m2K)
Roof	Pitched Roof with Timber Joist and Rafter	Roofing Tile	25	0.8
		Wood (Batten)	25	
		Roofing Felt	5	
		Timber Structure	140	
		Total	218	
External Wall	Solid Brickwork Masonry Wall (Single Leaf)	Dense Gypsum Plaster Finish (External)	13	2.1
		Solid Brickwork	220	
		Total	233	
Floors	Suspended Timber Floor	Timber Joist Structure	225	0.7
		Chipboard	25	
		Carpet	10	
		Total	260	
Ceiling	Generic Ceiling	Gypsum Wall Board	12.5	N/A
Windows	Double Glazing	Double Glazing, Timber Frame	6mm Glazing	2.0
Exterior Door	Wooden Door	Wooden Door	44	3.0



Ground Floor First Floor

Figure 7.12 Floor Plan for the detached House in the example

Due to limited resources, it was impossible for this research to provide an actual 3D as-built house model using a 3D laser scanner as an output of the Stage R0, along with housing condition data. However, 3D laser scanners provide a 3D building model with the basic dimensions after scanning, and, as shown in Figure 7.13, building a 3D housing model can minimise time and effort.

Existing Building 3D scanned Building Model

Figure 7.13 A sample of 3D laser scanned building, (English Heritage, 2011)

Although, the 3D scanning service is new to the construction industry, the 3D as-built house model is an option at present and this research explains its potential use for future because of its benefits.

7.4.3 Assessment Phase – The Stage R1: Prepare Refurbishment Project Plan

Once the housing condition data becomes available at Stage R0, a refurbishment project plan and design will be prepared at the Stage R1 as shown in Figure 7.14. The main input for this stage is the housing condition data although the 3D as-built house model can be another input instead of housing condition data in the case where a 3D scanner service is utilized. The Stage R1 is implemented to develop a refurbishment plan based on customers' requirements and preferences for housing refurbishment, and develop a 3D house information model of an existing house for the design development at the Stage R2.

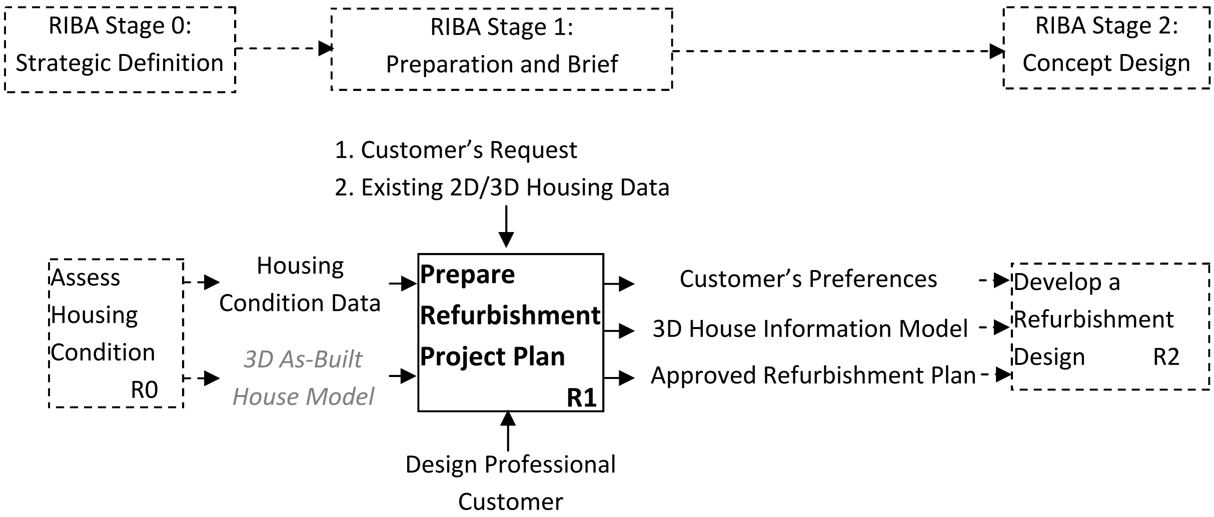


Figure 7.14 Stage R1 - Refurbishment Preparation

There are three essential outputs at this stage:

1) Customer's Preferences
2) 3D House Information Model
3) Approved Refurbishment Plan.

The customers' preferences and requirements for housing refurbishment are necessary for decision making on affordable solutions based on their viewpoints, although construction professionals may have different priorities and preferences about housing refurbishment (See subsection 3.5.2 and 6.3.5). Therefore, the customers' preferences for housing refurbishment should be clearly identified at this stage to improve customer's satisfaction.

Secondly, a 3D house information model is prepared to integrate essential information from various project stakeholders based on a BIM system. The model is a stepping stone to formulating holistic refurbishment solutions systematically. If the house information model does not provide physical dimensions and energy use, a holistic refurbishment solution will not be proposed. Therefore, housing condition data generated by a qualified assessor during the R0 stage is the key input to generating a house information model where physical and construction data are contained.

Finally, a proposed refurbishment plan is reviewed and approved by the customer to make sure their requirements are reflected in the proposed plan. This enables customers to make a decision as to whether or not they will refurbish. The primary refurbishment plan provides possible refurbishment solutions with refurbishment cost, energy cost saving and project duration.

In order to generate the essential outputs, there are three sub-processes under the Stage R1 as shown in Figure 7.15.

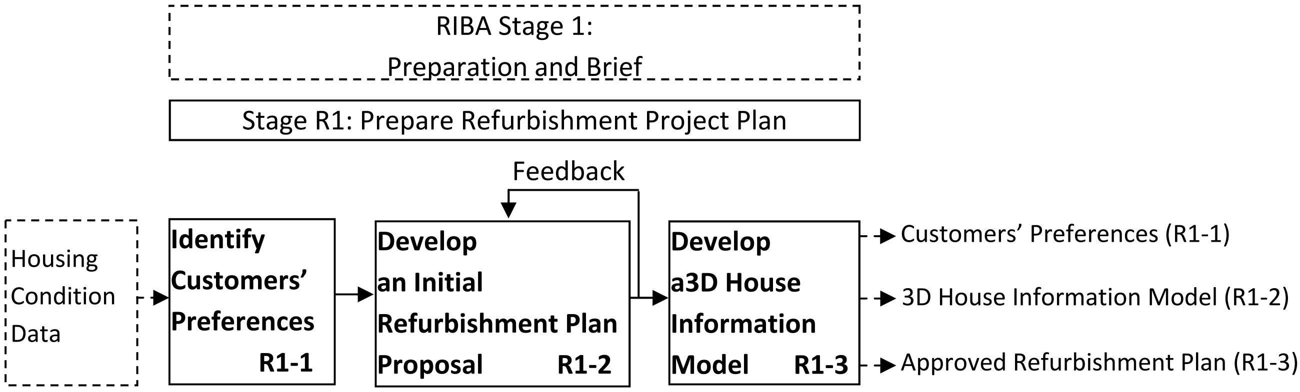


Figure 7.15 Sub-processes of Stage R1

The further explanation for each sub-processes are provided in the following subsubsections.

7.4.3.1 The Stage R2-1 – Identify Customers' Preferences

The detail information for Stage R2-1 is shown in Figure 7.16.

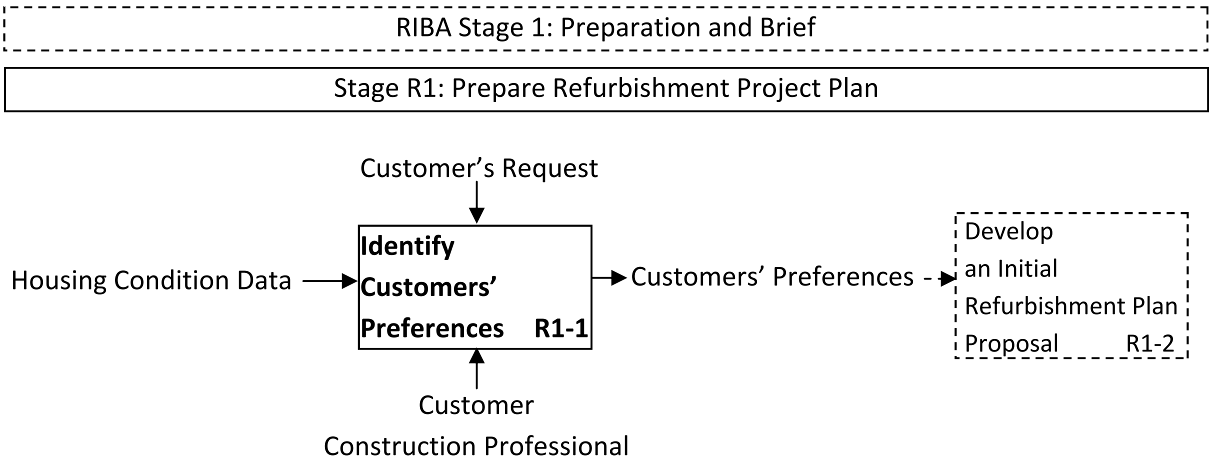


Figure 7.16 Stage R1-1

During this stage, construction professionals should identify customers' preferences regarding their priorities for the housing elements they want to refurbish, and their preferences for refurbishment measures and materials. Although the whole-house fabric will be refurbished eventually, construction professionals should communicate with customers to fulfil their requirements and to highlight the various trigger points that can provide opportunities to refurbish the whole-house fabric progressively (See Figure 3.7 in subsection 3.5.2). This is an important role for design professionals not to compromise opportunities for future refurbishment works. Thus, continuous feedback and communication between customers and professionals is essential to identify customers' preferences that provide a basis to select an affordable solution.

As the output of Stage R1-1, the customers' preferences include the following information:

1. Preference for Housing Element to Refurbish: Various trigger points can provide opportunity for customers to refurbish many different house elements. Design professionals should inform them that future refurbishment options are available, and the future works should not be compromised (See subsection 3.5.2).

2. Preference for Refurbishment Measures: Although refurbishment measures decided by customers' preferences, construction professionals need to advise customers accordingly based on their preferences. A risk analysis is performed when deciding upon refurbishment measures as there are always associated risks such as: moisture; mould growth; cold bridging and so on (See subsection 3.4.3).

3. Preference for Refurbishment Materials: The information about refurbishment materials is identified during this stage, and will be taken into consideration during the design phase when design professionals develop refurbishment design alternatives.

4. Initial Budget Guideline for Refurbishment: A range of initial budgets helps customers and professionals to consider refurbishment solutions within budget, and make a decision on an affordable refurbishment solution.

The first three preferences were presented in Section 6.3. The fourth can vary depending on customers.

7.4.3.2 The Stage R1-2: Develop an Initial Refurbishment Plan Proposal

Once the customers' preferences and an initial budget have been identified, construction professionals prepare an initial refurbishment plan, which, once approved by the customer moves to the next stage as shown in Figure 7.17.

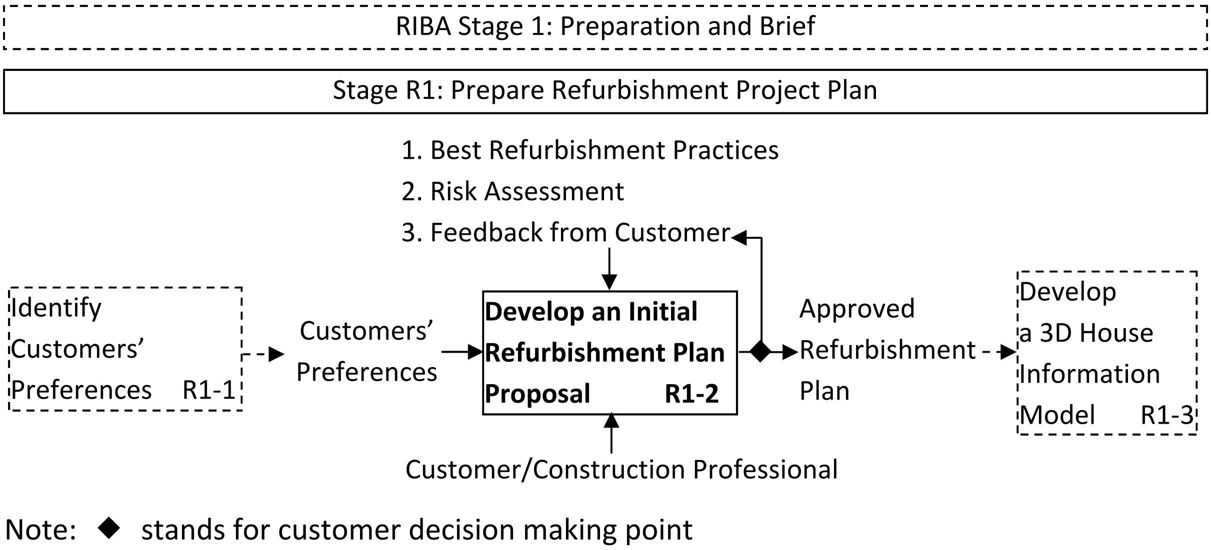


Figure 7.17 Stage R1-2

It is important to obtain approval from customers about the proposed refurbishment plan because developing a BIM model requires time and effort by the construction professionals that cannot be charged to customers without sufficient explanations about using BIM. In particular, it is challenging to persuade homeowners that BIM should be used for housing refurbishment, and it is more difficult to charge them extra for BIM model development. In contrast with owner-occupied housing, clients in the social housing sector are aware of the benefits of BIM. It is important to discuss with customers the use of BIM from the outset of refurbishment projects. A 3D BIM model is developed at the end of the assessment phase, as construction professionals generally do not want to develop a BIM model unless customers are fully committed to adopting the housing refurbishment (See Appendix 4).

When a refurbishment project plan is developed and approved, there are four constraints to be carefully considered.

1. Best Refurbishment Practices (See subsection 7.3.2, Table 44) – There are best refurbishment practices for each measure for each house element. Construction professionals should consider the best practices and propose an initial refurbishment plan to customers. Since the best practices provide a range of costs and CO_2 reduction for each refurbishment measure, construction professionals and customers can make an informed decision at the early stages of a refurbishment project. Furthermore, as the best practices are proven by practitioners and professional construction organizations, the potential empirical errors during the construction phase can be minimised.

2. Risk Assessment – Refurbishment measures should be carefully planned because of moisture and cold bridging. In particular, housing elements such as walls and roofs are vulnerable to moisture after refurbishment because the insulation material can block natural ventilation of the elements. Therefore, construction professionals must carefully plan a combination of refurbishment measures to achieve a planned energy performance of a refurbished house.

The proposed refurbishment plan provides the following information to customers to obtain customers' approval before proceeding to the design phase.

a. Planned Refurbishment Solution (Combination of Refurbishment Measures)
b. Early Cost Planning and Estimate of Refurbishment
c. Expected Energy Cost and CO_2 reduction after Refurbishment
d. Expected Project Duration (Disruption during Refurbishment)

3. Feedback from Customer - Once the proposed refurbishment plan is approved by the customer, construction professional can proceed to the next stage for developing a BIM model, and proceed to the design phase. However, when the proposed refurbishment is not accepted, they need to incorporate the feedback from customers and update the proposal until the customer approves it.

7.4.3.3 The Stage R1-3: Develop a 3D Housing Information Model (HIM)

Figure 7.18 has shown inputs, constraints, project stakeholders and outputs.

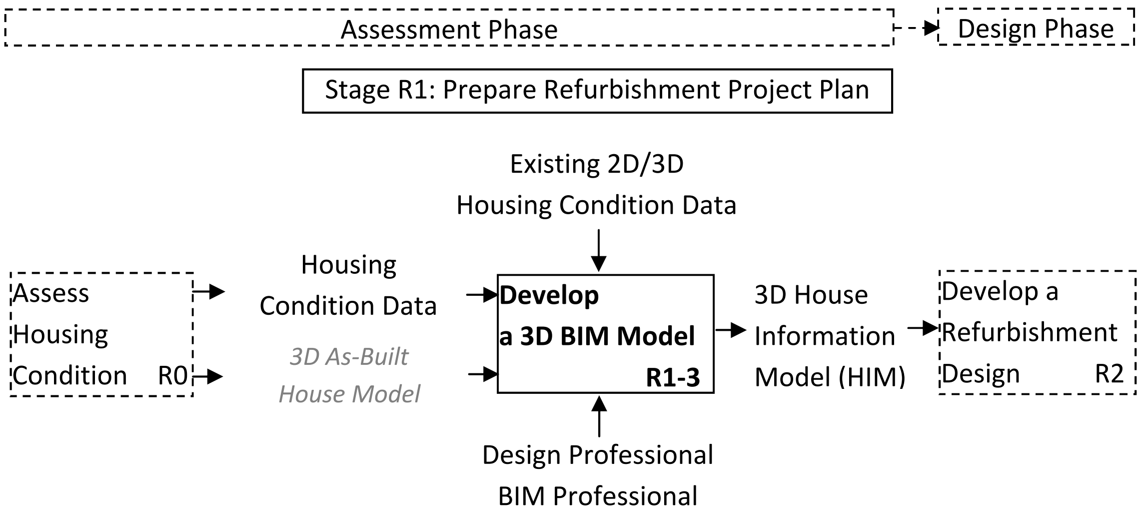


Figure 7.18 Stage R1-3

Note: The input - 3D As-Built House Model - is indicated in grey because 3D laser scanning is not widely utilized for housing refurbishment, although it is available in the market.

The outputs of Stage R0, the Housing Condition Data and the 3D As-Built House Model become the inputs to develop a 3D Housing Information model. In order to develop reliable refurbishment design alternatives at the design phase, these inputs are crucial because not all the UK's housing stock has as-built data such as floor plans, dimensions for house elements and construction information. The existing 2D or 3D housing condition data can be utilised for developing a Housing Information model if available. Design professionals and/or BIM professionals who provide a BIM service are responsible for creating a 3D Housing Information Model as shown in Figure 7.19.

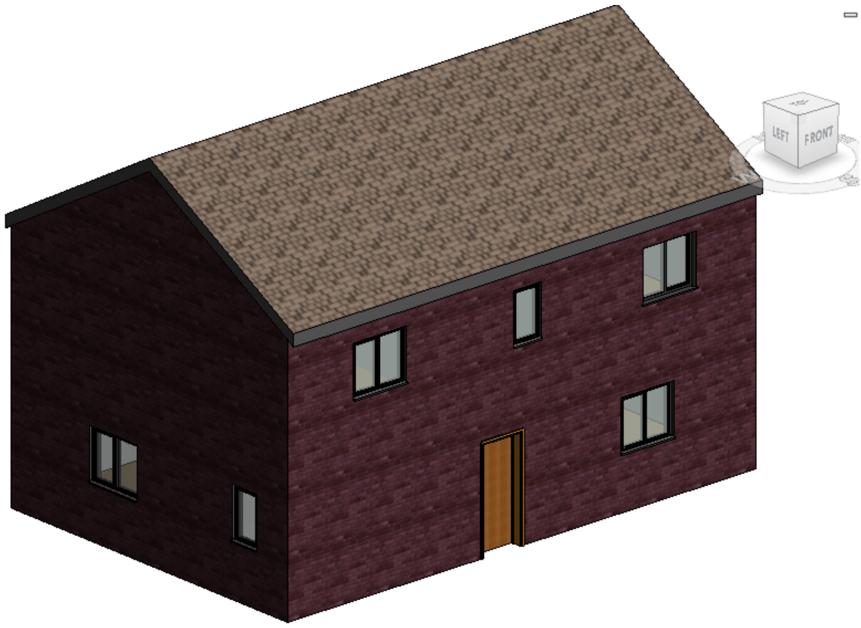


Figure 7.19 3D Housing Information Model (HIM)

This Housing Information Model provides a virtual 3D model based on the dimensions of an existing house by using BIM software like Autodesk Revit. It is common that housing condition data is developed through 2D drawings rather than a 3D model (NBS, 2014). However, as advanced technologies, like a 3D laser scanner, become available and more widespread in the construction sector, the housing sector will benefit from them. They will help to reduce the time and effort in creating 2D drawings and converting them to a 3D model because the dimension data, such as point cloud data sets, are automatically collected by a 3D scanner and converted to a 3D model as shown in Figure 7.19.

A 3D Housing Information model contains parametric information that all the information related to building elements are already embedded into the objects. As a result, all the housing condition data for each house element measured during Stage R1 are converted and incorporated into a Housing Information Model as shown in Figures 7.20 to 7.25.

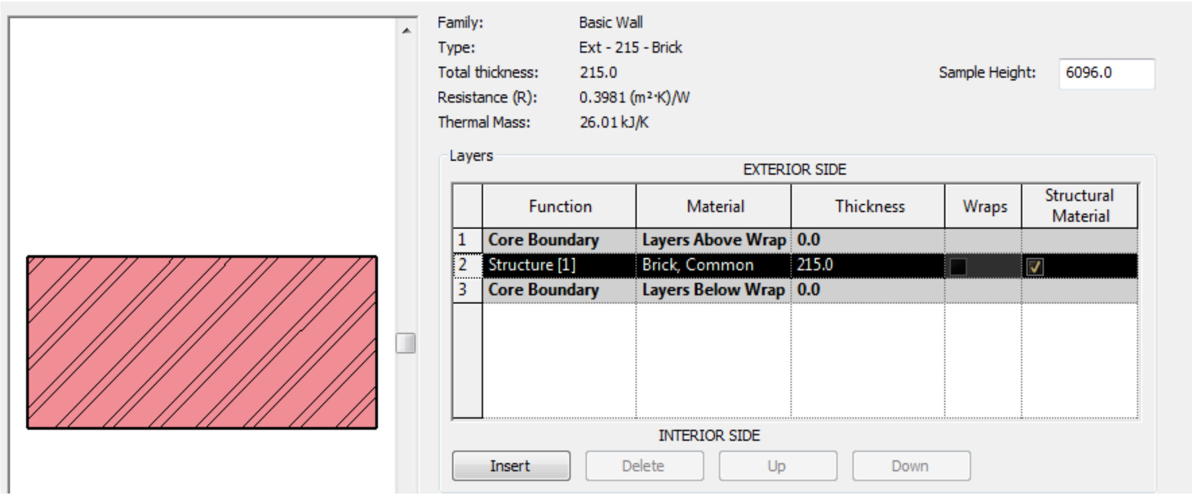


Figure 7.20 Solid wall

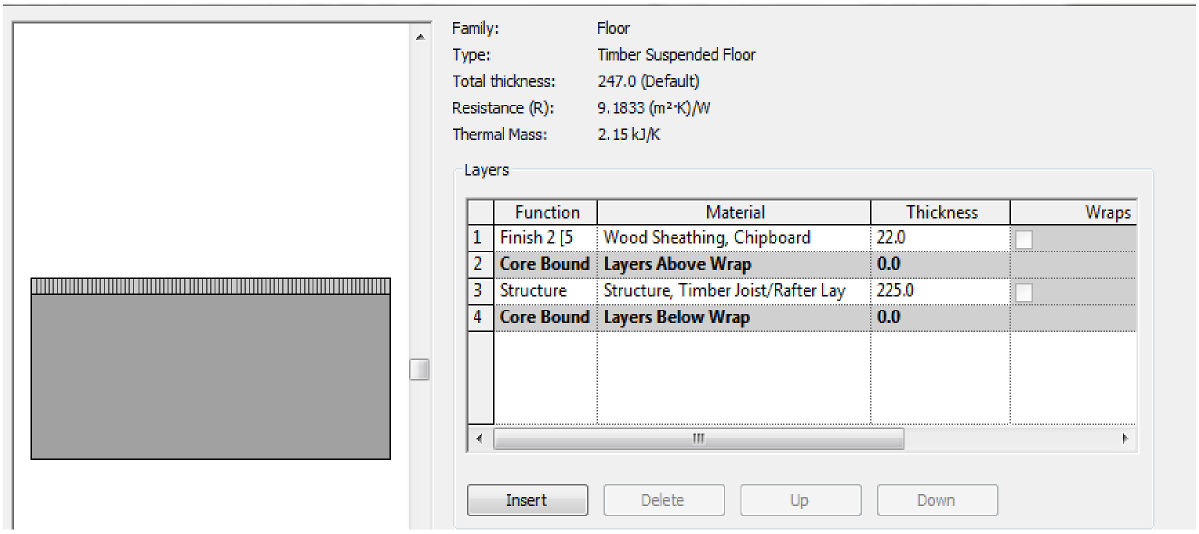


Figure 7.21 Suspended Timber Floor

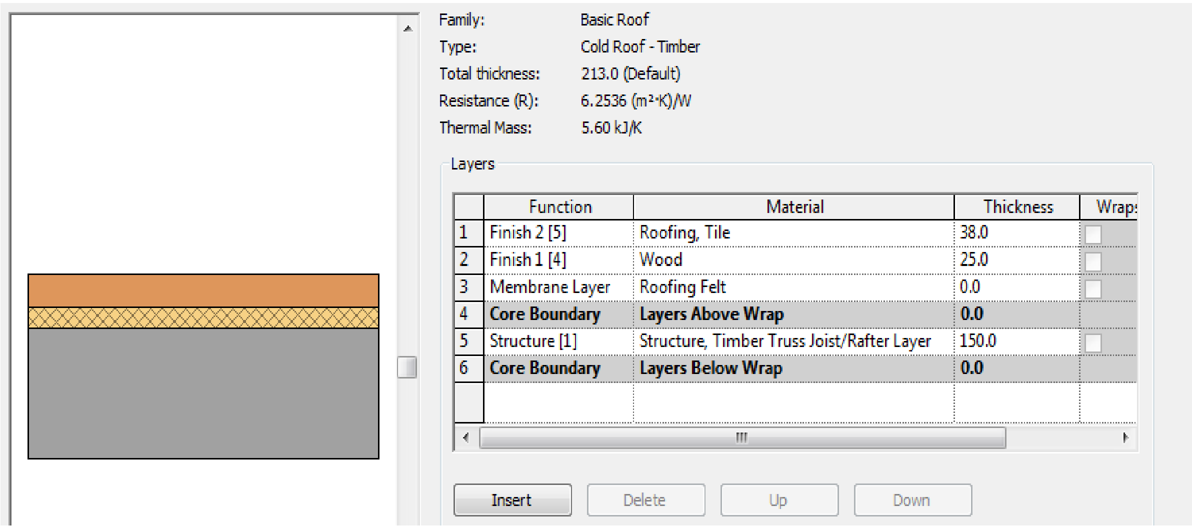


Figure 7.22 Pitched Roof

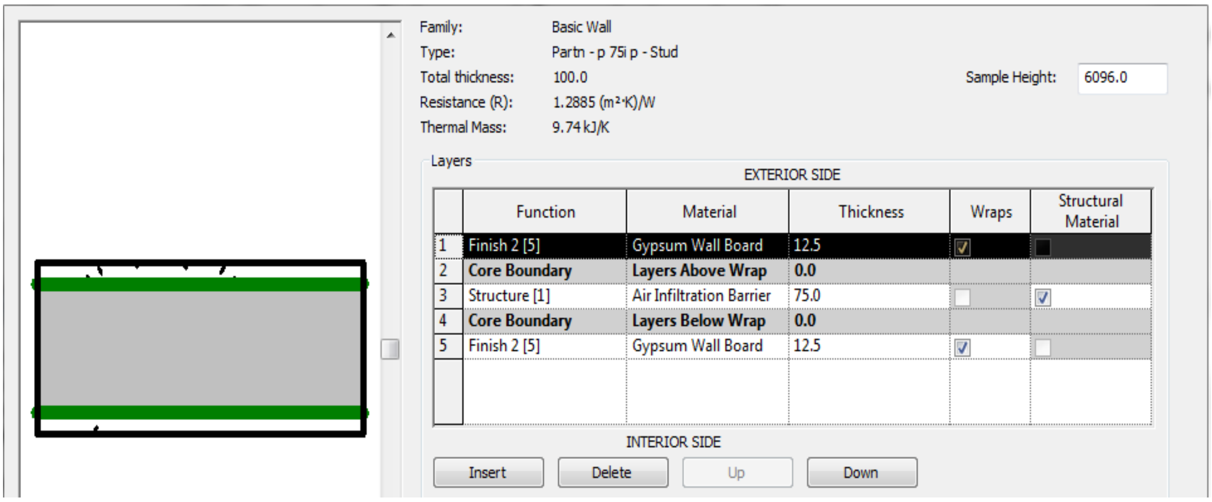


Figure 7.23 Partitioned Wall

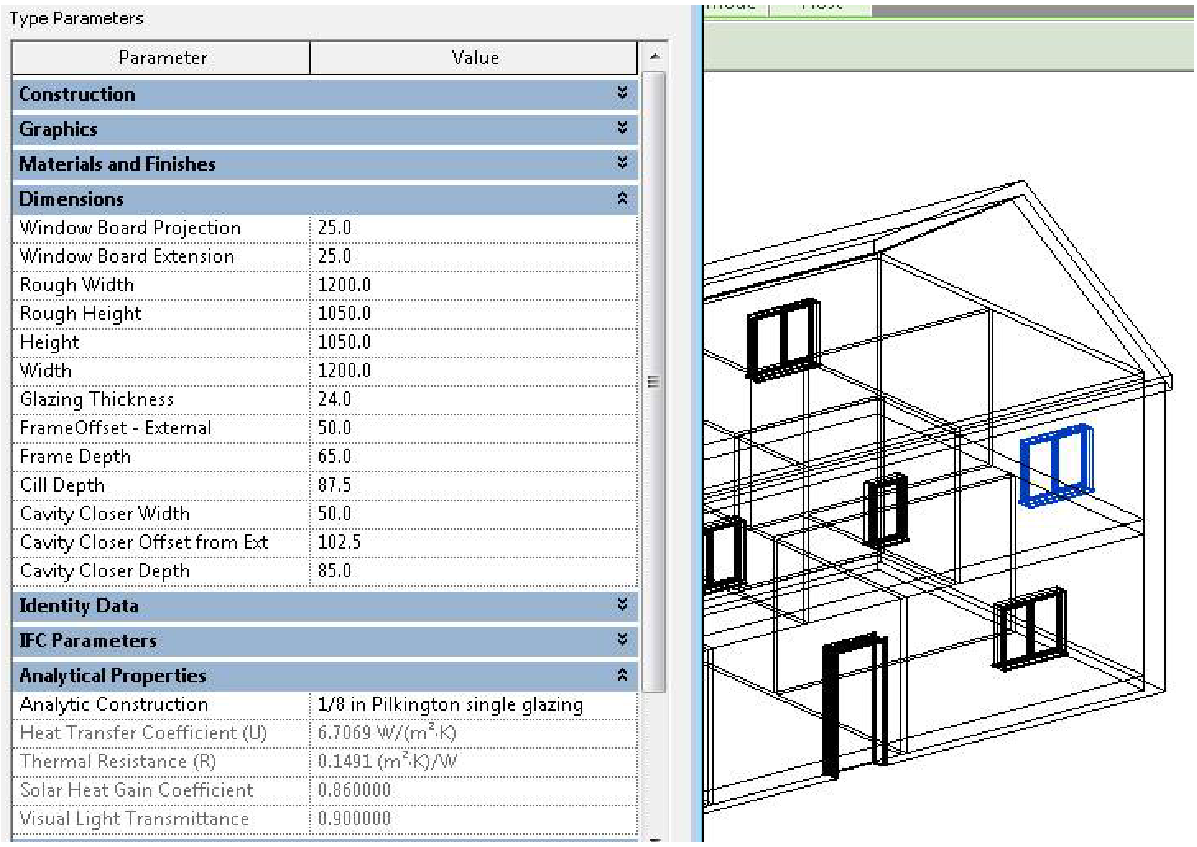


Figure 7.24 Window

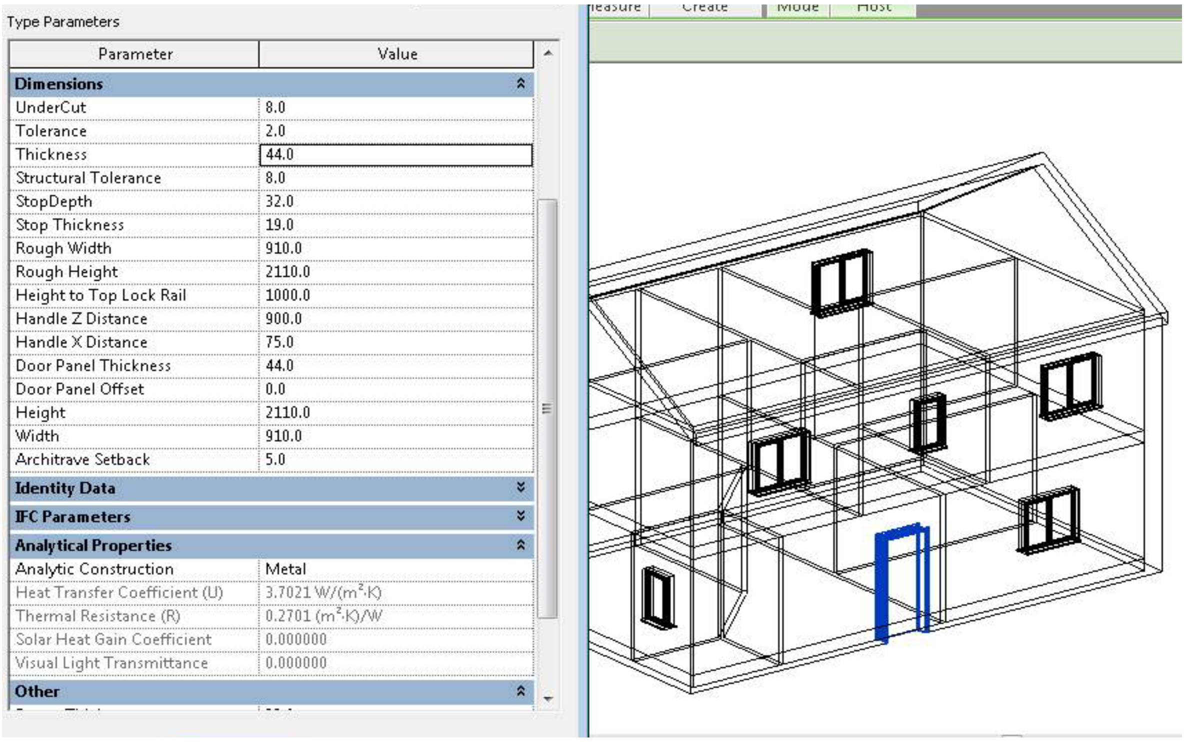


Figure 7.25 Door

These provide a snapshot of each housing element with its parametric information such as dimensions, U-values and construction details including as-built data sets of an existing house. The dimensions of elements are automatically changed according to the modification by refurbishment designs and updated through a project life cycle. As a concept of BIM the parametric design principle is applied and relevant information on material quantities, material costs, U-value and embodied CO_2 are instantly updated when they are available without any effort from the quantity surveyor. The material take-off function can simply create a bill of quantities in a customised table as shown in Figure 7.26, and this function meets the requirements of Level 2 BIM maturity mandated by the government by 2016 (See Section 4.4).

Material Quantity Take-Off								
Level	Family and Type	Material: Name	Material: Cost	Material: Embodied CO2	Material: Area	Material: Vol	Total Cost	Total Embodied CO2
Ground Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£24.56		67 m²	1.47 m³	£1645.14	
Ground Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£7.79		67 m²	15.07 m³	£521.81	
First Floor	Basic Ceiling: Generic	Gypsum Wall Board	£28.04	0.00	65 m²	0.00 m³	£1810.55	
First Floor	Basic Ceiling: Generic	Gypsum Wall Board	£28.04	0.00	64 m²	0.00 m³	£1807.19	
First Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£24.56		67 m²	1.47 m³	£1645.14	
First Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£7.79		67 m²	15.07 m³	£521.81	
B1010375: 6					397 m²	33.09 m³	£7951.64	
	Basic Roof: Cold Roof - Timber	Wood	£0.00	0.00	90 m²	2.26 m³	£0.00	
	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter	£12.49	0.00	90 m²	13.56 m³	£1128.93	
	Basic Roof: Cold Roof - Timber	Roofing, Tile	£66.01	0.00	90 m²	3.43 m³	£5966.45	
	Basic Roof: Cold Roof - Timber	Roofing Felt	£5.83	0.00	90 m²	0.00 m³	£526.96	
Loft	Floor: Roof Ceiling Joist	Structure, Timber Joist/Rafter Layer	£7.79		67 m²	6.70 m³	£521.81	
B1020400: 5					429 m²	25.95 m³	£8144.15	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		54 m²	11.43 m³	£4712.52	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		54 m²	1.08 m³	£580.77	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		42 m²	9.11 m³	£3709.69	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		42 m²	0.85 m³	£456.14	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		49 m²	10.34 m³	£4267.18	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		49 m²	0.98 m³	£525.98	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		39 m²	8.43 m³	£3433.69	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		39 m²	0.78 m³	£422.20	
B2010100: 8					368 m²	42.98 m³	£18108.17	

Figure 7.26 Material Take-off Function in BIM

As shown in Figure 7.27, existing CAD files may need to be imported into the BIM software as the 2D or 3D CAD data has no parametric information and so has less capability. For example there would be no instant update information like BIM software (See section 4.3). The imported 2D or 3D CAD data can be converted to a 3D BIM system since the basic information in the drawings can be used to reconstruct a floor plan and dimensions of each space in a house.

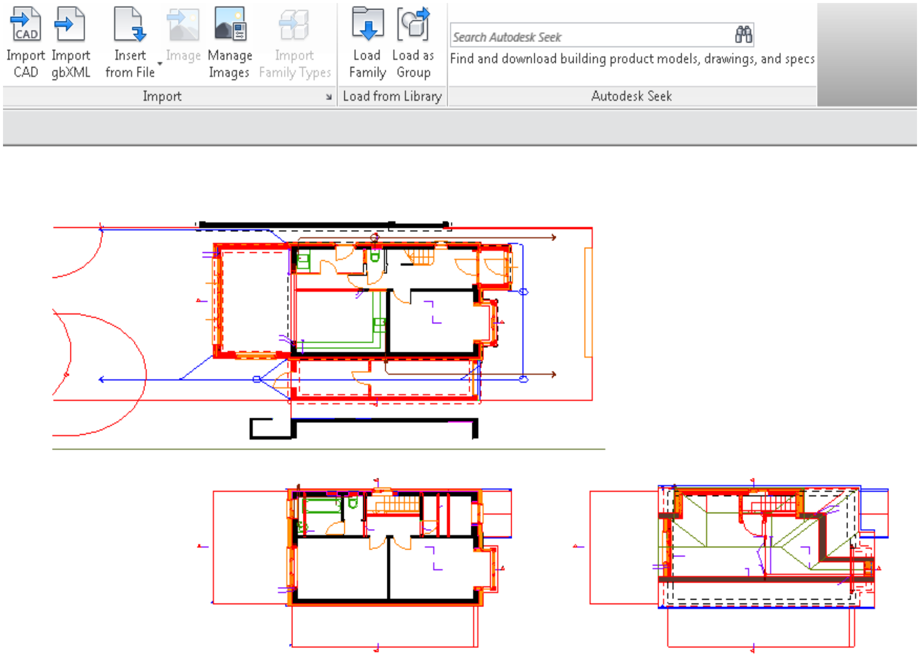


Figure 7.27 Import 2D/3D CAD into 3D BIM systems Result

As shown in Figure 7.28, building data imported from 3D CAD is presented in a 3D manner in the BIM system. However all the elements, structures and service systems are presented as one mass without parametric information such as dimensions, thickness and thermal information because they are not object-oriented and cannot be separately converted into a BIM object with parametric information. A table of material take-off produced from 3D CAD information is empty due to demerits of using 2D or 3D CAD system as shown in Figure 7.29.

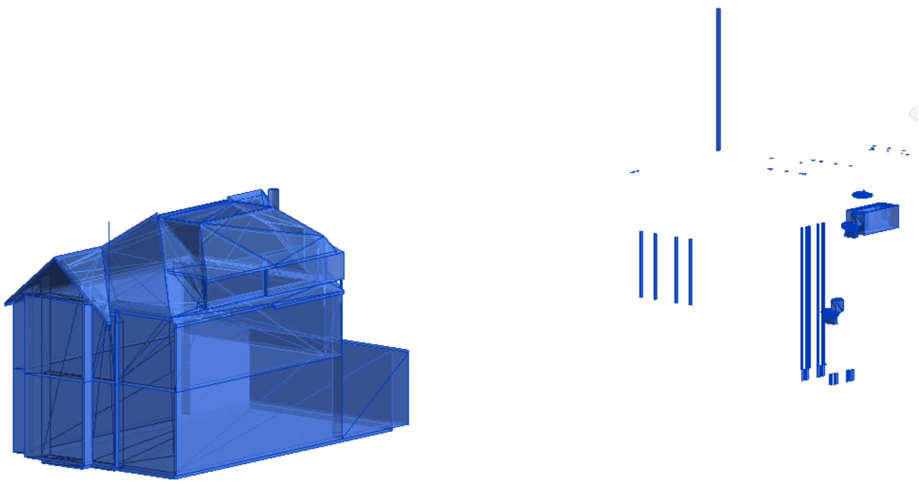
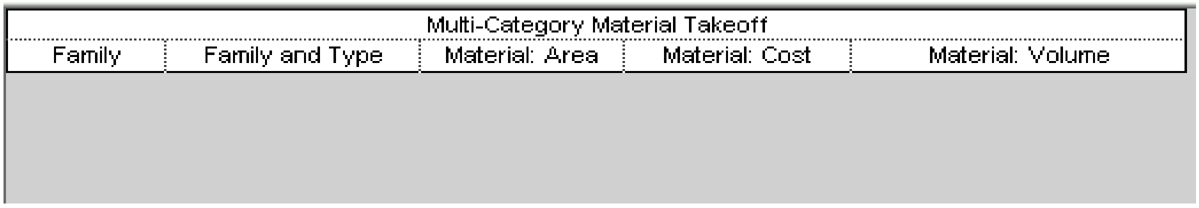


Figure 7.28 Import 3D CAD into 3D BIM systems Result



Multi-Category Material Takeoff				
Family	Family and Type	Material: Area	Material: Cost	Material: Volume

Figure 7.29 Material Take-off Result from 2D and 3D CAD imported model

The more widely BIM becomes adopted in the housing sector with advanced and sophisticated technologies like a 3D laser scanning, the more time and effort that can be saved through the sub-processes as shown in Figure 7.30. As the 3D scanning is used during the assessment stage, the "Develop a 3D House Information Model (HIM)", which is currently Stage R1-3 will be merged into Stage R0.

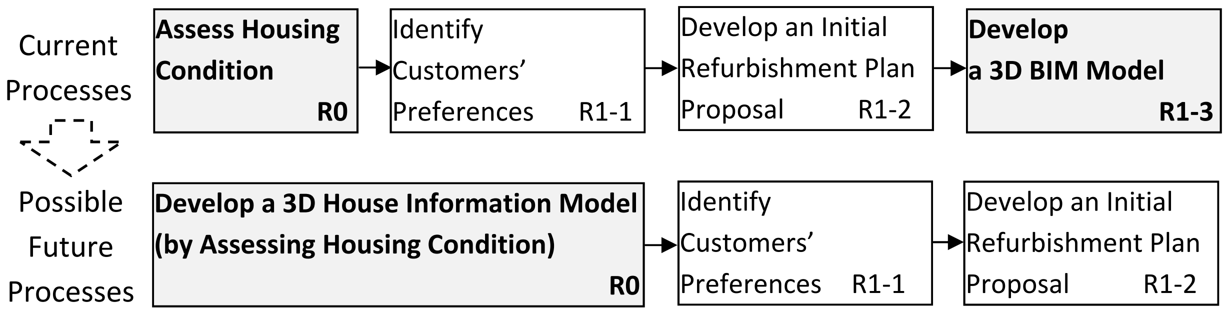


Figure 7.30 Possible Future Processes in the Assessment Phase

A hypothetical example of a detached solid wall is demonstrated to describe the information flows and interactions. Figure 7.31 elaborates this information flows through the stages with project stakeholder involvement. For example, a roof is selected as the first priority house element for refurbishment since the survey result of refurbishment priorities has identified both homeowners and construction professionals as the first priority (See subsubsection 6.3.3.3).

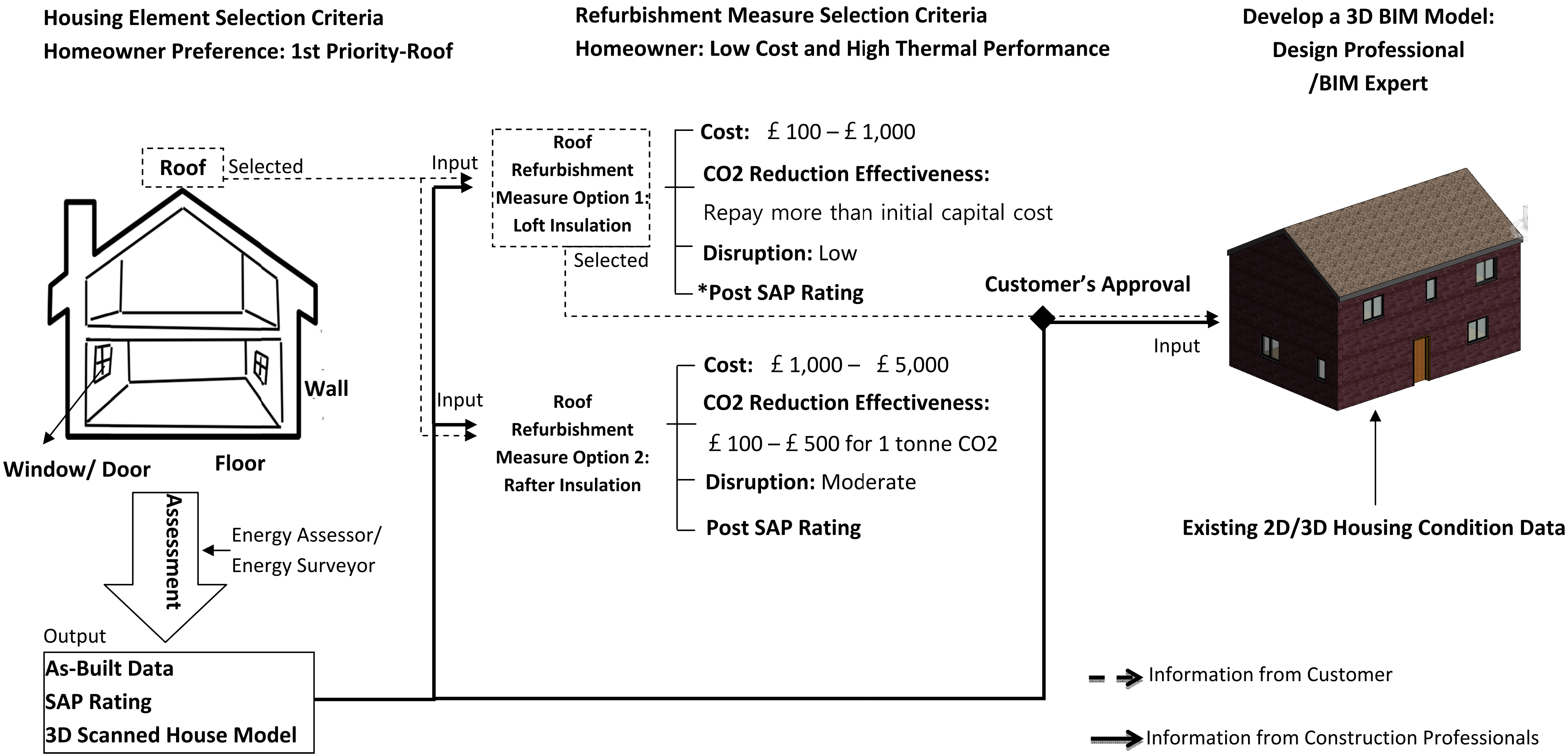


Figure 7.31 Information Flows at the Assessment Phase, From Stage R1 to Stage R2

*In order to calculate the post SAP Rating, it requires service information of a house and qualified energy assessor. Thus, this research will exclude the Post SAP rating.

7.4.4 Design Phase – The Stage R2: Develop a Refurbishment Design

The design phase comprises two stages – R2 and R3 – as shown in Figure 7.32. In this section, further detailed information about Stage R2 is provided.

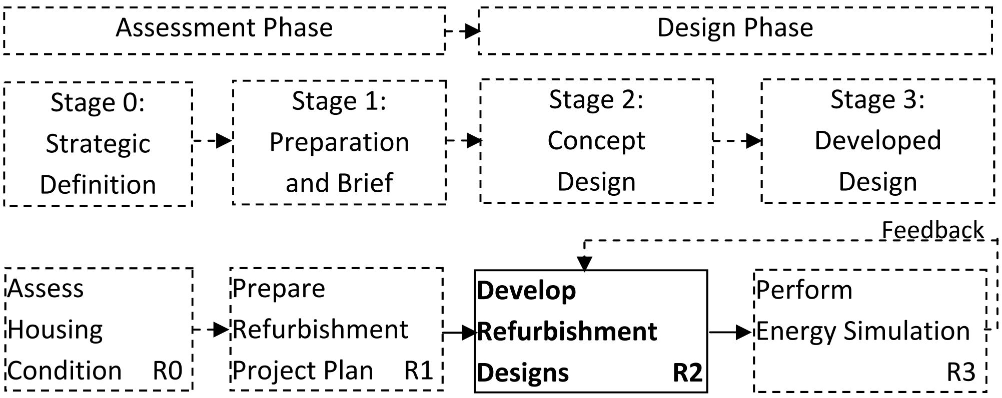


Figure 7.32 Two Stages of the Design Phase

The purpose of this is to develop a refurbishment design based on the approved refurbishment plan but with more detailed cost and environmental information on its design. This refurbishment design entails LCC and LCA information to perform a comparative analysis among various design alternatives as shown in Figure 7.33

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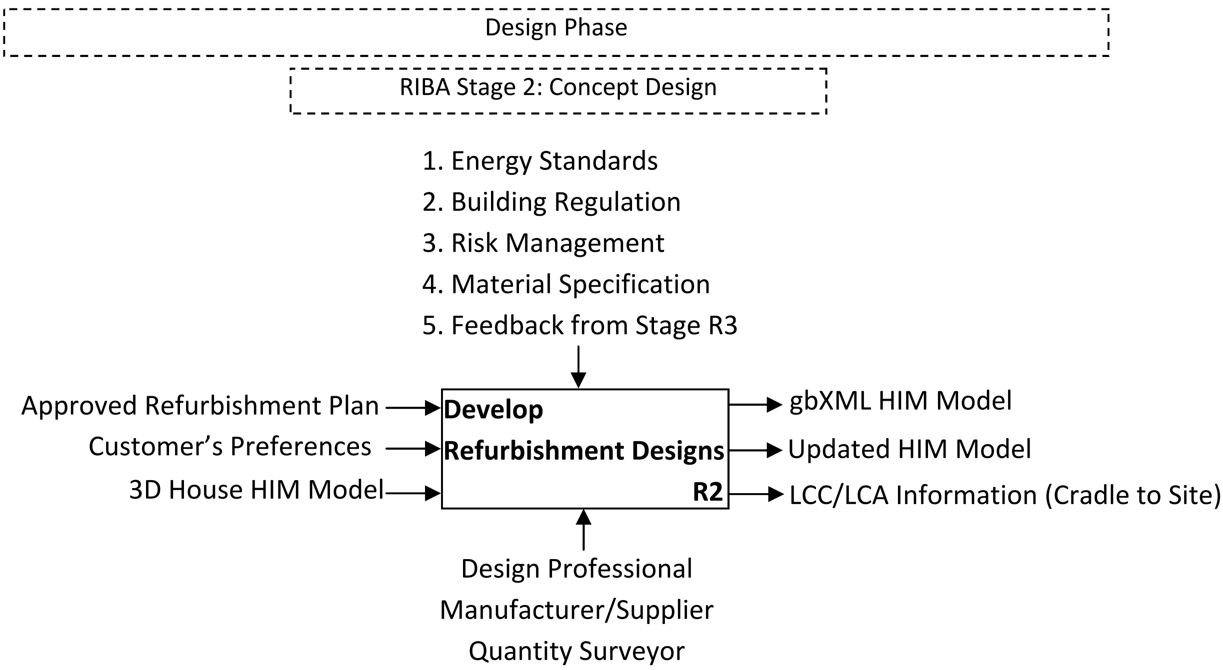


Figure 7.33 Stage R2 - Refurbishment Preparation

Figure 7.34 shows Stage R2 divided into more detailed sub-processes, which are described in the next subsubsection 7.4.4.1.

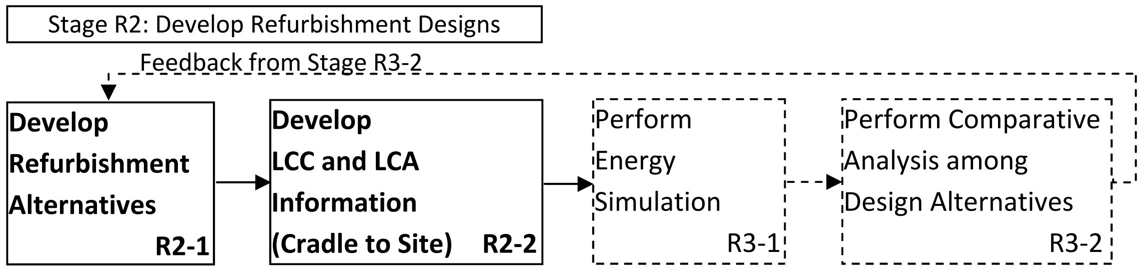


Figure 7.34 Subsidiary Processes of Stage R2

7.4.4.1 The Stage R2-1: Develop Refurbishment Design Alternatives

Figure 7.35 illustrates the process map at Stage R2-1, where there are three inputs. The approved refurbishment plan has four types of information produced during the Stage R1-2, which enables design professionals to develop detailed refurbishment design alternatives. The customer's preference about refurbishment materials is taken into account as a priority in considering design alternatives. The selected refurbishment materials directly impact initial costs and embodied CO_2, and eventually influence on LCC and LCA in terms of cost-effectiveness and energy efficiency. For example, the initial cost and thermal performance can have substantial impacts when customers select a certain type of refurbishment measures and materials (See Section 6.3). Based on customer's preferences, design professionals are able to generate material options and further develop the 3D housing information model generated from the Stage R1-3.

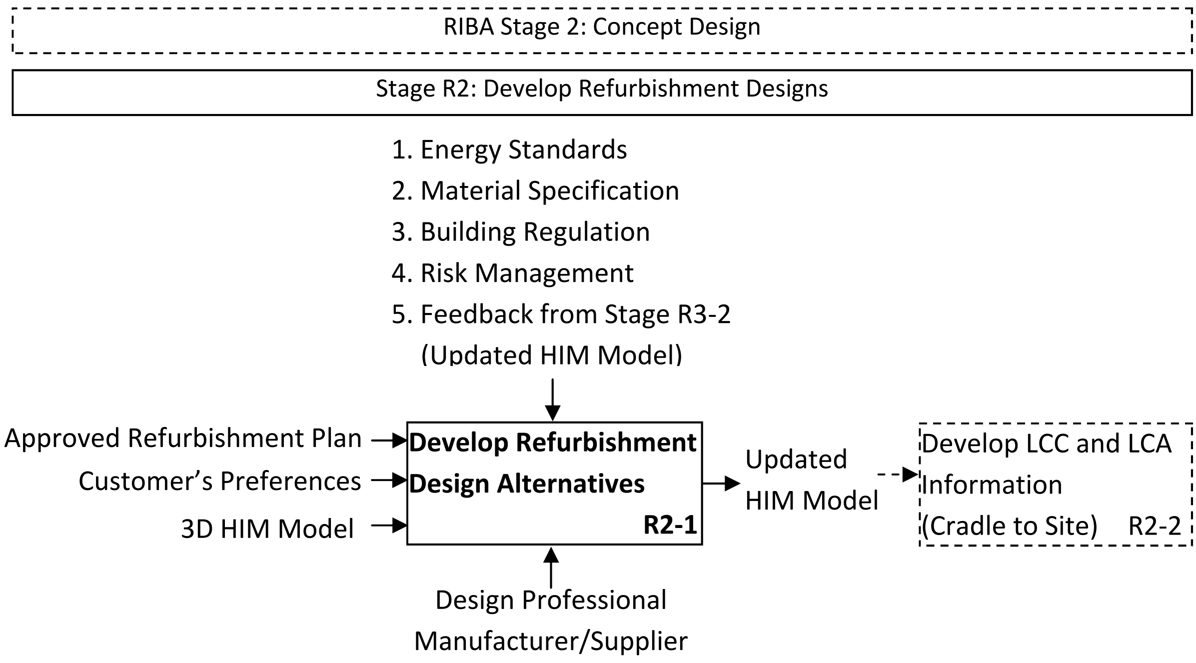


Figure 7.35 Stage R2-1

Five constraints provide a developing guideline on refurbishment design alternatives:

1. Energy standards
2. Material specification
3. Building regulations
4. Risk assessment
5. Feedback from Stage R3-2

1. Energy Standards – The energy standards determine the U-value of house elements as shown in Table 51. There are four different U-values for the whole-house fabric refurbishment that are mandated and recommended by the UK government. The BR 2010/2013 (Minimum) and the FEES (Maximum) are mandated by the government in the Building Regulation Part La, and BR 2010 and 2013 (Notional) are recommended. The thickness of insulation materials are determined to achieve the U-values, depending on the energy standards. Eventually, the U-values impact the material specifications that are directly related with the initial costs and LCC, and embodied CO_2 and LCA. Therefore, design professionals should pay careful attention on the energy standards from the beginning of the design phase in order to meet the customer's budget.

Table 51. U-values of Current Various Energy Efficiency Standards for House Fabric

Housing Element	BR 2010/2013* (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES** (Maximum)
Wall	0.3	0.22	0.18	0.15
Floor	0.25	0.18	0.13	0.13
Roof	0.2	0.15	0.13	0.13
Window	2.0	1.4	1.4	1.2
Door	2.0	1.2	1.2	1.0

Note: *BR: Building Regulation Part L – Minimum energy standard mandated by the UK government at present. The U-values mandated by BR 2010 and 2013 are the same. BR Notional: Advanced energy efficiency standards between BR and FEES that are recommended in the Building Regulation Part L.

**FEES: Fabric Energy Efficiency Standard – Maximum energy standard mandated by the UK government for zero carbon home from 2016.

2. Material Specification: The thickness of insulation materials varies in the energy standards - see Table 52.

Table 52. Thickness of Insulation Materials for Each Energy Efficiency Standard

Housing Element	Insulation Material	Energy Performance Standard			
		BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES
Wall	Fibre Glass	120mm	170mm	210mm	260mm
	EPS	100mm	140mm	175mm	215mm
Floor	Fibre Glass	145mm	170mm	260mm	260mm
	EPS	120mm	140mm	215mm	215mm
Roof	Fibre Glass	190mm	260mm	300mm	300mm
	EPS	155mm	215mm	250mm	250mm
Window	Timber Framed	Double Glazing 24mm (U-value - Frame: 2.71, Glazing: 1.75)	Triple Glazing 42mm (U-value - Frame: 3.1, Glazing: 1.27)	Triple Glazing 42mm (U-value - Frame: 3.1, Glazing: 1.27)	Triple Glazing 42mm (U-value - Frame: 0.85, Glazing: 1.27)
Door	Wooden Door	45mm	90mm	90mm	105mm

Note: Composition of Window - Glazing: 6mm, Cavity: 12mm, Wooden Door used the pine.

Currently, professional construction organisations such as the NBS provide an open BIM object library where construction professionals can obtain and share necessary BIM objects free of charge as shown in Figure 7.36.

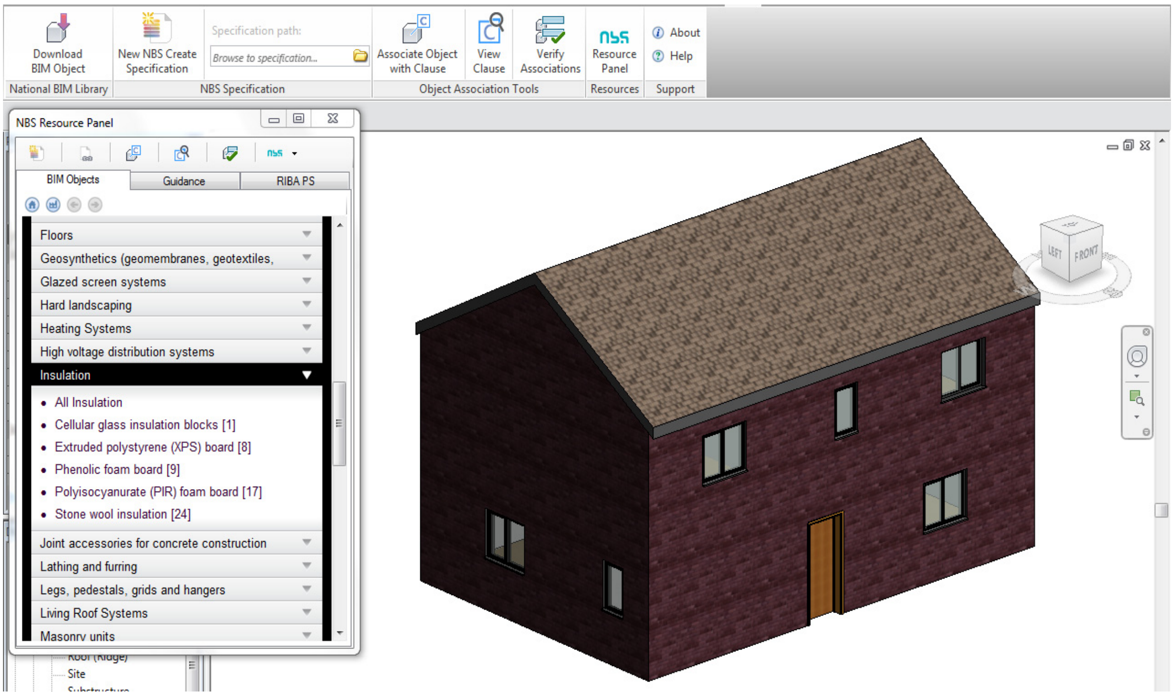


Figure 7.36 NBS BIM Library in Autodesk Revit for Construction Materials

Despite the availability of various BIM objects such as construction materials and building services produced by various manufacturers that are suitable for different BIM software such as Autodesk Revit, Bentley, ArchiCAD and Vectorworks, the current BIM objects are mainly developed for new-build construction. In particular, it is difficult to obtain any BIM objects for solid wall housing refurbishment. Therefore, a basic solid wall house model should be created from generic BIM objects in the Autodesk Revit library and modified with allowable information. For example, current wall insulation materials, which are available from the NBS open BIM library, mainly focus on creating and applying for cavity wall insulation. Possible housing refurbishment options have limitations as the construction type and house shape is already constrained. Furthermore, as it is already pre-fixed a certain amount of design flexibility, it could be much easier to develop a generalised model or library for housing refurbishment per built year and housing types.

To assess cost-effectiveness, energy performance and environmental impact through LCC and LCA, material costs, embodied CO_2 and CO_2 associated with construction works are essential. Although the NBS BIM library currently provides some basic BIM objects, all the necessary information is not available. Figure 7.37 shows a sample NBS object of floor insulation material without cost and U-value where a lot of information is missing.

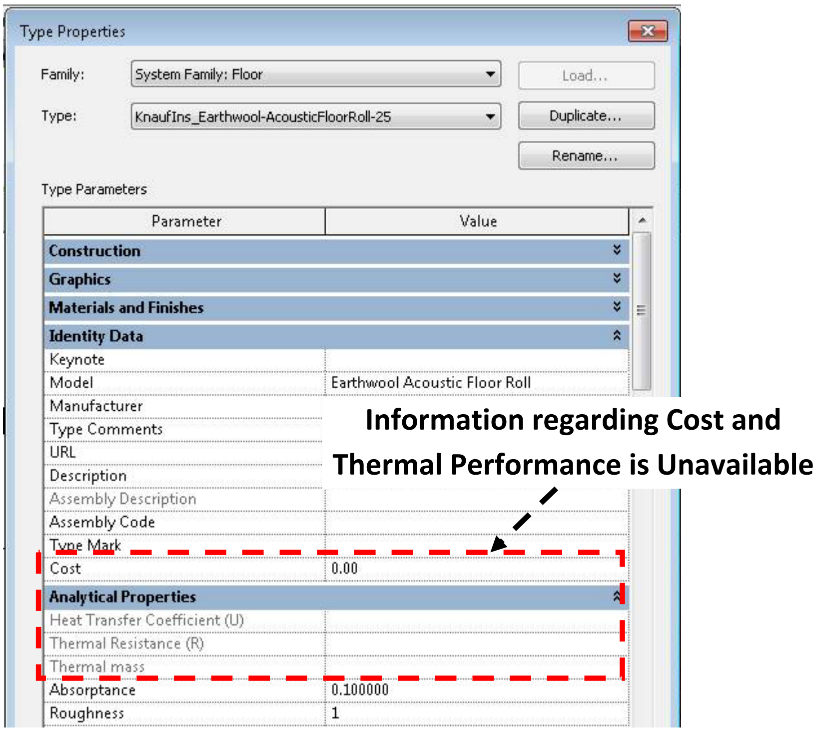


Figure 7.37 A sample BIM object From the NBS library

This essential information can be manually embedded into BIM objects with the information provided by manufacturers and suppliers in a standardised manner.

Furthermore, cost and CO_2 information of insulation materials are not fully provided to calculate LCC and LCA in BIM system; there are only two insulation materials – Fibre Glass and Expended Polystyrene (EPS) – commonly available in the data sets which are SMM7, Autodesk Revit, IES VE/IMPACT and Carbon Book (See Section 7.3). Other materials available in the current market cannot be found in the data sets, and apart from these two general materials for insulation there are too many different types of insulation materials available from manufacturers or suppliers. It is necessary to seek and create the data sets with its cost and CO_2 information when a certain type of materials is applied. In this research, two insulation materials (See Table 51) are used for LCC and LCA calculation and energy performance simulation.

3. Building Regulations –Building regulations should be reviewed in order to avoid any problem related to housing refurbishment. For example, an external wall requires a planning permission when it more than 25% of its surface area is refurbished. There is a lead time to obtain permission for refurbishment, which should be considered in developing a refurbishment project schedule.

4. Risk Assessment: As moisture and cold bridging is considered during the stage R2-2, the continuity of insulation for each house element should be carefully designed to achieve a planned level of energy performance. When insulation materials are installed, the continuity of insulation can be easily broken at the junctions of each housing element such as between loft joists and roof eaves and wall and floor. As a result, a refurbished house might not be able to achieve the planned energy performance. Early involvement of constructors during the design phase is desirable to improve buildability such as the continuity of insulation during the construction phase.

Risk assessment of new materials like Vacuum Insulated Panel (VIP) should be conducted when they are introduced to the housing sector to minimise possible risk and uncertainty. VIP needs to maintain a vacuum in order to achieve the expected U-value. However, if unskilled constructors handle it in the same way that they handle conventional insulation materials by drilling a hole to fix the material to a wall or roof, the integrity of the vacuum will be compromised and would fail to meet the required U-value. As a house requires various customised dimensions of refurbishment materials, the installation of new materials like the VIP is challenging due to its standard type and size.

5. Feedback from Stage R3-2: The proposed refurbishment design can be reviewed and revised as a result of a comparative analysis. Considering all the constraints and inputs, 190mm fibre glass is adopted for loft insulation as the most cost and energy-efficient measure as shown in Figure 7.38.

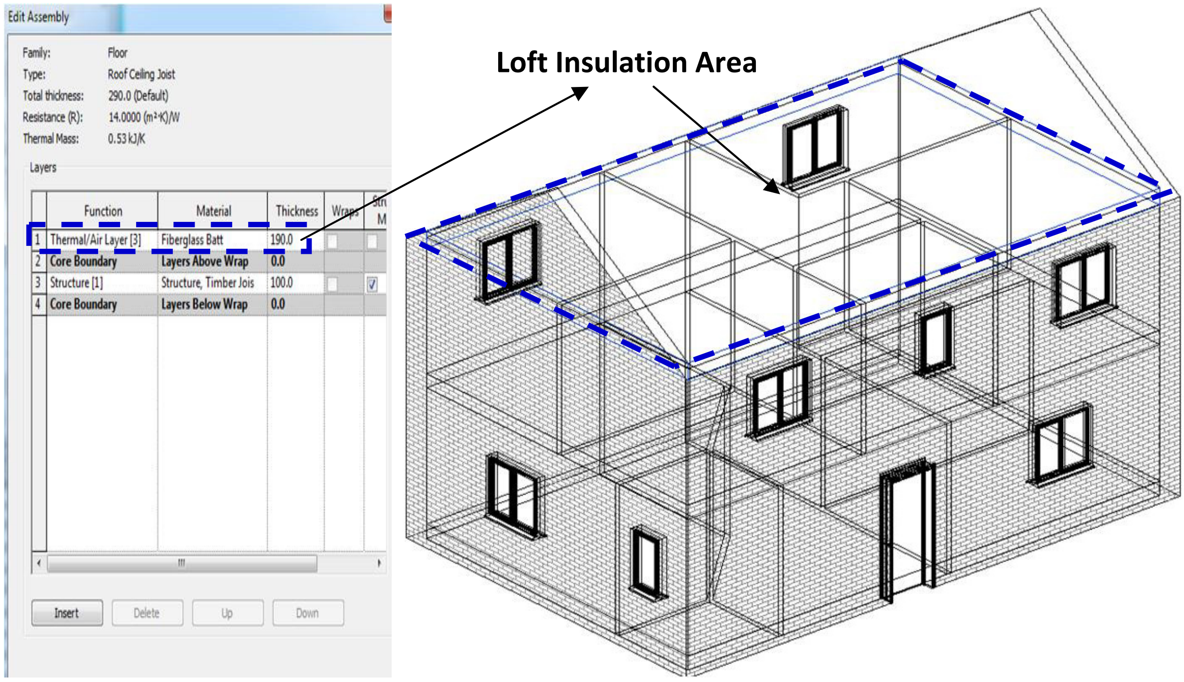
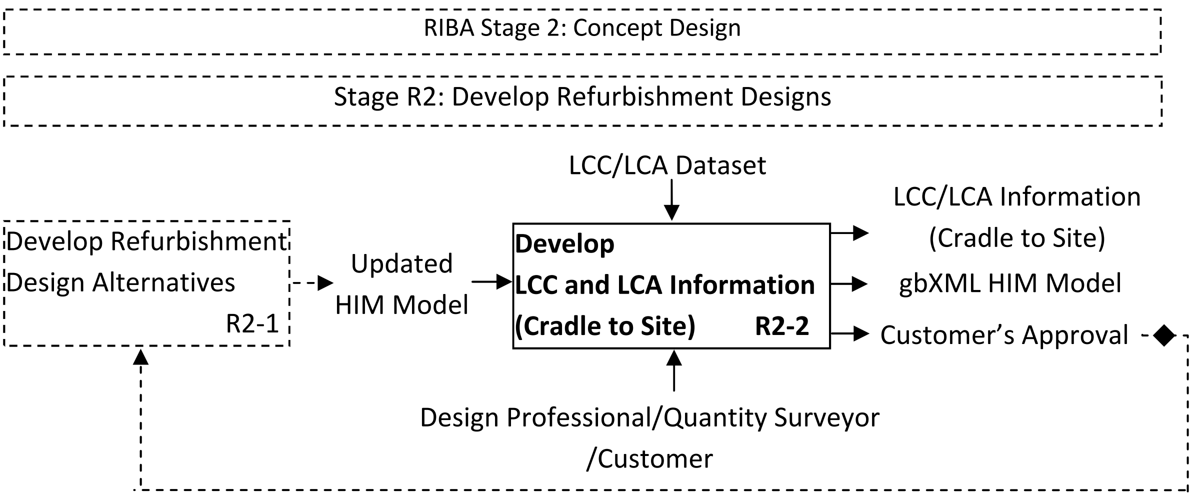


Figure 7.38 Insulation Material Specification and a Detached Solid Wall House

7.4.4.2 The Stage R2-2: Develop LCC and LCA Information (Cradle to Site)

Following Stage R2-1 where the refurbishment measure is selected (in this case the loft insulation, see Figure 7.38), a Cradle to Site study (See Figure 3.14 in Section 3.6) of LCC and LCA information is performed at Stage R2-2. This enables customers to review a proposed refurbishment design to see if it is within their budget, and allows the embodied CO_2 to be compared by design professionals. However, this stage does not include the full consideration of the operation and maintenance phase as the entire analysis of LCC and LCA will be fully implemented during Stage R3. Detailed information about the Stage R2-2 is described in Figure 7.39.



Note: ◆ stands for customer decision making point

Figure 7.39 Stage R2-2

There are three outputs at this stage: 1) LCC/LCA Information (Cradle to Site), 2) gbXML HIM Model, and 3) Customer's Approval

The first output is the LCC/LCA Information (Cradle to Site). When a Housing Information Model is updated, the initial cost (in particular the construction cost) and CO_2 information (embodied CO_2) can be generated automatically by the 'material take-off' function in the BIM software. This function can generate and update a bill of quantity automatically without the quantity surveyor's involvement when designs are revised. In Figure 7.40, the material costs are manually assigned to each material as currently most BIM objects do not include any cost or CO_2 information for construction materials. Therefore, full datasets of LCC and LCA (Cradle to Site) cannot be provided for comparative analysis.

Material Quantity Take-Off								
Level	Family and Type	Material: Name	Material: Cost	Material: Embodied CO2	Material: Area	Material: Vol	Total Cost	Total Embodied CO2
Ground Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£24.56		67 m²	1.47 m³	£1645.14	
Ground Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£7.79		67 m²	15.07 m³	£521.81	
First Floor	Basic Ceiling: Generic	Gypsum Wall Board	£28.04	0.00	65 m²	0.00 m³	£1810.55	
First Floor	Basic Ceiling: Generic	Gypsum Wall Board	£28.04	0.00	64 m²	0.00 m³	£1807.19	
First Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£24.56		67 m²	1.47 m³	£1645.14	
First Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£7.79		67 m²	15.07 m³	£521.81	
B1010375: 6					397 m²	33.09 m³	£7951.64	
	Basic Roof: Cold Roof - Timber	Wood	£0.00	0.00	90 m²	2.26 m³	£0.00	
	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter	£12.49	0.00	90 m²	13.56 m³	£1128.93	
	Basic Roof: Cold Roof - Timber	Roofing, Tile	£66.01	0.00	90 m²	3.43 m³	£5966.45	
	Basic Roof: Cold Roof - Timber	Roofing Felt	£5.83	0.00	90 m²	0.00 m³	£526.96	
Loft	Floor: Roof Ceiling Joist	Structure, Timber Joist/Rafter Layer	£7.79		67 m²	6.70 m³	£521.81	
B1020400: 5					429 m²	25.95 m³	£8144.15	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		54 m²	11.43 m³	£4712.52	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		54 m²	1.08 m³	£580.77	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		42 m²	9.11 m³	£3709.69	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		42 m²	0.85 m³	£456.14	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		49 m²	10.34 m³	£4267.18	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		49 m²	0.98 m³	£525.98	
	Basic Wall: Ext - 215 - Brick	Brick, Common	£87.59		39 m²	8.43 m³	£3433.69	
	Basic Wall: Ext - 215 - Brick	Plaster	£10.77		39 m²	0.78 m³	£422.20	
B2010100: 8					368 m²	42.98 m³	£18108.17	

Figure 7.40 Partial Sample of Material Take-off Function in BIM systems

Despite the 'material take-off' function in a BIM software, the quantity surveyor is still responsible for cost planning and estimation of refurbishment designs because any BIM software or tools cannot automatically detect conflicts or faults on the model such the overlapping places between house elements. For the demonstration purpose, the loft insulation is applied as seen in Figure 7.41. Thus, it is inevitable that other tools and software like MS Excel, COBie need to be involved with the BIM tools to generate reliable information of relevant costs and CO_2 in a standardised format/template (Crotty, 2011).

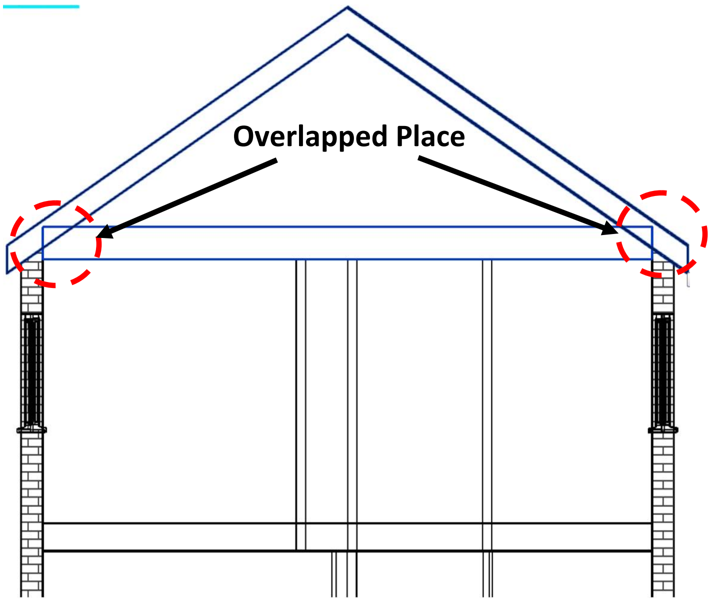


Figure 7.41 Overlapping of Refurbishment Material at the Loft Insulation

It is recommended and has been proven effective and efficient that data in a spread sheet are easily imported and exported to most BIM tools to complete the data sets for a model (See Section 4.5.2) Once the datasets are given in materials' area (m^2) and volume (m^3), they can be manipulated by quantity surveyors to generate reliable insulation material quantity and construction cost and embodied CO_2 using a spread sheet. As shown in Figure 7.42, MS Excel, used in conjunction with BIM software, provides an example of LCC and LCA study in a spread sheet during Stage R2-2. This result is developed from the Figure 7.42 where the information of embodied CO_2 is empty.

NRM Code	Element	Assembly Code from Revit (SMM7)	Level	Family	Family and Type	Material: Name	Material: Cost (Material Cost + Labor Cost)	Material: Embodied CO2 (Cost)	Material: Area	Material: Volume	Construction Embodied CO2	Total Cost	Total Embodied CO2
1	Substructure												
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	24.56	0.54	67	1.47	2.42	£ 1,645.52	162.9338
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer, 75x225	8.78	0.71	67	15.07	3.045	£ 588.26	214.7147
						Floor member 200 & 250 median			134	16.54		£ 2,233.78	377.6485
2	Superstructure												
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	24.56	0.54	67	1.47	2.42	£ 1,645.52	162.9338
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	8.78	0.71	67	15.07	3.045	£ 588.26	214.7147
2.2.1	Upper Floor	B1010375	Ground Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	28.04	0.38	65	0.78	29.044	£ 1,822.60	1888.1564
2.2.1	Upper Floor	B1010375	First Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	28.04	0.38	65	0.78	29.044	£ 1,822.60	1888.1564
									263	16.54		£ 5,878.98	4153.9613
						SMM7 Pitched roof members including ceiling joist	Revit does not include celing joist and Carbon book also does not include						
2.3.1	Roof Structure	B1020400	Loft	Floor	Floor: Roof Ceiling Joist	Structure, Timber Joist/Rafter Layer 100x150		0.71	67	6.7	4.058	£ -	276.643
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Wood Strutt 50x150	6.61	0.71	90	2.26	2.184	£ 594.90	198.1646
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter Layer	12.49	0.71	90	13.56	4.058	£ 1,124.10	374.8476
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing, Tile 65mm lap 100mm gauge	£ 58.40	0.45	90	3.43	37.56	£ 5,256.00	3381.9435
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing Felt	6.83	0.41	90	0	5.22	£ 614.70	469.8
									429	25.95		£ 7,589.70	4701.3987
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common cement mortar 1:3	87.59	0.23	54	11.43	98.017	£ 4,729.86	5295.5469
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	54	1.08	3.29	£ 581.58	177.7896
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	87.59	0.23	42	9.11	98.017	£ 3,678.78	4118.8093
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	10.77	0.12	42	0.85	3.29	£ 452.34	138.282
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	87.59	0.23	49	10.34	98.017	£ 4,291.91	4805.2112
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	10.77	0.12	49	0.98	3.29	£ 527.73	161.3276
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	39	8.43	98.017	£ 3,416.01	3824.6019
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	10.77	0.12	39	0.78	3.29	£ 420.03	128.4036
									184	42.98		£ 18,098.24	18649.9721

Figure 7.42 Partial LCC and LCA (cradle to site) study information using Excel (Appendix 8)

Once the required dataset is prepared and assigned to a BIM object, there is another limitation of BIM. This is in the generation of LCC and LCA (Cradle to Site) information in an adequate manner.

The information on costs and CO_2 of construction materials has different classification systems and they are categorised by unclassified coding systems as shown in Table 53.

Table 53. Unstandardised Coding System among Different Data Sources

Coding System	**Building Element and Construction Materials**				Reference
	Roof - Pitched Roof, Timber	Roof - Insulation, Fibre Glass	Lowest Floor - Suspended Timber Floor	Lowest Floor - Wood Chipboard	
NRM 1	2.3.1	2.3.1	1.1.3	1.1.3	NRM
Assembly Code	B1020400	B1020400	B1010375	B1010375	Autodesk Revit
SMM7 (Materials Costs)	G20055	3015103A	G20052	K20002	SMM7
SMM6 (Embodied CO_2 for Construction Works)	G202911S	PA003	G202102F	K111308D	Black Book
None (Embodied CO_2 for Raw Material)	None	None	None	None	University of Bath

Not all building elements are classified under the same code and the general code of buildings components are currently changing from SMM7 to NRM. A standardised data format/template in the shared classification should make the datasets of a Housing Information Modelling more reliable and efficient in calculating the bill of quantity and generating a cost management plan. Thus, construction professional organizations such as the NBS, which provide or plan to provide open BIM objects library, should take into consideration a standardised coding system for further BIM object development.

A triple-glazed window is essential to achieve the FEES for the maximum CO_2 reduction and energy efficiency according to government mandates (See Table 50 in Section 7.4.4.1). However, insufficient data about costs (material and labour costs) and CO_2 impacts (embodied CO_2 and CO_2 associated with construction works) for the triple-glazed window are not available in any one of the data sources listed in the Table 52. At present, the only information that can be obtained is from the manufacturers or special traders. As a result, the information on cost and CO_2 impact can vary between suppliers. In this research, the costs and embodied CO_2 are calculated by using a simple calculation based on the costs and embodied CO_2 using SMM7 and the Black Book. More detail on this is provided in subsubsection 7.4.5.1.

The second output is the gbXML HIM Model. Upon approval of the refurbishment design alternatives, a gbXML, which is a type of data format developed for energy simulation, should be provided through Housing Information Modelling to perform energy simulation for each refurbishment design alternative during stage R2-2

The third output is the Customer's Approval. Once the LCC analysis of refurbishment design alternatives has been performed, the construction cost and energy saving should be agreed and approved by the customer. If customers are not satisfied with the construction costs and energy saving, construction professionals need to revise the proposed designs based on customers' feedback.

7.4.5 Design Phase – The Stage R3: Perform Energy Simulation

This stage focuses on formulating LCC and LCA (Cradle to Grave) studies to identify the most economical and eco-friendly refurbishment design among the various refurbishment alternatives. Figure 7.43 illustrates the detailed information in Stage R3; with this stage further decomposed in Figure 7.44.

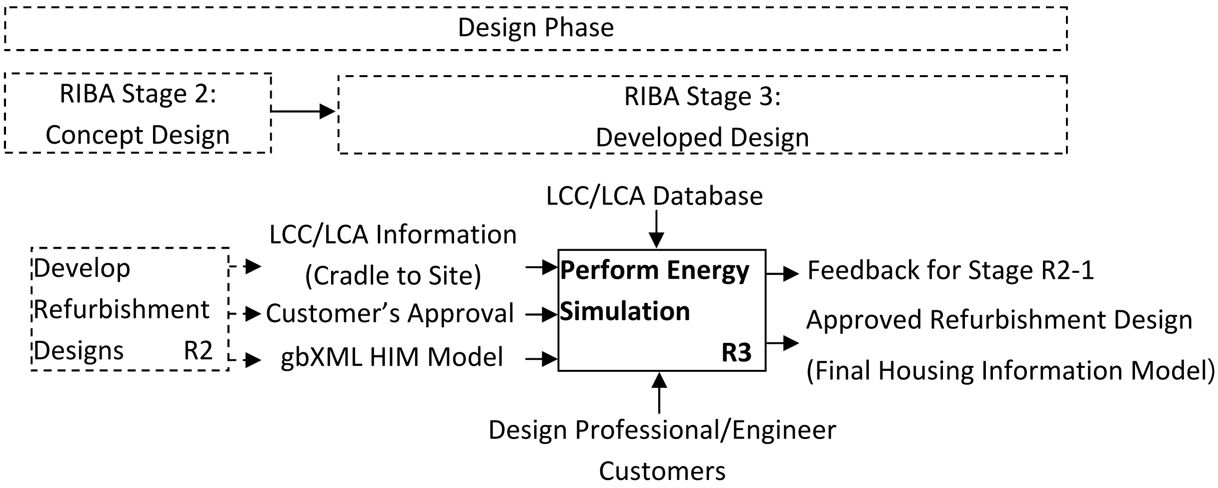


Figure 7.43 Stage R3

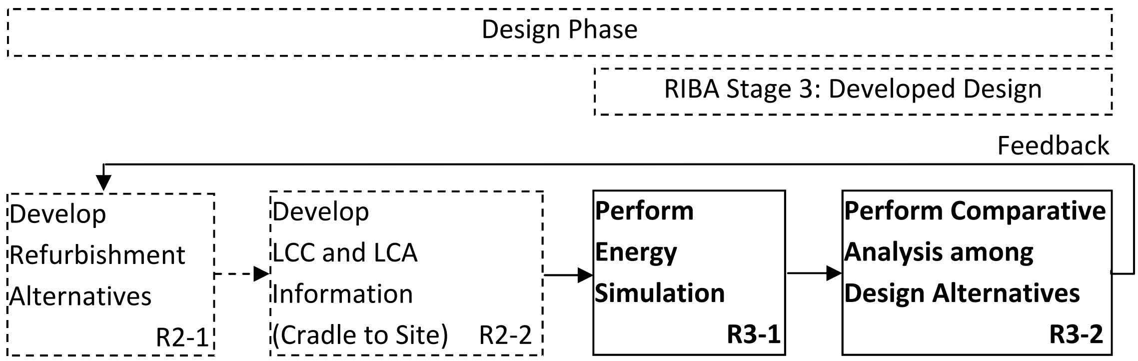


Figure 7.44 Sub-processes of Stage R3

Further details about each sub-process will be provided in the following subsubsections.

7.4.5.1 The Stage R3-1: Perform Energy Simulation

The detailed information about Stage R3-1 is described as shown in Figure 7.45.

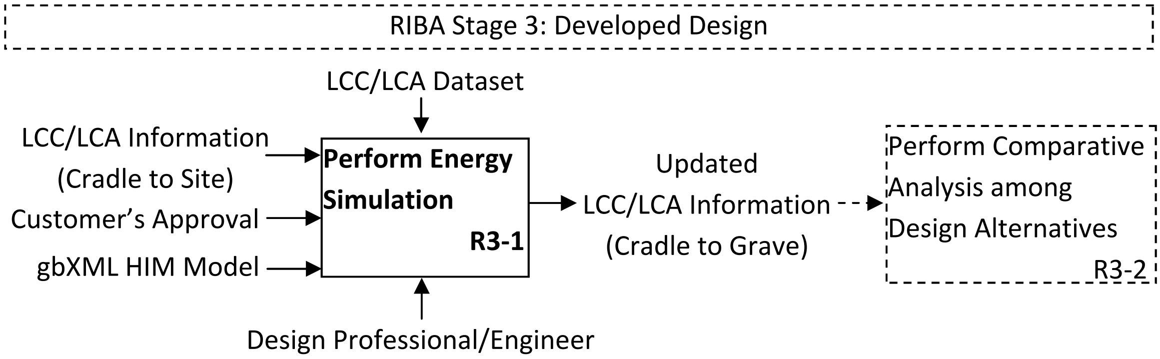


Figure 7.45 Stage R3-1

The key objective of this stage is to achieve the results of the LCC and LCA studies (Cradle to Grave) through an energy simulation for each refurbishment design alternative from Stage R2-1. In order to calculate the Cradle to Grave result, it is critical to generate the expected energy performance data for a refurbished house because the operational energy costs and CO_2 performance need to be added to the construction costs and embodied CO_2 calculated at the previous Stage R2-2. The final refurbishment design will be determined at this stage, based on the LCC and LCA study analysis through the entire life cycle of a house.

Once the gbXML model (generated at stage R2-2) is imported, the energy simulation software – IES VE/IMPACT – is able to perform energy simulation and generate the LCC and LCA (Cradle to Grave) information for the comparative analysis.

However, the current study found that there is no universal format. For example, the IFC format cannot be exchanged between different BIM software to share information as shown in Figure 7.46. The geometric arrangement is broken when IFC data is transferred to another BIM software, IES VE/IMPACT in this case. All the geometric information is not presented in the same way although the IFC data format is supposed to be a communication channel between different BIM software. However, the gbXML transferred all the essential geometric information as it was built at Stage R2-1.

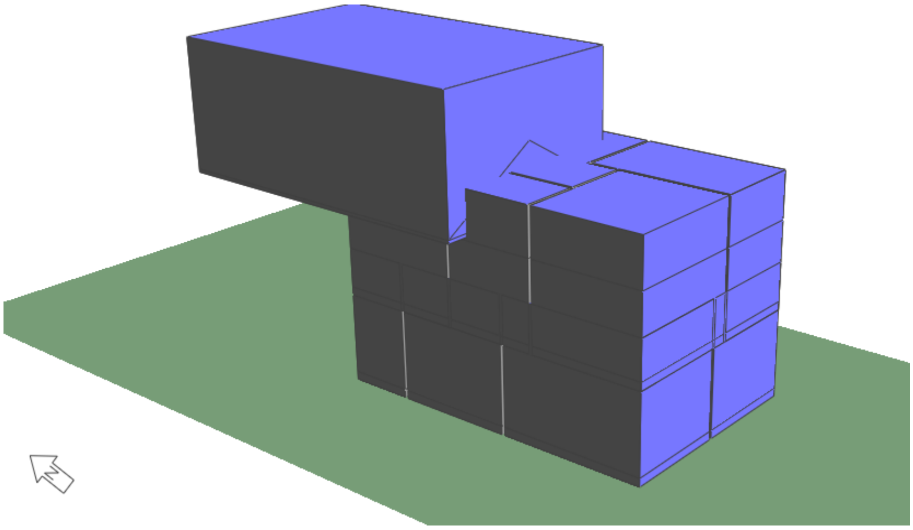


Figure 7.46 IFC Import Result, Sample Detached Solid Wall House

Interoperability between different BIM software is a critical technical barrier (See subsection 4.5.2), yet the interoperability issues are still not resolved although the concept of IFC and gbXML data formats within BIM system should exchange necessary data without any conflicts. Thus, the gbXML file format instead of IFC format was used in this research.

When energy performance simulation is performed by IMPACT other limitations should be taken into account in producing the LCC and LCA (Cradle to Grave) datasets: a) Insulation Material Data Loss and b) an unstandardised Construction Materials Dataset.

a) Insulation Material Data Loss: Through the previous stages, refurbishment design alternatives are reflected in the Housing Information Model developed in Revit, and the updated HIM is imported into IES VE/IMPACT in the gbXML format. It is found that only the geometric information in the gbXML file is transferred and other information regarding insulation materials is not. The missing information about the insulation materials needs to be manually entered and reviewed in IES VE/IMPACT. As a demonstration purpose, the loft, floor and external wall insulation were used for testing data loss as shown in Figure 7.47, 7.48 and 7.49. As a result, it was confirmed that the data loss is not only limited to a certain house elements.

The fibre glass (loft insulation) and wood (flooring) were put into Autodesk Revit as shown in Figure 7.47, and then this model was exported to the IES VE/IMPACT, but only the geometric information was successfully imported. IMPACT did not recognise the materials used, only referring to them as concrete and insulation material - see Figure 7.50 and 7.51.

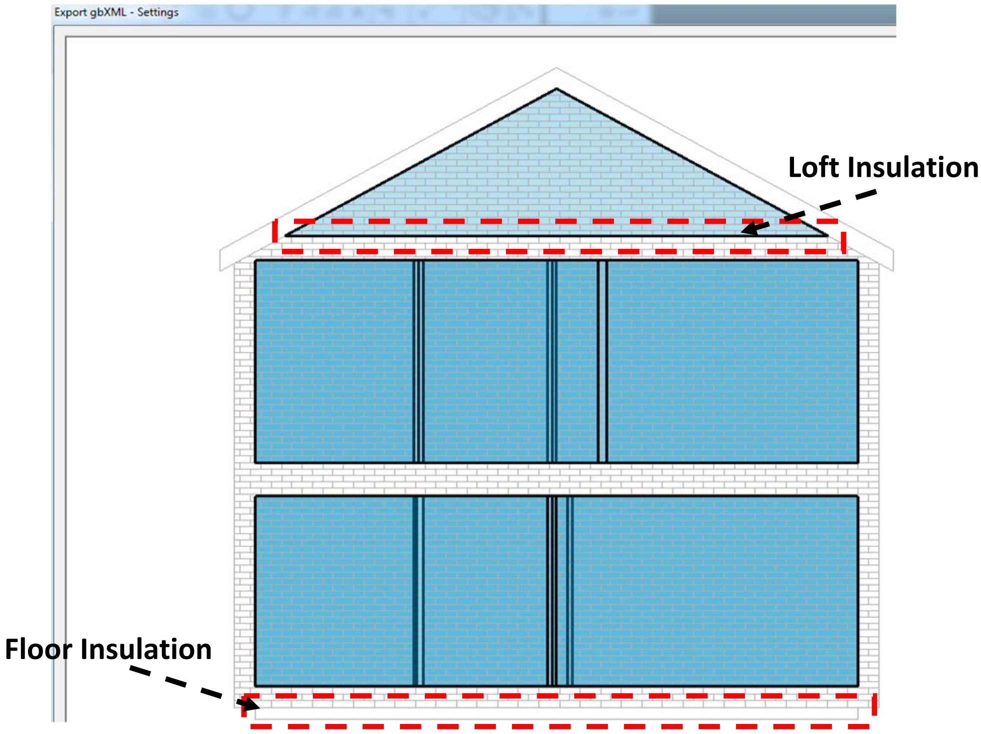


Figure 7.47 gbXML Model with Loft and Floor Insulation

The external wall insulation was also examined as shown in Figure 7.48.

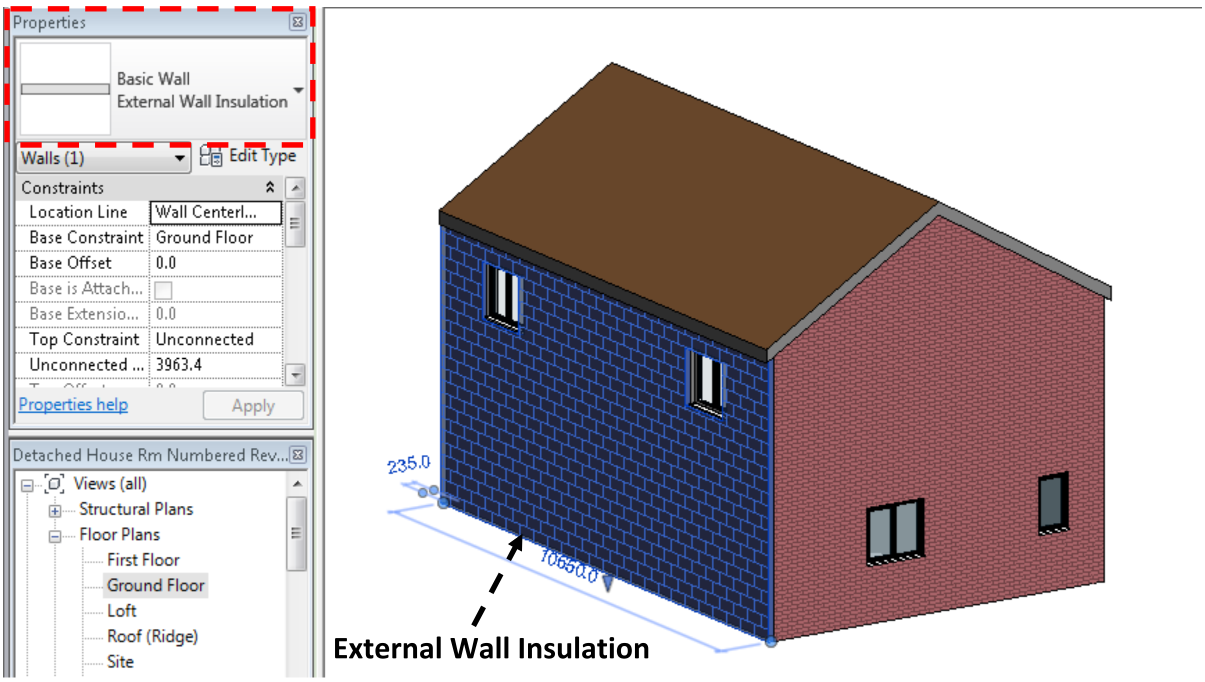


Figure 7.48 BIM (Revit) Model with External Wall Insulation

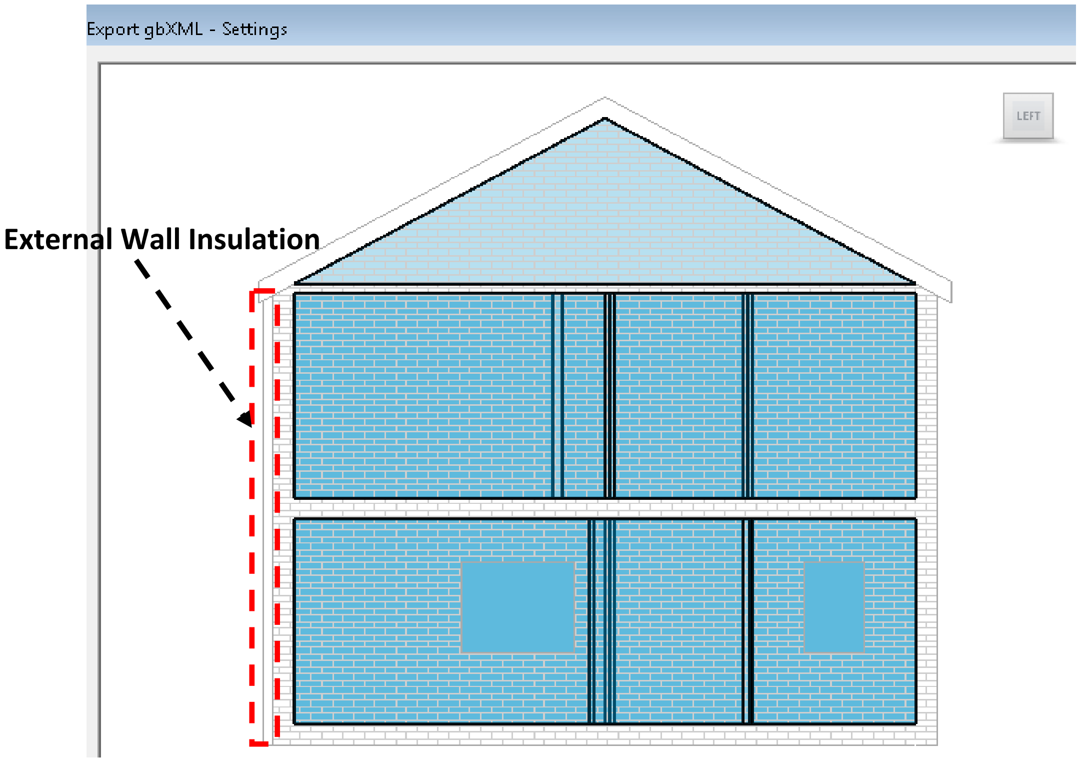


Figure 7.49 gbXML Model with External Wall Insulation

Although the geometric information is successfully imported, the insulation materials applied to the loft and floor have not been imported as shown in Figure 7.50 and 7.51. In the IES IMPACT recognised the materials as concrete and insulation material was not presented.

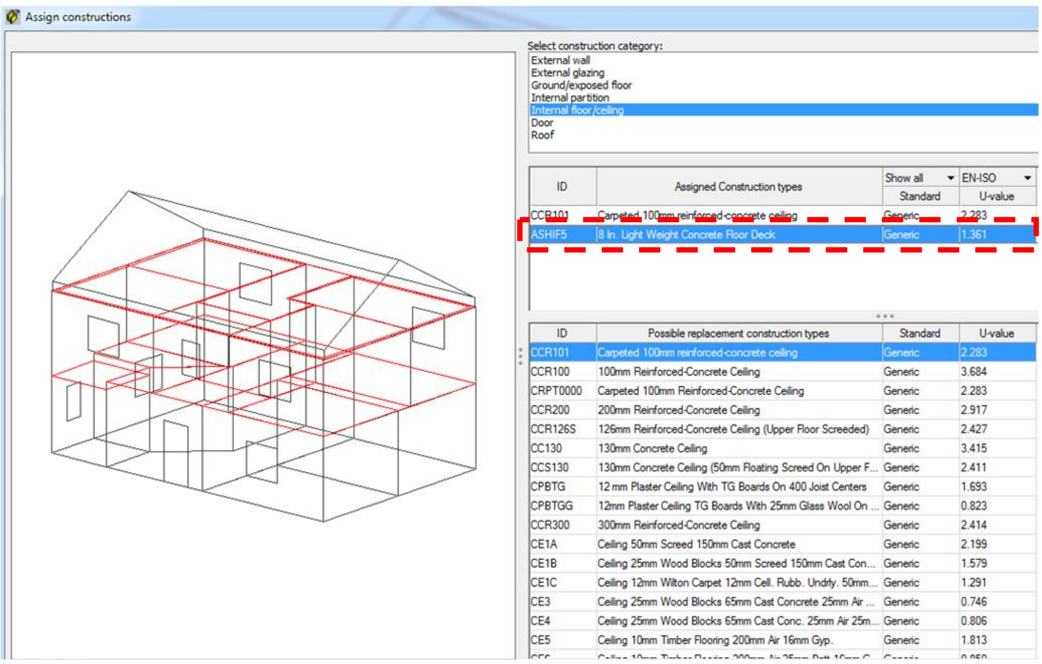


Figure 7.50 Imported gbXML Model with Loft Insulation in the IES VE/IMPACT

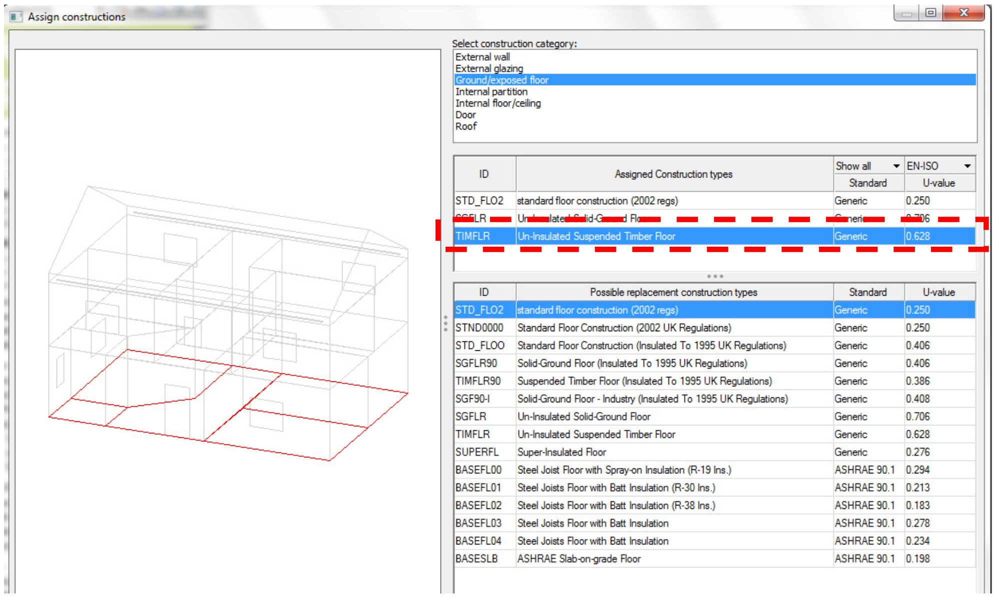


Figure 7.51 Imported gbXML Model with Floor Insulation in IES VE/IMPACT

As shown in Figure 7.51, the gbXML file has the insulation material information in the model, however, when the file imported into IMPACT, the insulation data has been lost as shown in Figure 7.52 and 7.53.

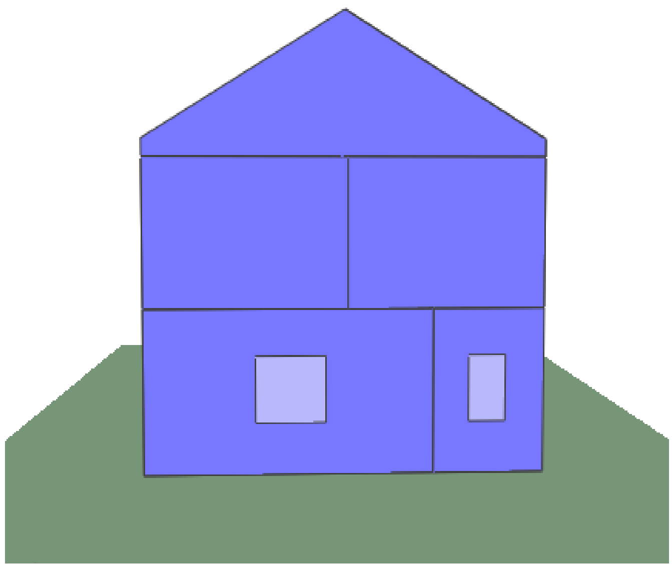


Figure 7.52 Imported gbXML Model with External Wall Insulation in IMPACT

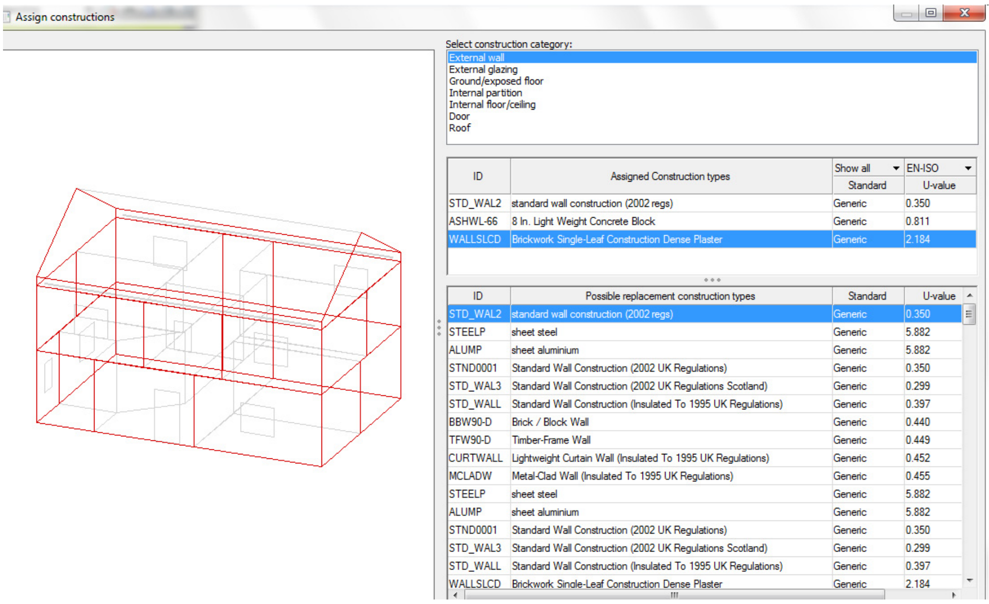


Figure 7.53 Imported gbXML Model with External Wall Insulation in IES VE/IMPACT

The lack of interoperability may limit the collaborative works between BIM software and project key project stakeholders. This research shows that entering information between different software and reviewing transferred information is inevitable.

b) Unstandardised Construction Materials Dataset: The costs and CO_2 information of BIM objects should be created in a standardised format in both BIM software (Revit) and LCC/LCA software (IES VE/IMPACT). However, the Revit has its own generic material database provided by third parties, and IES VE/IMPACT also has its own dataset and data format based on the green guide to specification developed by the BRE. Once all the essential information is manually entered in BIM objects, a review the information of cost and CO_2 if both pieces of software have the same information. Figure 7.54 shows the LCC cannot be currently calculated from the generic construction material database while Figure 7.55 shows the LCC can be calculated from the IES VE/IMPACT database. Loft insulation was taken as an example to demonstrate this.

ID2	ID3	Element	CM	Code	Rate	Quantity	Lifecycle total £
2.2.1		Upper floors (UF)		121			
		8 In. Light Weight Concrete Floor Deck [ASHIF5]	A	6	0.00	142	0.00
2.3.1		Roof structure		122			
		4 In. Light Weight Concrete [ASHRF28]	A	6	0.00	82	0.00
2.4		Stairs and ramps (STR)	A	2	950.00	0	0.00
2.5		External walls (EWAL)		124			
		8 In. Light Weight Concrete Block [ASHWL-66]	A	6	0.00	183	0.00
2.6.1		External windows		126			
		Large Double-Glazed Windows (Reflective Coating) - Industry [DGL-...	A	6	0.00	9	0.00
2.6.2		External doors	A	43	1,000.00	1	2,700.00

Figure 7.54 LCC outcome of Generic Construction Material Database

ID2	ID3	Element	CM	Code	Rate	Quantity	Lifecycle total £
2.2.1		Upper floors (UF)		121			
		8 In. Light Weight Concrete Floor Deck [ASHIF5]	A	6	0.00	142	0.00
2.3.1		Roof structure		122			
		Timber trussed rafters and joists with insulation; roofing underlay; counterbat...	A	6	130.00	82	16,203.20
2.4		Stairs and ramps (STR)	A	2	950.00	0	0.00
2.5		External walls (EWAL)		124			
		8 In. Light Weight Concrete Block [ASHWL-66]	A	6	0.00	183	0.00
2.6.1		External windows		126			
		Large Double-Glazed Windows (Reflective Coating) - Industry [DGL-R-I]	A	6	0.00	9	0.00
2.6.2		External doors	A	43	1,000...	1	2,700.00

Figure 7.55 LCC outcome of IMPACT Construction Material Database

The requirement of standardisation for the LCC analysis is applied to the LCA analysis. The latter's output can be achieved by IMPACT but not by BIM software - see Figures 7.56 and 7.57.

ID2	ID3	Element	Code	Quant	Units	Product	Constrn	Use (B1-7)	EoL (C1-4)	Ecopts	kgCO2
2.2		Upper floors (UF)	121		m²	0	0	0	0	0	0
		[ASHIF5] 8 In. Light Weight Concr...	6	142.0	m²	0	0	0	0	0	0
2.4		Stairs and ramps (STR)	139		m²	0	0	0	0	0	0
2.1		Frame	135		m²	0	0	0	0	0	0
2.3		Roof (ROO)	122		m²	0	0	0	0	0	0
		[ASHRF28] 4 In. Light Weight Con...	6	82.0	m²	0	0	0	0	0	0
2.5		External walls (EWAL)	124		m²	0	0	0	0	0	0
		[ASHWL-66] 8 In. Light Weight Co...	6	183.1	m²	0	0	0	0	0	0

Figure 7.56 LCA outcome of Generic Construction Material Database

ID2	ID3	Element	Code	Quant	Units	Product	Constrn	Use (B1-7)	EoL (C1-4)	Ecopts	kgCO2
2.2		Upper floors (UF)	121		m²	0	0	0	0	0	0
		[ASHIF5] 8 In. Light Weight Concr...	6	142.0	m²	0	0	0	0	0	0
2.4		Stairs and ramps (STR)	139		m²	0	0	0	0	0	0
2.1		Frame	135		m²	0	0	0	0	0	0
2.3		Roof (ROO)	122		m²	0	0	0	0	0	0
		[GGOP624] Timber trussed rafter...	6	82.0	m²	21	0.68	20	6.7	47	7000
2.5		External walls (EWAL)	124		m²	0	0	0	0	0	0
		[ASHWL-66] 8 In. Light Weight Co...	6	183.1	m²	0	0	0	0	0	0

Figure 7.57 LCA outcome of IMPACT Construction Material Database

Although there are issues regarding interoperability and dataset, IES VE/IMPACT's energy simulation can calculate the total amount of CO_2 emission and energy costs (Electricity and Gas) as shown in Figure 7.58 and Figure 7.59.

Carbon Dioxide

Month	System (boilers, chillers, fans,pumps)	Lights	Equip.
A-Z	Hi/Lo	Hi/Lo	Hi/Lo
Jan	595.5	217.1	208.3
Feb	437.2	196.1	188.1
Mar	411.5	217.1	208.3
Apr	389.7	210.1	201.6
May	401.5	217.1	208.3
Jun	499.0	210.1	201.6
Jul	527.8	217.1	208.3
Aug	531.6	217.1	208.3
Sep	427.1	210.1	201.6
Oct	404.3	217.1	208.3
Nov	449.5	210.1	201.6
Dec	558.4	217.1	208.3
Total	5,633.2	2,556.4	2,452.4

Summary

kgCO2

The maximum value in each column is highlighted in red. The minimum value in each column is highlighted in blue. More than one value may be highlighted

Total carbon dioxide emissions = 10,642.0kgCO2

Figure 7.58 Total CO_2 emission calculation per a year calculated by IES VE/IMPACT

Cost Analysis

Utility Type	Supplier	Tariff Description	Flat Rate	Tariff Units	Cost of Proposed	Cost of Baseline
Electricity	Electricity Commerc	Commercial Unrestricted Tariff (£ G		£/kWh	172.1	
Gas	Gas Commercial Su	Commercial Standard Tariff A (£ GE		£/kWh	294.23	
Oil	Oil Commercial Sup	Commercial Standard Tariff (£ GBP		£/l	0	
Coal	Coal Commercial Su	Commercial Standard Tariff (£ GBP		£/T	0	
Miscellaneous	Electricity Commerc	Commercial Unrestricted Tariff (£ G		£/kWh	0	
Renewable	Electricity Supplier1	Sell price for excess electricity		£/kWh	0	
				Total(£)...	466.33	0

Figure 7.59 Total Energy Costs (Electricity and Gas) per a year calculated by IES VE/IMPACT

Thus, in order to resolve the current issues and formulate LCC and LCA data, manual calculation using MS Excel generated from the previous LCC and LCA study at R2-2, in conjunction with the various data sources (See subchapter 7.3), is needed. In addition, an update is required using the information regarding LCC and LCA provided by the IMPACT database (Table 56). As a result, the total construction cost and embodied CO_2 (Figure 7.60) and total LCC (Figure 7.61) for 60 years are calculated as shown in Figure 7.60 and Figure 7.61 by incorporating the energy simulation results (Appendix 8, 9, 10). Further discussion about LCC and LCA is provided in the Section 7.5.

NRM Code	Element	Assembly Code from Revit (SMM7)	Level	Family	Family and Type	Material: Name	Material: Cost (Material Cost + Labor Cost)	Material: Embodied CO2 (Cost)	Material: Area	Material: Volume	Construction Embodied CO2	Total Cost	Total Embodied CO2
1	Substructure					Floor member 200 & 250 median for cost							
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	67	1.47	2.42	£ 1,645.52	162.9338
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer, 75x225	£ 8.78	0.71	67	15.07	3.045	£ 588.26	214.7147
												£ 2,233.78	377.6485
2	Superstructure												
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	67	1.47	2.42	£ 1,645.52	162.9338
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£ 8.78	0.71	67	15.07	3.045	£ 588.26	214.7147
2.2.1	Upper Floor	B1010375	Ground Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	65	0.78	29.044	£ 1,822.60	1888.1564
2.2.1	Upper Floor	B1010375	First Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	65	0.78	29.044	£ 1,822.60	1888.1564
					Fibre Glass	145	£ 0.05	4.25	67	9.715	0.25	£ 510.04	2494.3263
					EPS	120	£ 0.20	12	67	8.04	0.33	£ 1,588.70	2781.5366
												£ 5,878.98	4153.9613
						SMM7 Pitched roof members including ceiling joist, Revit does not include celing joist and Carbon book also does not include							
2.3.1	Roof Structure	B1020400	Loft	Floor	Floor: Roof Ceiling Joist	Structure, Timber Joist/Rafter Layer 100x150		0.71	67	6.7	4.058	£ -	276.643
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Wood Strutt 50x150	£ 6.61	0.71	90	2.26	2.184	£ 594.90	198.1646
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter Layer	£ 12.49	0.71	90	13.56	4.058	£ 1,124.10	374.8476
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing, Tile 65mm lap 100mm gauge	£ 58.40	0.45	90	3.43	37.56	£ 5,256.00	3381.9435
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing Felt	£ 6.83	0.41	90	0	5.22	£ 614.70	469.8
					Fibre Glass	190	£ 0.05	4.25	67	12.73	0.25	£ 668.33	3268.4275
					EPS	155	£ 0.20	12	67	10.385	0.33	£ 2,052.08	3592.8181
												£ 7,589.70	4701.3987

Figure 7.60 Partial Construction Costs and Embodied CO_2 of a Detached House (Appendix 8)

	Construction Costs	Maintenance Costs						Opreation Costs		Occupancy Costs		End of life cost		
Year	Construction Costs	Major Repair Costs	Routine Maintenance Costs	Decorate Costs	Minor Repair Costs	Replace Costs	Reactive Repair Costs	Clean Costs	Energy Costs	Waste Treatment	Sewage	End of life cost	Total LCC	
0	£ 7,065.57												£ 7,065.57	
1			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N4
2			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N5
3			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N6
4			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N7
5			£ 1,362.40		£ 26.02		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,276.79	=N8
6			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N9
7			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N10
8			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N11
9			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N12
10		£ 14.48	£ 1,362.40		£ 26.02		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,291.26	=N13
11			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N14
12			£ 1,362.40	£ 2,825.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,916.25	=N15
13			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N16
14			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N17
15		£ 260.16	£ 1,362.40	£ 270.00	£ 26.02		£ 131.14	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,840.36	=N18
16			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N19
17			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N20
18			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N21
19			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N22
20		£ 14.48	£ 1,362.40	£ 2,555.76	£ 26.02		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 4,847.02	=N23
21			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N24
22			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N25
23			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N26
24			£ 1,362.40	£ 2,825.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,916.25	=N27
25			£ 1,362.40		£ 26.02		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,276.79	=N28
26			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N29
27			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N30
28			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N31
29			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N32
30		£ 321.42	£ 1,362.40	£ 270.00	£ 83.98	£ 3,772.26	£ 131.14	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 6,731.84	=N33
31			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N34
32			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N35
33			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N36
34			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N37
35		£ 102.01	£ 1,362.40		£ 236.27	£ 173.72	£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,762.78	=N38
36			£ 1,362.40	£ 2,825.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,916.25	=N39
37			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N40
38			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N41
39			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N42
40		£ 14.48	£ 1,362.40	£ 2,555.76	£ 59.43		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 4,880.44	=N43
41			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N44
42			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N45
43			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N46
44			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N47
45		£ 260.16	£ 1,362.40	£ 270.00	£ 26.02		£ 131.14	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,840.36	=N48
46			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N49
47			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N50
48			£ 1,362.40	£ 2,825.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,916.25	=N51
49			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N52
50		£ 304.28	£ 1,362.40		£ 26.02		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,581.06	=N53
51			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N54
52			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N55
53			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N56
54			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N57
55			£ 1,362.40		£ 26.02		£ 97.72	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 2,276.79	=N58
56			£ 1,362.40	£ 2,555.76				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 4,646.25	=N59
57			£ 1,362.40	£ 270.00				£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,360.49	=N60
58			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N61
59			£ 1,362.40					£ 180.36	£ 294.23	£ 156.00	£ 97.50		£ 2,090.49	=N62
60		£ 321.42	£ 1,362.40	£ 2,825.76	£ 83.98	£ 5,805.01	£ 131.14	£ 242.92	£ 294.23	£ 156.00	£ 97.50		£ 11,320.35	=N63
NPV	£ 7,065.57	£ 1,540.30	£ 65,101.04	£ 38,726.31	£ 635.61	£ 9,585.59	£ 1,241.53	£ 9,206.97	£ 14,059.51	£ 7,454.32	£ 4,658.95		£ 151,480.00	
	=B64												=NPV(A67,N4:N63)+B64	

0.78% =A67

Figure 7.61 LCC study (Cradle to Grave) applying BR 2010/2013 (Minimum) energy standard using fibre glass for a detached solid wall house.

7.4.5.2 The Stage R3-2: Perform Comparative Analysis among Design Alternatives

The purpose of this stage is to compare the refurbishment design alternatives based on the LCC and LCA information. Detailed information about Stage R3-2 is shown in Figure 7.62.

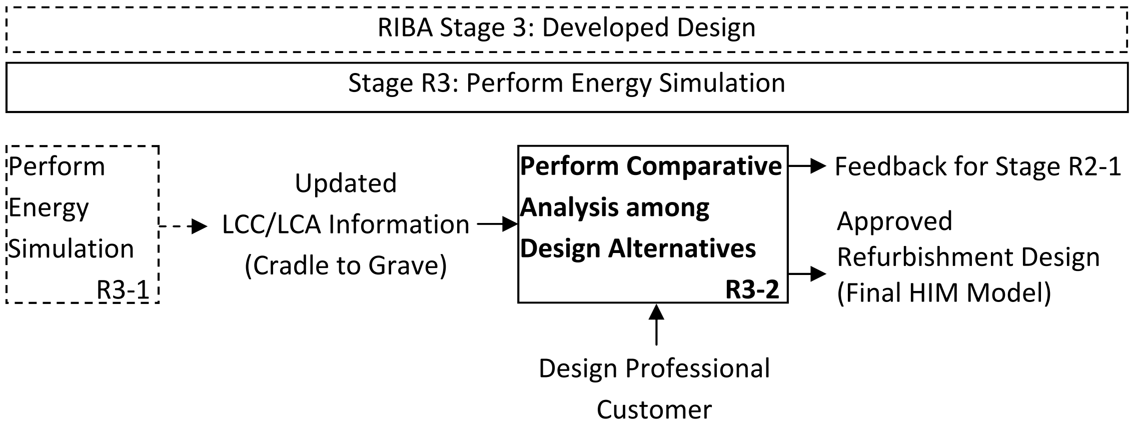


Figure 7.62 Stage 3-2

The comparative analysis at this stage produces the following outputs:

1. Feedback to Stage R2-1: Customers review the comparison of different refurbishment design alternatives, and communicate with the design professional. This feedback goes back to stage R2-1 to refine and redesign refurbishment alternatives in accordance with the customer's feedback until an approved refurbishment design is achieved.

2. Approved Refurbishment Design (Final HIM Model): The approved or revised refurbishment design is incorporated into a Housing Information Model. This model should have the information that requires careful attention when constructors handle insulation materials as stated at stage the R2-1. In order to secure the efficient information update flow, any updated information on the selected insulation materials and comparative analysis through the Stage R3 should be fed into the imported Housing Information Model in BIM software.

However, there is an issue related to the broken feedback loop of the HIM Model Updates between sub-processes R2-1 and R3-2 as shown in Figure 7.63.

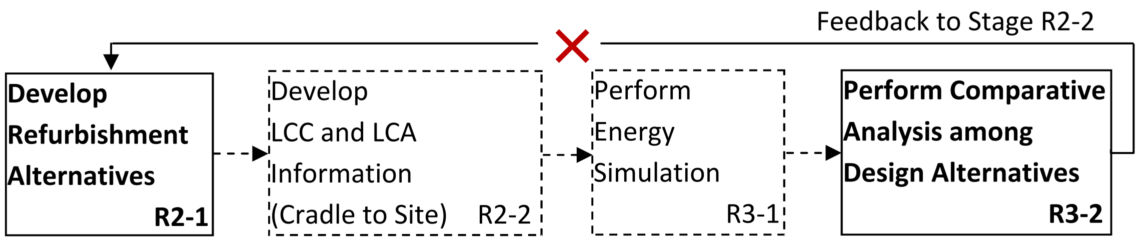


Figure 7.63 Broken Feedback Loop between sub-process R2-2 and R3-2.

Due to the different material datasets and interoperability problems between the different software packages, the feedback loop between BIM and the energy simulation software does not work efficiently. When the updated model with insulation material information is exported to BIM, it is presented as a simple symbol or picture with no parametric information of updated building elements as shown in Figures 7.64 and 7.65.

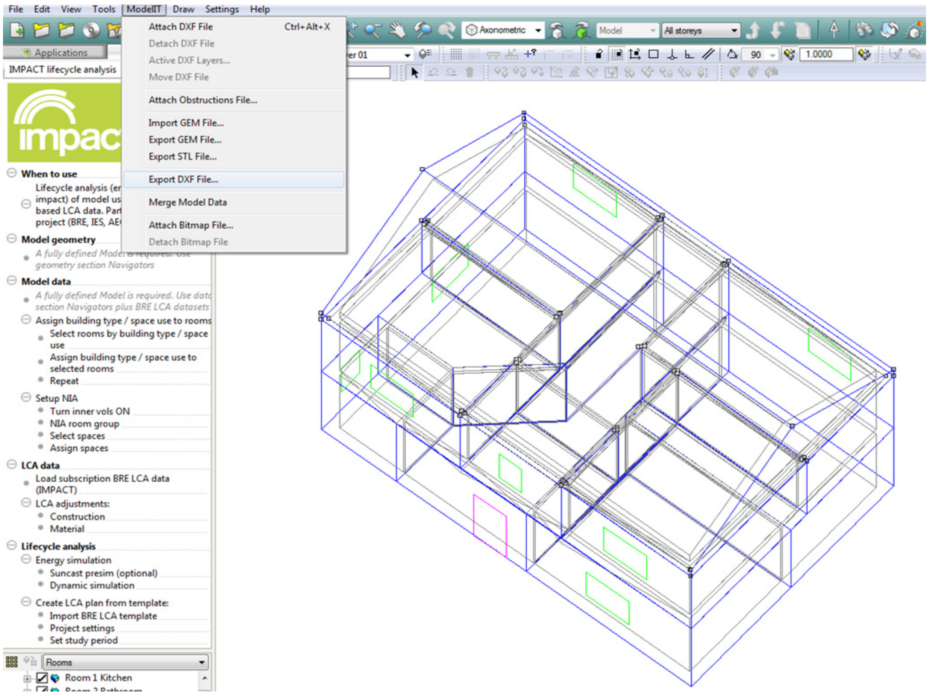


Figure 7.64 Export from IMPACT to Revit as DXF Data Format

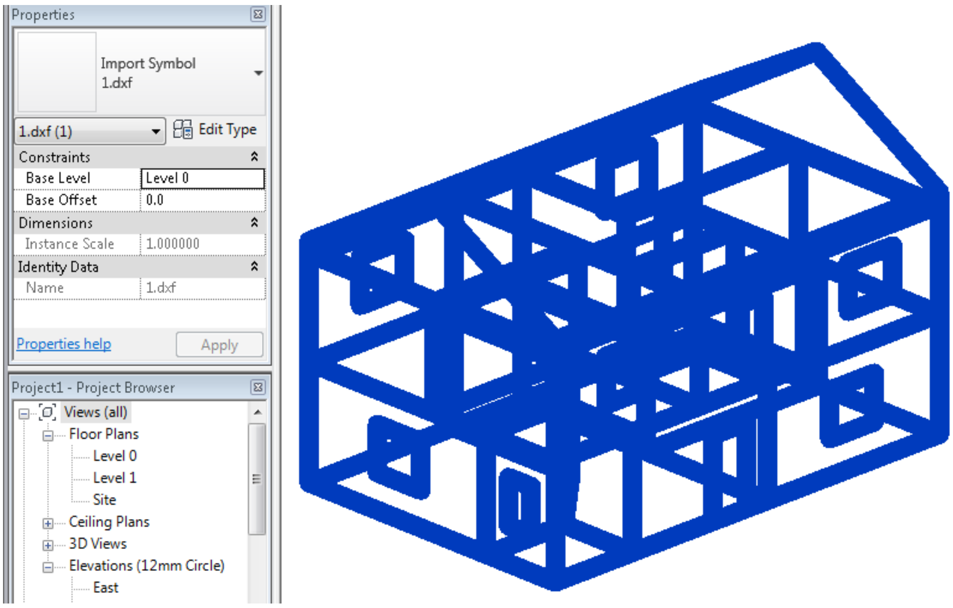


Figure 7.65 Result of Import the DXF Data Format in Revit

As a result, this broken feedback loop can cause unproductive reworks to update the BIM model. In order to achieve seamless collaboration and data exchanges, a BIM library with standardised material classification should be established. Currently, there is no definitive solution for this broken feedback loop between the different BIM software. Although it is challenging to fully utilize BIM for seamless feedback loops for design updates due to interoperability issues, this will eventually be resolved using the IFC data exchange format since many researchers are striving to develop a data exchange format using the IFC format (See Subsection 4.5.2).

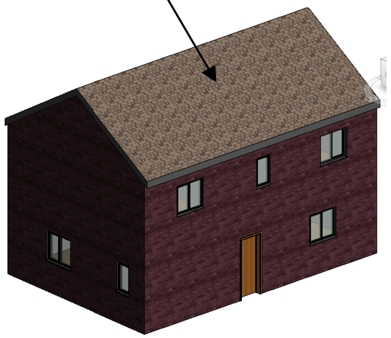
The outcomes of comparative analysis on different refurbishment materials and energy standards are as shown in Table 54. The following diagram presents the information flows through the design stage and project stakeholder involvements, and the final results of Stage R3-2: LCC and LCA Study (60 years) for detached, semi-detached/end terraced, and terraced houses are presented. The IES VE/IMPACT database settings of LCC and LCA study such as costs and life cycles are also provided.

Develop Refurbishment Alternatives Stage

Perform Energy Performance Simulation Stage

Constraint: Customer's Preferences → **Insulation Material Selection Criteria: Low Initial Cost and High Thermal Performance** → **Constraints (from External): a) Energy Standards, b) Building Regulation c) Risk Management, d) Material Specification**

Loft Insulation (Selected Measure from Stage R2)



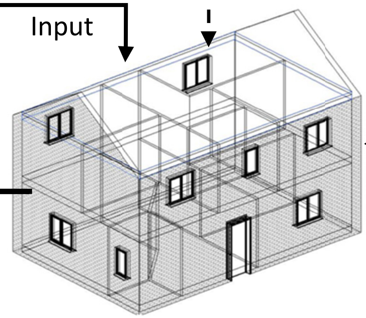
3D BIM Model

Input → Material Option 1- Fibre Glass:
Cost: £ 5.25/m^2
Thermal Performance (k=0.042)

Input → Material Option 2- EPS:
Cost: £ 9.88/m^2
Thermal Performance (k=0.035)

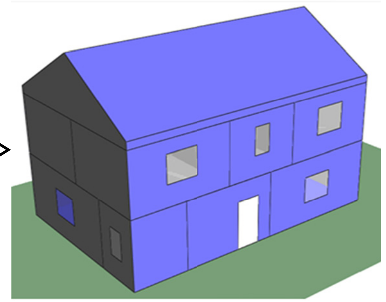
Option 1 and 2 Applied

Input



Updated 3D BIM Model

Feedback



Energy Performance Simulation Model

Output

Refurbishment Design Alternative 1 (Using Fibre Glass)

Refurbishment Design Alternative 2 (Using EPS)

Comparative Analysis →

Description		Energy Standards			
		BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Construction Cost	Alternative 1	**Customer's Approval, Selected Alternative (Assumed)**			
	Alternative 2	-	-	-	-
Energy Cost	Alternative 1	-	-	-	-
	Alternative 2	-	-	-	-
.....	.....	.....-	-.....	-.....	.....-

*** Detailed Information about Refurbishment Designs depending on different energy standards will be provided following pages in Table 54, 55 and 56.**
The comparative analysis will be provided in Subchapter 7.5.
The formula for LCC and LCA calculation is provided in Table 57.

Table 54. Final Result of Stage R3-2: LCC and LCA Study (60 years) for Whole-House Fabric Refurbishment – Detached House

Detached House			Current Basic Model	Energy Standards			
				BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Demand (KWh/yr/m^2)			209.8	52.5	44.8	41.5	39.3
CO_2 Emission (kg/yr/m^2)			84.5	43.4	41	41	41
Energy Demand (MWh/yr)			38.4	9.6	8.1	7.6	7.2
CO_2 Emission (kg/yr)			10,985	5,635.5	5,355.6	5,328.5	5,328.3
Energy Cost (£ /yr)			1,150	295	252.54	234.75	224.75
Life Cycle Cost (£)	Construction Cost	Fibre Glass	41,371.35	7,065.57	9,055.37	9,899.04	10,425.47
		EPS		12,004.63	15,690.73	18,419.59	19,917.36
	Operating Cost	Fibre Glass	205,359.48	144,414.43	146,069.73	145,829.16	145,938.91
		EPS		148,325.25	151,469.01	152,497.49	153,668.72
	Total Cost	Fibre Glass	246,730.83	151,480.0	155,125.10	155,728.2	156,364.38
		EPS		160,329.88	167,159.74	170,917.08	173,586.08
Life Cycle Assessment (kg)	Embodied CO_2 (Cradle to Site)	Fibre Glass	34,994.9	12,197.25	16,624.06	20,750.04	23,140.86
		EPS		13,505.52	18,336.66	23,114.4	25,689.4
	Total (Cradle to Grave)	Fibre Glass	45,979.9	17,832.75	21,979.66	26,078.54	28,469.16
		EPS		19,141.02	23,692.26	28,442.9	31,017.7

Table 55. Final Result of Stage R3-2: LCC and LCA Study (60 years) for Whole-House Fabric Refurbishment – Semi-Detached/End Terraced House

Semi-Detached/End Terraced			**Current Basic Model**	**Energy Standards**			
				BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Demand (kWh/yr/m^2)			274.3	66.3	54.8	48.7	45
CO_2 Emission (kg/yr/m^2)			105.1	46.7	43.7	42.5	41.7
Energy Demand (MWh/yr)			36	8.7	7.2	6.4	5.9
CO_2 Emission (kg/yr)			9,454.8	4,207.2	3,929.5	3,822.2	3,756.5
Energy Cost (£ /yr)			1,078.7	266.3	223.4	200	184.43
Life Cycle Cost (£)	Construction Cost	Fibre Glass	32,794.94	5,742.68	7,343.17	8,845.20	9,313.88
		EPS		9,666.66	12,633.56	15,626.69	16,950.57
	Operation Cost	Fibre Glass	197,053.94	141,081.55	141,917.82	143,575.71	143,344.72
		EPS		144,319.75	146,409.23	149,109.73	149,824.78
	Total Cost	Fibre Glass	229,848.88	146,824.23	149,261	152,420.9	152,658.6
		EPS		153,986.41	159,042.79	164,736.42	166,775.35
Life Cycle Assessment (kg)	Embodied CO_2 (Cradle to Site)	Fibre Glass	28,302.39	9,725.01	13,346.31	16,601.90	18,710.29
		EPS		10,771.70	14710.09	18,486.26	20,756.82
	Total (Cradle to Grave)	Fibre Glass	37,757.19	13,932.21	17275.81	20,424.1	22,466.79
		EPS		14,978.9	18639.59	22,308.46	24,513.32

Table 56. Final Result of Stage R3-2: LCC and LCA Study (60 years) for Whole-House Fabric Refurbishment – Terraced House

Terraced House			Current Basic Model	Energy Standards			
				BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Demand (kWh/yr/m²)			307.6	78.2	64.5	57.2	51.2
CO_2 Emission (kg/yr/m²)			112	48.6	45	43.4	42.2
Energy Demand (MWh/yr)			26.3	6.7	5.5	4.9	4.4
CO_2 Emission (kg/yr)			6,716.2	2,917.9	2,695.5	2,602.6	2,532.4
Energy Cost (£)			789.6	207.6	173.8	155.6	141.5
Life Cycle Cost (£)	Construction Cost	Fibre Glass	23,949.07	4,830.93	6,711.13	8,040.43	8,479.04
		EPS		7,773.90	10,696.91	13,133.80	14,279.80
	Operation Cost	Fibre Glass	178,400.73	138,054.12	139,428.08	141,225.9	141,044.1
		EPS		140,588.7	142,952.93	145,569.1	146,175.7
	Total Cost	Fibre Glass	202,349.8	142,885.05	146,139.22	149,266.33	149,523.16
		EPS		148,362.6	153,649.84	158,702.92	160,455.46
Life Cycle Assessment (kg)	Embodied CO_2 (Cradle to Site)	Fibre Glass	20,967.9	7,495.79	10,456.70	12,867.58	14,694.12
		EPS		8,286.12	11,483.02	14,285.32	16,245.98
	Total (Cradle to Grave)	Fibre Glass	27,684.1	10,413.69	13,152.2	15,470.18	17,226.52
		EPS		11,204.02	14,178.52	16,887.92	18,778.38

Table 57. LCC and LCA Study Rate and Cycle Provided by IES VE/IMPACT database

House Element	Major Repair Rate (% of Construction Cost)	Major Repair Cycle	Minor Repair Rate (% of Construction Cost)	Minor Repair Cycle	Reactive Repair Rate (% of Construction Cost)	Reactive Repair Cycle	Decorate Cost/m^2	Decorate Cycle	Replace Rate (% of Construction Cost)	Replace Cycle	Clean Cost/m^2	Clean Cycle	Operation Cost	Occupancy Cost (a)	Routine Maintenance Cost (b)
Upper floors	20%	35yrs							155%	65yrs					
Roof	7%	30yrs	5%	40yrs	5%	15yrs			70%	60yrs	£ 0.10				
External walls	25%	50yrs	5%	30yrs		5yrs	£ 4.63	4yrs	135%	60yrs	£ 0.34	5yrs			
Dense Plaster			11%	35yrs	2%	5yrs	£ 9.26	4yrs	130%		£ 0.69				
Windows	10%	15yrs	1%	5yrs	3%	5yrs	£ 7.50	3yrs	145%	30yrs	£ 5.01	1yrs			
External doors	10%	10yrs							120%	35yrs					

Occupancy Costs (a)			**Routine Maintenance Costs (b)**		
Description	Rate/m^2	Gross Internal Floor Area (GIFA)	Description	Rate/m^2	Gross Internal Floor Area (GIFA)
Waste treatment Cost	£ 1.20	____m^2	Annual Fabric Repair Cost	£ 5.63	____m^2
Sewage Cost	£ 0.75	____m^2	Annual Inspection Cost	£ 4.85	____m^2

7.5 Reliability Check for the Housing Information Modelling Framework

In order to examine the validity of the proposed framework, this research has performed a comparative analysis between a benchmarked refurbished house - detached solid wall house - by Energy Saving Trust (EST, 2009) and the hypothetical model used for this research.

Table 58. Comparative Analysis Table between EST House and Hypothetical House

Description	EST House (Floor Area: 104 m^2)		Hypothetical House (Floor Area: 130 m^2)	
	Pre-Refurbishment	Post-Refurbishment	Pre-Refurbishment	**Post-Refurbishment**
Roof U-value	2.30	0.10	2.30	**0.10**
Wall U-value	2.10	0.18	2.18	**0.18**
Floor U-value	0.74	0.15	0.70	**0.15**
Window U-value	4.80	1.50	4.83	**1.54**
Door U-value	3.00	1.00	3.03	**1.03**
Energy Demand for Heating (kWh/yr/m^2)	597	73 (89% Reduction)	209.8	**40.8 (80% Reduction)**
Energy Cost for Heating (£)	1,498	251 (83% Reduction)	1,150	**225 (80% Reduction)**
CO_2 Emission for Heating (kg/yr/m^2)	84.9	5.2 (94% Reduction)	84.5	**40.6 (52% Reduction)**

Table 58 shows that the reduction rates for energy demand for heating and energy cost for heating are similar. However, the amounts of CO_2 emission for heating are different because the EST house has included the hot water and secondary heating while hypothetical house has one heating source. Furthermore, the EST house also includes upgrade of services such as new boiler and mechanical ventilation and efficient lightings while this research only adopted the whole-house fabric refurbishment. As a result, a 42% difference is identified. In addition, the dataset for the EST house used SAP 2009 database whereas the hypothetical house used the IES VE/IMPACT dataset developed by BRE. This outcome calculated by the proposed framework renders similar results to the previous studies that whole-house fabric refurbishment can achieve about a 60% reduction of CO2 emission. Thus, the framework can be regarded as valid for housing refurbishment projects using BIM

7.6 Conclusion

A theoretical BIM framework for housing refurbishment – the Housing Information Modelling (HIM) framework – was developed by modifying standards and guidelines for BIM enabled construction project and housing refurbishment. The framework was developed by combining generic construction project processes and refurbishment specific processes based on the BIM standards. This research integrated essential project phases and processes for developing a housing refurbishment specific framework.

The framework was examined through a hypothetical housing refurbishment case study, it was revealed that BIM could be used for improving the energy efficiency of a house for its whole life cycle by formulating a refurbishment solution with comparing various refurbishment alternatives based on the LCC and LCA result. It was also revealed that there are limitations to fully utilize BIM such as a lack of standardised dataset of BIM object library, technical interoperability issues between different BIM software tools and a lack of LCC and LCA dataset for housing refurbishment.

The following chapter will present the analysis of the LCC and LCA results formulated by the framework in this chapter.

Chapter 8 Whole Life cycle Financial and Environmental Impacts Studies

8.1 Introduction

Using the three major housing types (detached House, semi-detached/end terrace and terrace), the relationship between LCC and LCA for refurbishment design alternatives is discussed in whole-house fabric refurbishment. The analysis uses different types of insulation materials: the fibre glass and EPS. For the LCC and LCA study a 60-year life cycle is applied with a net present value method (NPV) based on a discount rate (d) of 0.78%. Equation A (Flanagan and Jewell, 2005) shows the calculation of this discount rate with the interest rate (r) of 3.5% (HM Treasury, 2011) and the inflation rate (i) of 2.7% (ONS, 2014d).

$$\frac{(1+r)}{(1+i)} - 1 = d \text{ (Equation A)}$$

The NPV with the net discount rate were used as this is the most reliable method to consider the time value of money compared to other methods include the simple payback method and internal rate of return (Flanagan and Jewell, 2005). More detailed information about NPV calculation will be provided in Appendix 11 – Detached House, Appendix 12 – Semi-detached/End Terraced House, and Appendix 13 – Terraced House.

8.2 Detached House Refurbishment Result

8.2.1 Energy Efficiency and Financial Impact

When LCC is used as a decision-making criterion for refurbishment, it is important to compare the LCC of a refurbished building to an existing building. When the LCC of a refurbished building is lower than an existing building, it can be considered to be economically beneficial for customers to refurbish their homes (Gustafsson, 1992). Figure 8.1 indicates that all the LCC results of refurbishment with different energy standards are lower than the LCC of the existing house. Thus, it is economically beneficial to refurbish a detached solid-wall house to gain energy efficiencies.

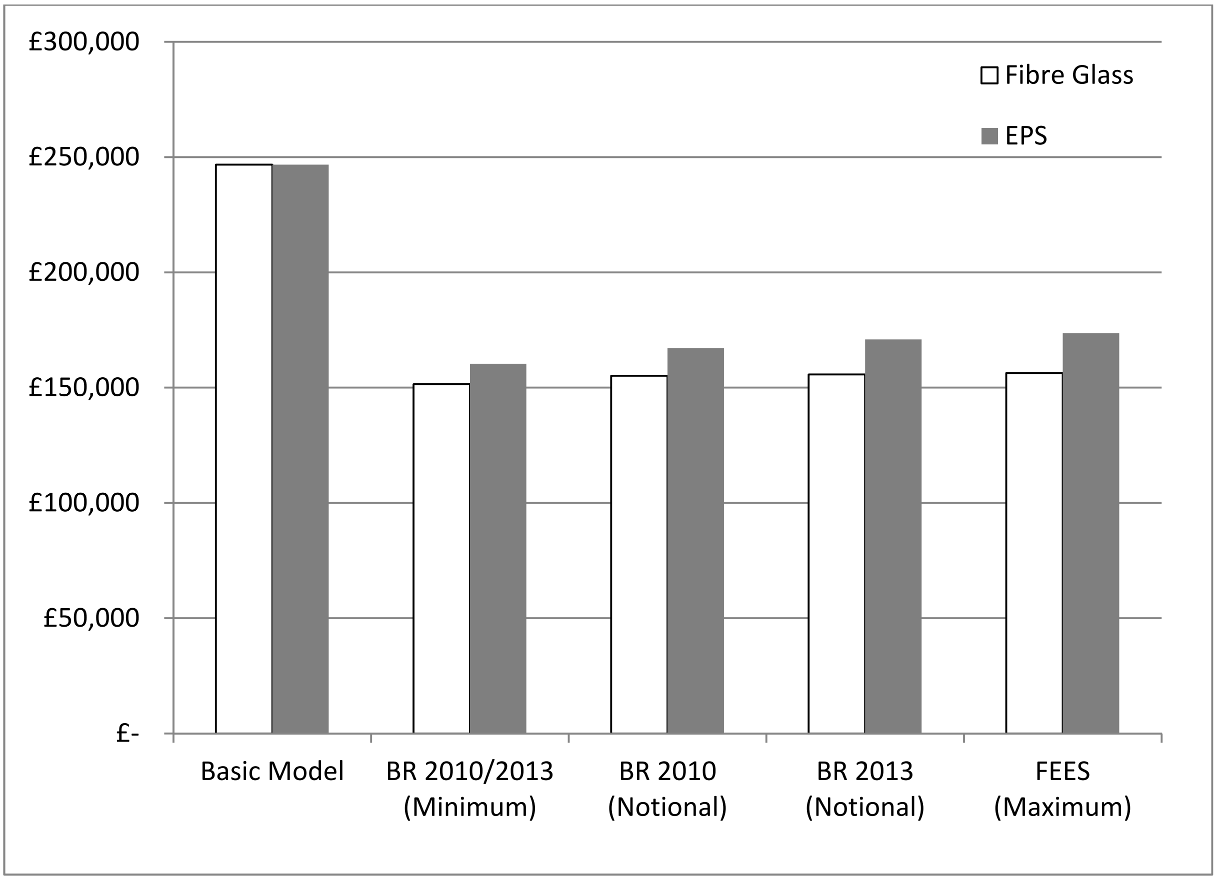


Figure 8.1 LCC Comparison between Existing House and Refurbished House

As shown in Figure 8.2, the LCC continues to increase as higher energy standards are adopted. There are differences in the LCC between using the fibre glass and the EPS because the initial material cost of fibre glass (£5.25/m^2) is less than the EPS (£9.88/m^2). This difference in material costs impacts on construction costs and operating costs such as major and minor repairs because operating costs are calculated as a percentage of the construction costs (see Table 56).

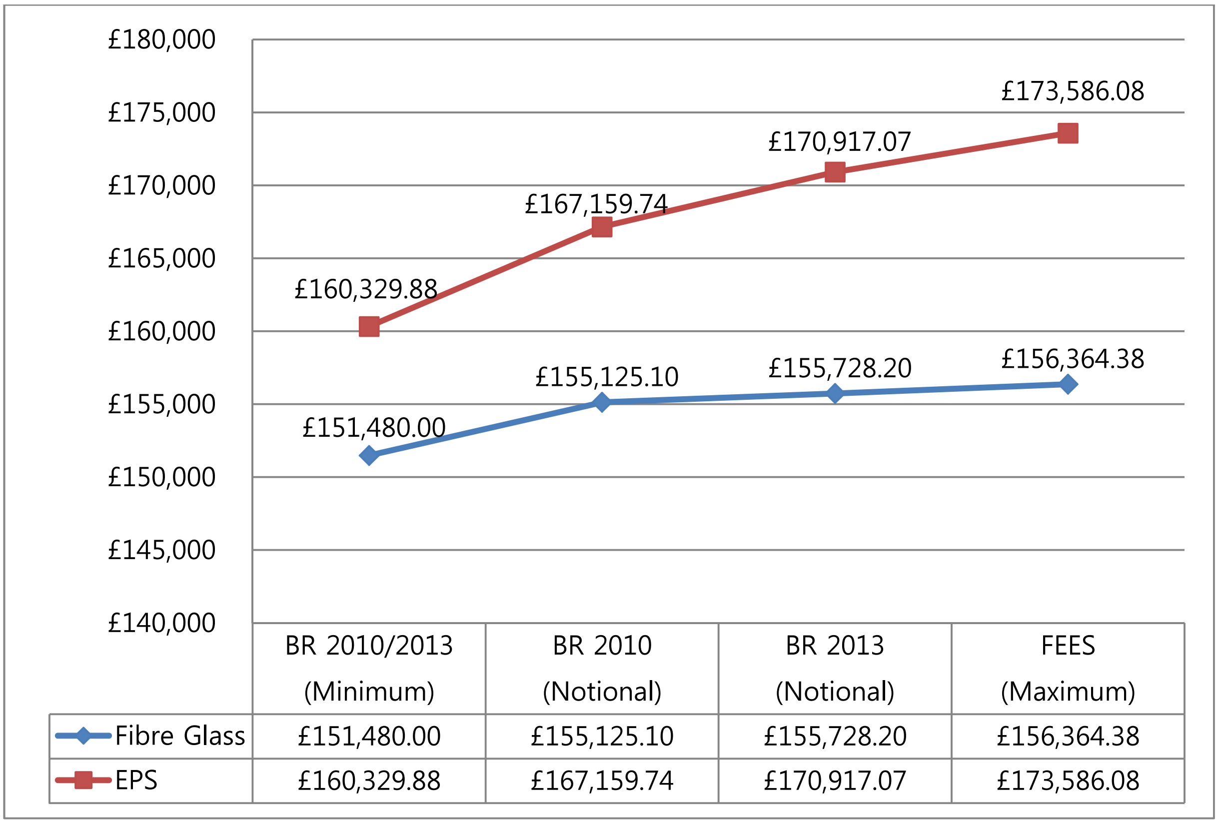


Figure 8.2 LCC Comparison of Fibre Glass and EPS

Figure 8.2 and Table 59 indicate that the differences of the life cycle costs for the fibre glass from the minimum (BR 2010/13) energy performance requirements to the maximum (FEES). The life cycle costs are much smaller when fibre glass is used compared to the EPS. The life cycle costs for the fibre glass with higher-than-the-minimum energy standards are £155,125.10, £155,728.20 and £156,364.38 for BR 2010 (Notional), BR 2013 (Notional) and FEES (Maximum) respectively. The total life cycle costs continue to increase, however the rate of increase continues to decrease as shown in Table 58. Based on this result, construction professionals can advise and persuade customers to adopt a higher energy standard if that is what they wanted from the beginning at Stage R1.

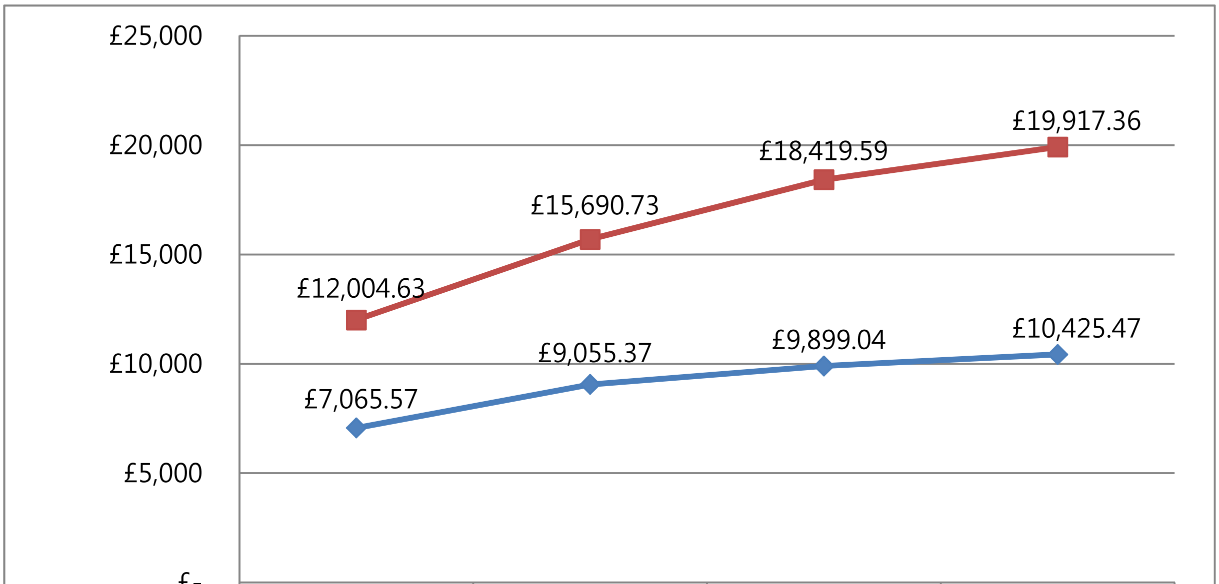
Table 59. LCC Increase Comparison for Upgrading Energy Standards

Insulation Materials	Upgrade A to B	Upgrade A to C	Upgrade A to D
Fibre Glass	£ 3,645.10	£ 4,248.19 (B to C = £ 603.09)	£ 4,884.37 (C to D = £ 636.18)
EPS	£ 6,829.86	£ 10,587.2 (B to C = £ 3,757.34)	£ 13,256.21 (C to D = £ 2,669.01)

Note: A: BR 2010/2013 (Minimum), B: BR 2010 (Notional),
C: BR 2013 (Notional), D: FEES (Maximum)

The costs in the parenthesis indicate the increased amounts of construction cost between the two different energy standards. For example, the B to C for the fibre glass indicates that additional £ 603.09 is required between B and C. These life cycle costs for these options are investigated further in individual cost items; the construction cost and the operating costs including maintenance, operation and occupancy costs. The end of life costs are excluded (See Section 7.3.5).

Figure 8.3 indicates that construction costs for both material options continue to increase according to different energy standards. This is because more insulation materials are required to meet the higher energy standards in terms of the U-values of house elements and thickness of insulation materials. While the total construction cost increases, the rate of increase continues to decrease because the changes of U-values of house elements and thickness of insulation materials become less (See Table 51 at subsubsection 7.4.4.1). In addition, since fibre glass costs £5.25/m^2, which is much lower than EPS at £9.88/m^2, the gap may increase depending on the amount of material used.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	£7,065.57	£9,055.37	£9,899.04	£10,425.47
EPS	£12,004.63	£15,690.73	£18,419.59	£19,917.36

Figure 8.3 Construction Cost Comparison between Fibre Glass and EPS

These construction costs have a major impact on a customer's decision on insulation options as the initial cost for refurbishment is the most influential decision making factors for housing refurbishment (See Section 6.3). If only the construction costs are considered, the BR 2010/2013 (Minimum) energy standard should be adopted based on the customers' preferences.

Figure 8.4 reveals that the operating costs of the EPS has the same pattern as the construction cost, while the operating costs of the fibre glass does not continuously increase. Even the operating costs with the BR 2013 (Notional) and the FEES (Maximum) are less than the operating costs with the BR 2010 (Notional). Based on this result, construction professionals can advise customers that a higher energy standard such as BR 2013 (Notional) or FEES (Maximum) is more beneficial than BR 2010 (Notional), when they wish to achieve high energy efficiency.

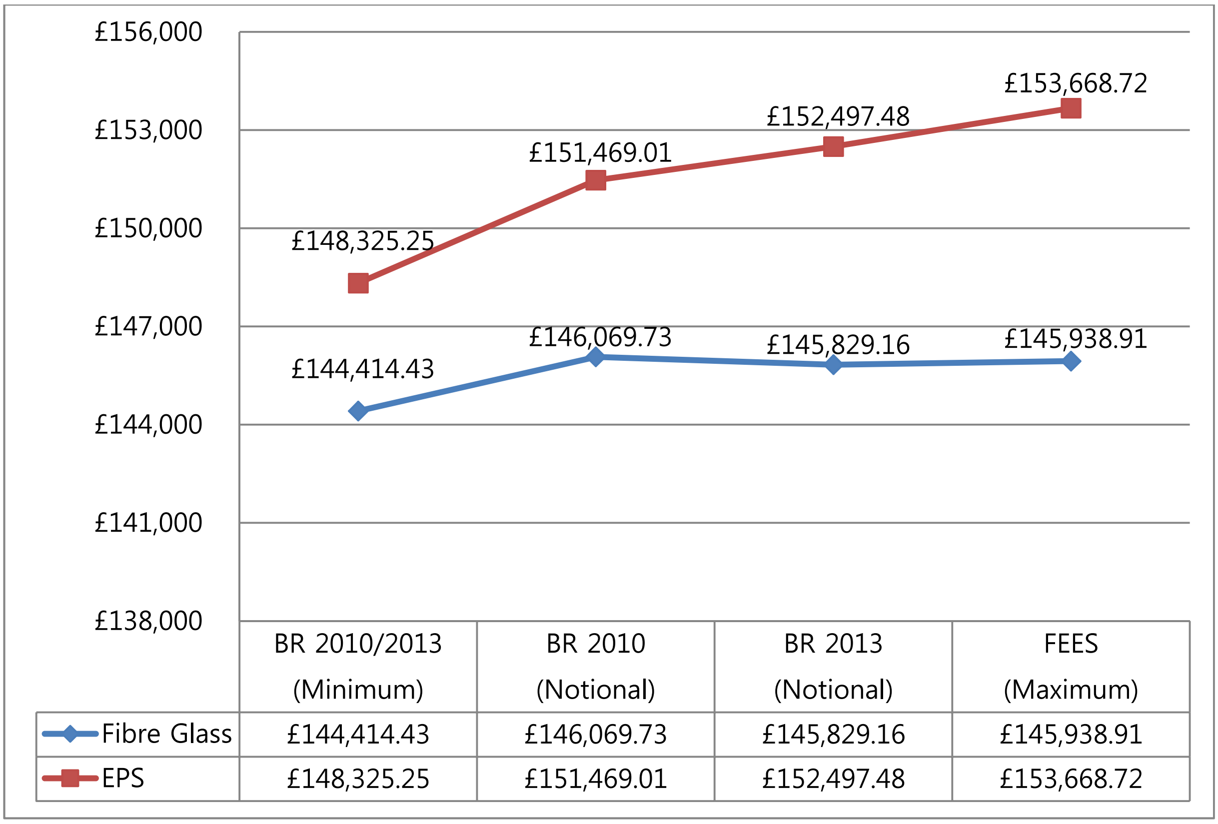
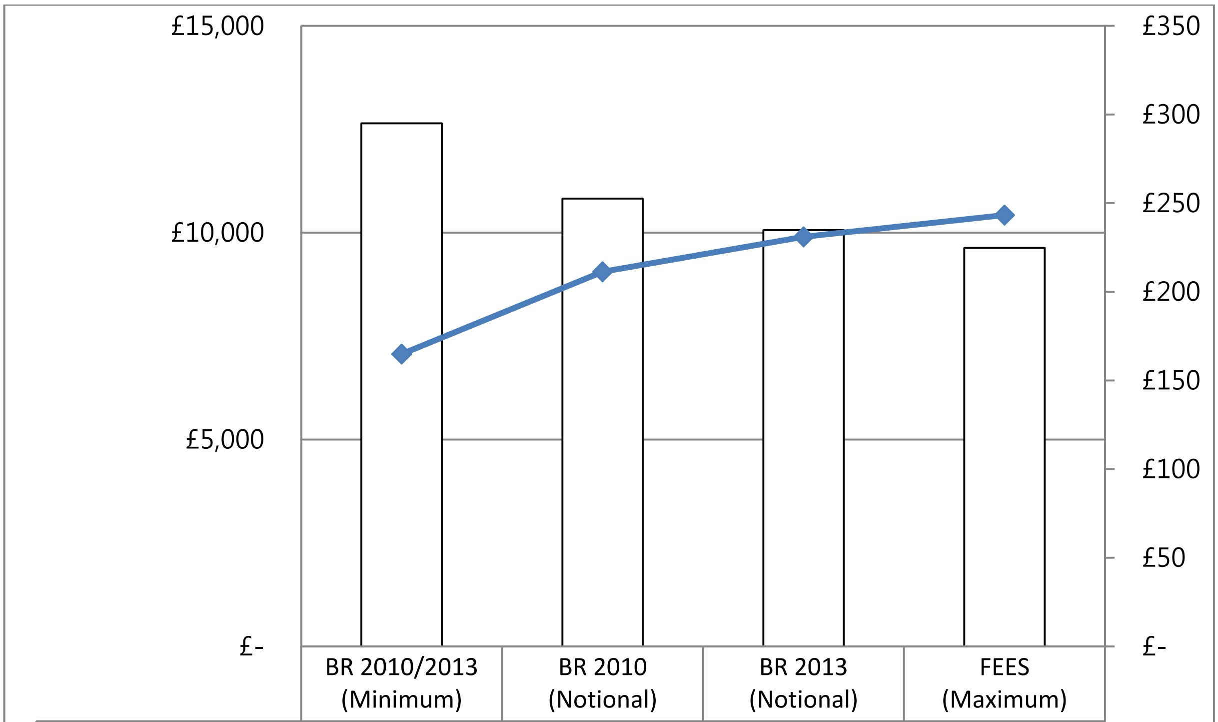


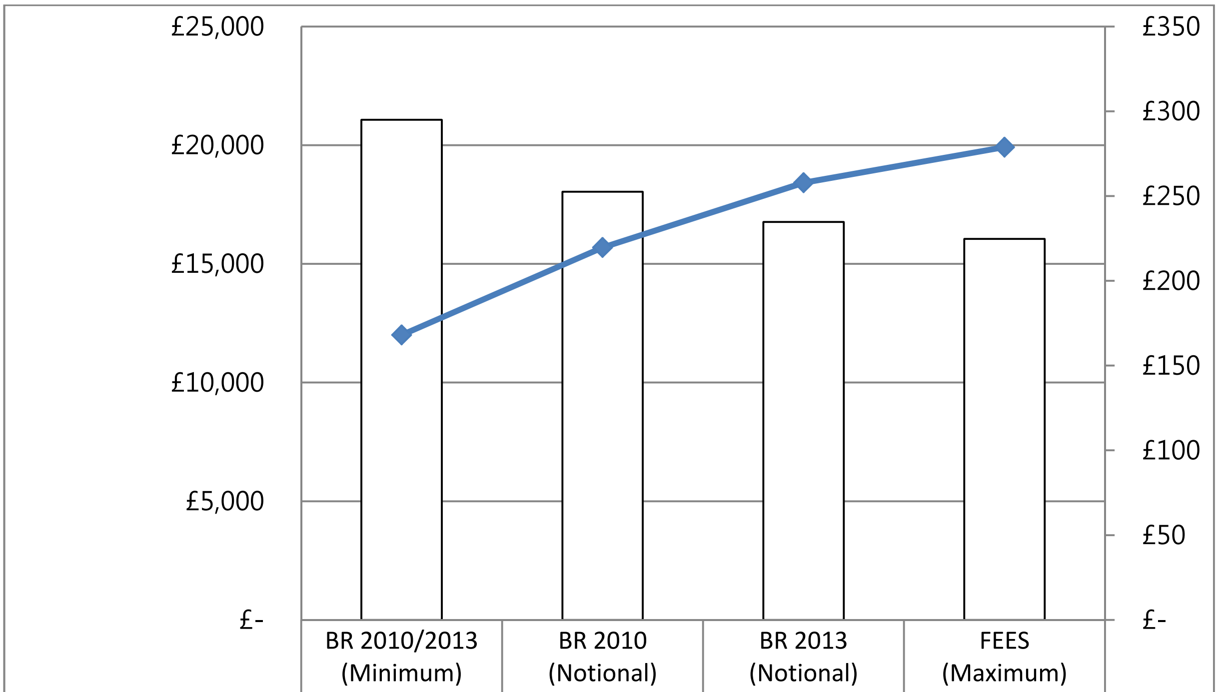
Figure 8.4 Operating Costs Comparison between Fibre Glass and EPS (NPV Applied 60 years)

The fluctuation of operating costs is caused by the inverse proportion relationship between construction cost and energy cost. The construction cost continues to increase for applying higher energy standard, while the operating energy costs continue to decrease as energy performance continues to be improved as shown in Figures 8.5 and 8.6. This relationship needs to be considered at the early design stage with design professionals being responsible for identifying the optimum point where the total cost of construction cost and energy cost result are at the minimum level.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Cost	£295.00	£252.54	£234.75	£224.75
Construction Cost	£7,065.57	£9,055.37	£9,899.04	£10,425.47

Figure 8.5 Construction Cost and Energy Cost - Fibre Glass



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Cost	£295.00	£252.54	£234.75	£224.75
Construction Cost	£12,004.63	£15,690.73	£18,419.59	£19,917.36

Figure 8.6 Construction Cost and Energy Cost – EPS

However, the operating energy costs reduction reaches a point where a significant reduction can no longer be achieved as shown in Figure 8.7. The amounts of energy cost reduction continue to diminish even though higher energy standards are applied. This indicates a limitation in achieving energy cost reduction by adopting only the whole-house fabric refurbishment.

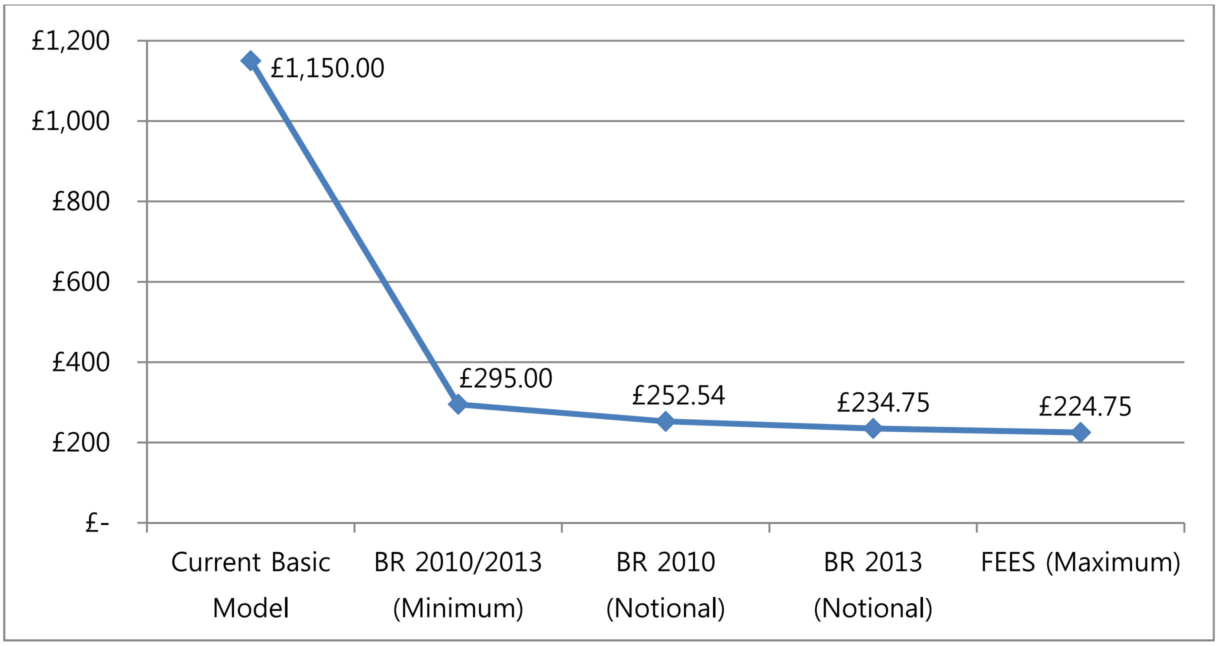


Figure 8.7 Energy Cost Reduction for Each Energy Standard

The construction cost for reducing £1 of the operating energy cost is shown in Figure 8.8 for each energy standard. For example, fibre glass costs £8.26 to reduce the operating energy cost by £1 while EPS costs £14.04. This difference is caused by the material costs that are the most influential impact factors on the construction costs since the size of installation areas and other construction works are assumed to be the same.

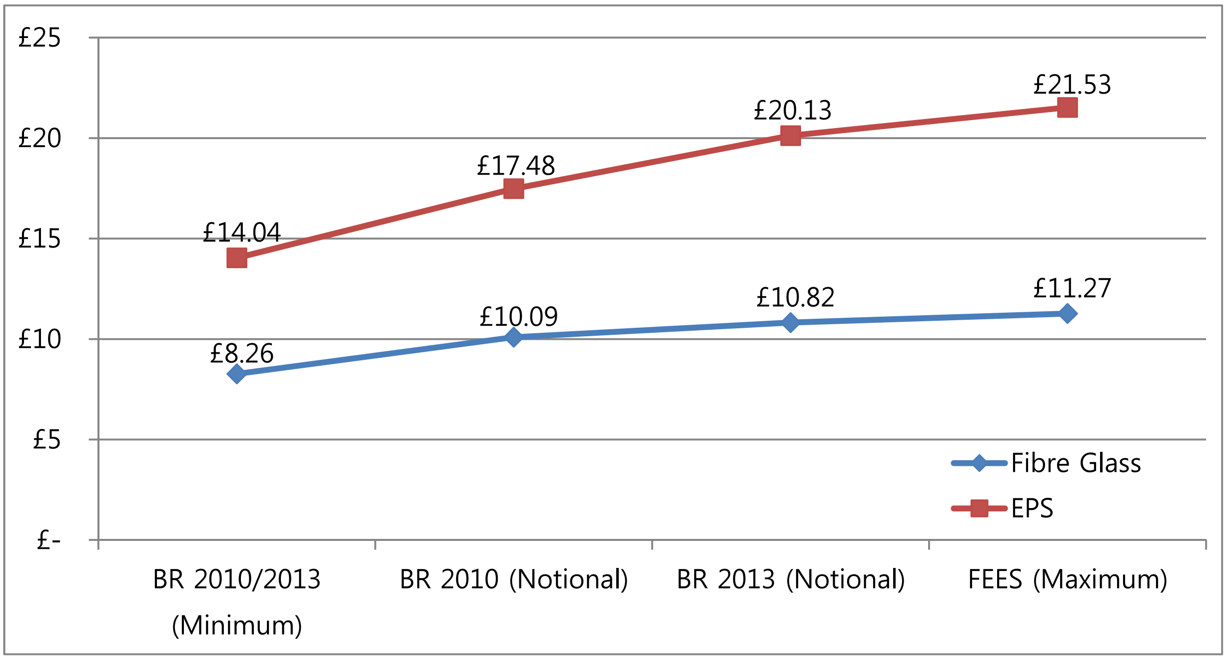


Figure 8.8 Construction Cost for Reducing £ 1 of Energy Cost - Fibre Glass and EPS

According to homeowners' preferences, the BR2010/2013 (Minimum) energy standard and using fibre glass is the most economic option in terms of unit price and long-term savings. Although the amount of construction costs increase by higher energy standard, operating costs can be saved over the life cycle. LCC is highly influenced by the material costs, and thus, it is critical for a customer and a construction professional to understand the financial implication of different energy standards and refurbishment materials to achieve better decision-making.

The payback period for the invested construction cost is mainly considered when construction professionals develop refurbishment design alternatives and, most customers want that payback period to be less than 10 years (See Section 3.5.1). This simple payback period calculation is widely accepted in the construction industry to get a quick idea of cost savings. However, this method ignores external environments during the payback period such as the time value of money. A discount rate should be applied to the economic analysis as the prices of materials such as oil and construction products are very likely to fluctuate over the period. Figure 8.9 shows the differences between the simple payback and discounted payback methods for fibre glass. It shows that there is a maximum one year difference between two payback period methods.

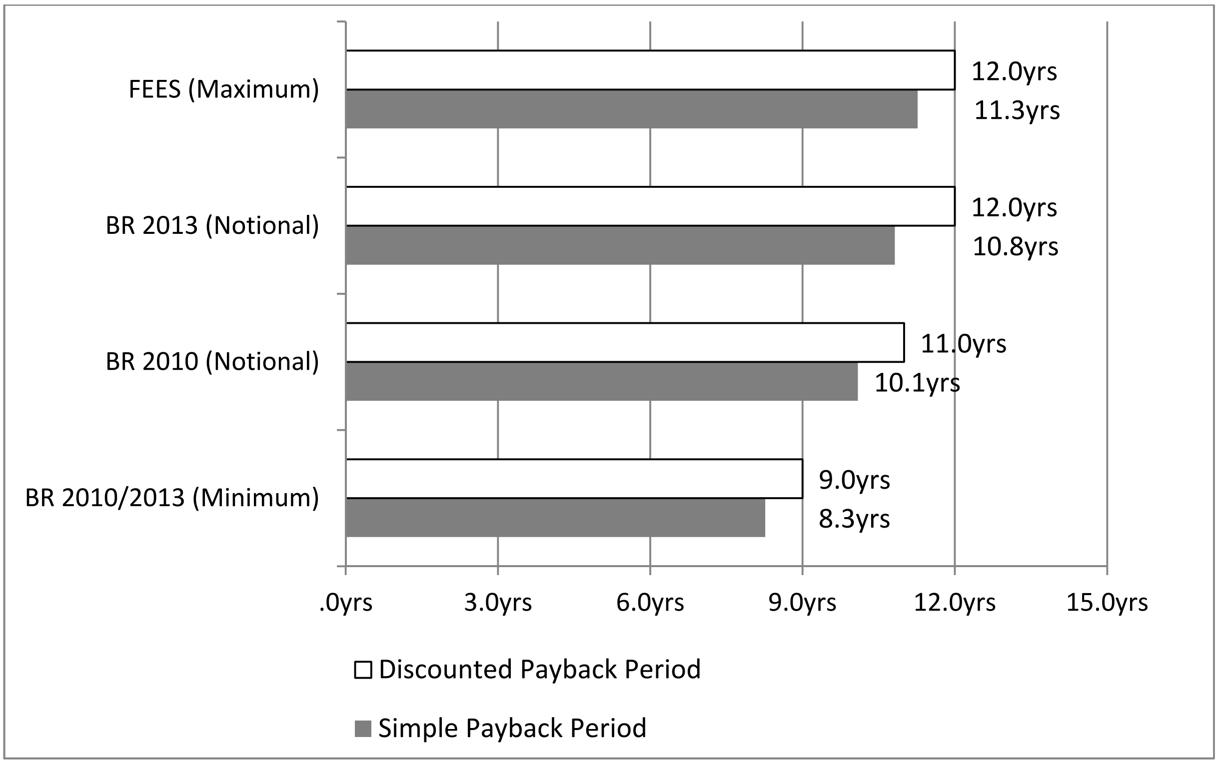


Figure 8.9 Simple Payback Period vs. Discounted Payback Period - Fibre Glass

This gap is much bigger in the EPS as there is at least one year difference and a maximum of 3 years difference as shown in Figure 8.10.

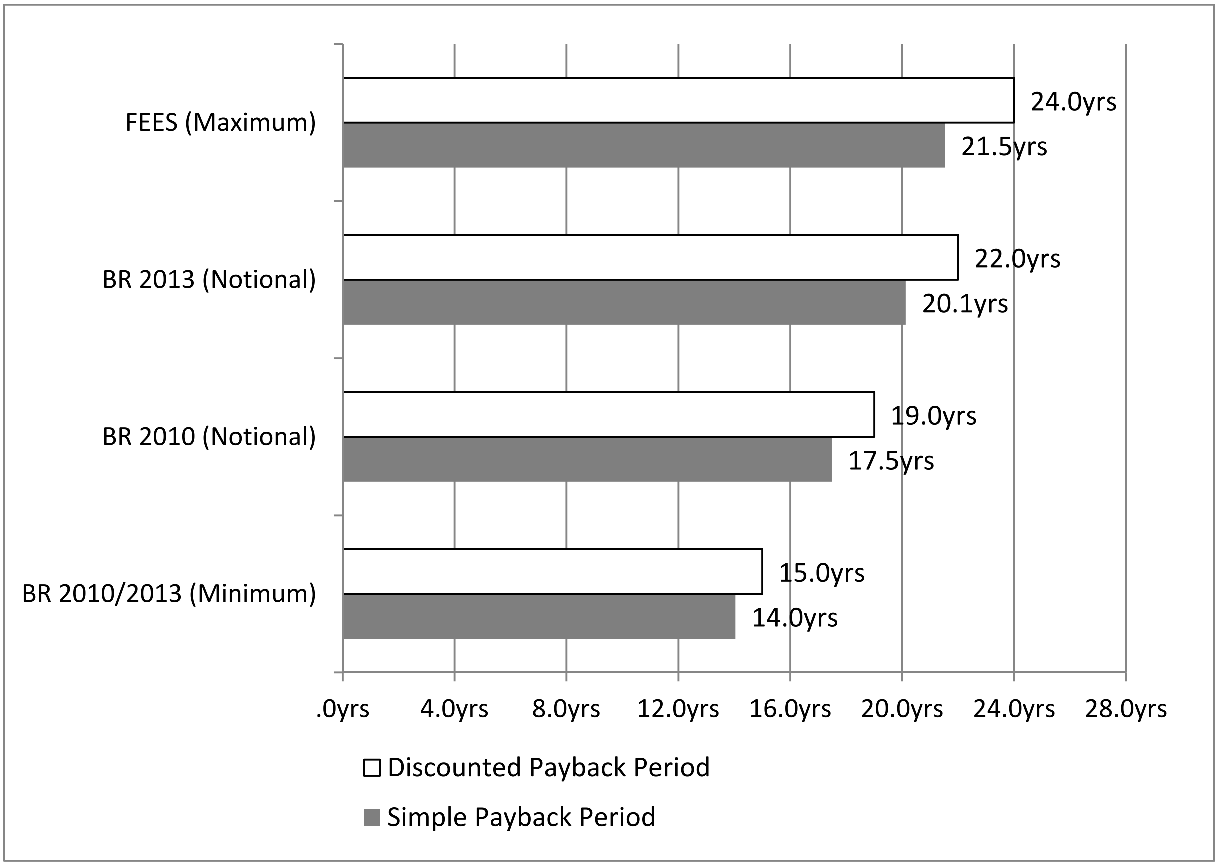


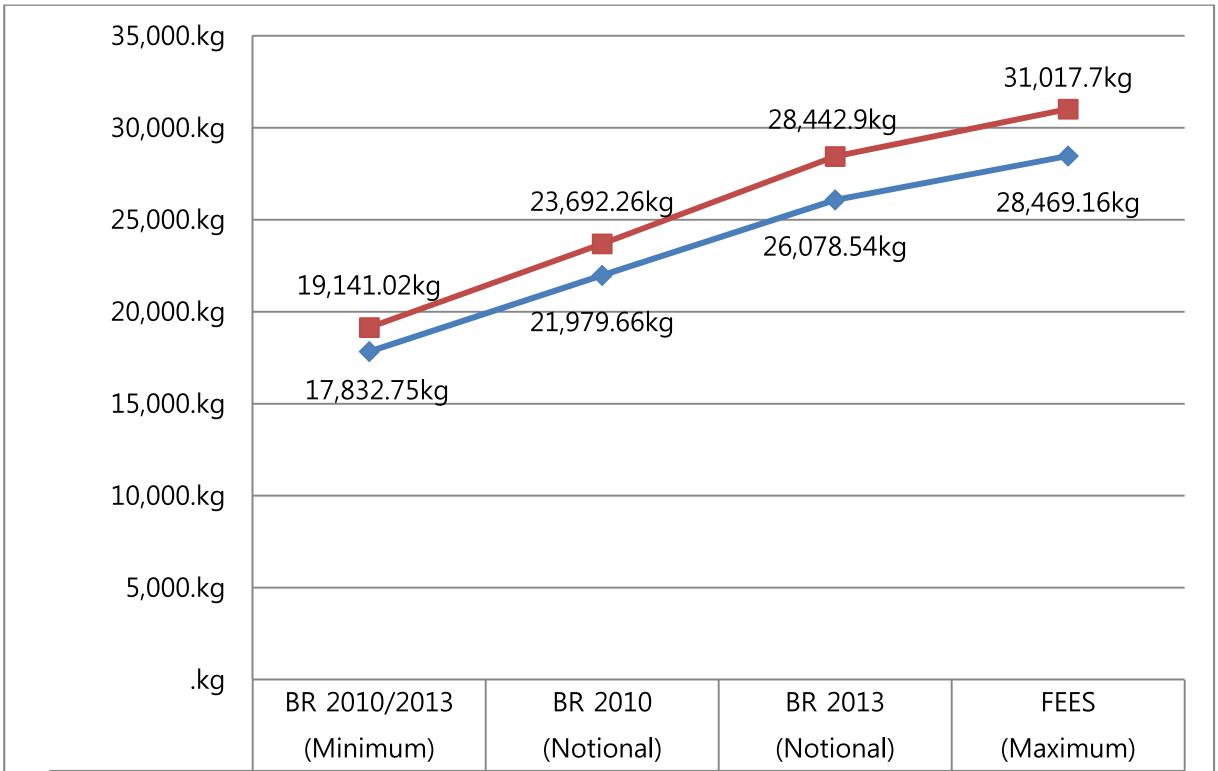
Figure 8.10 Simple Payback Period vs. Discounted Payback Period – EPS

The discounted payback period could be highly influential depending on the inflation rates and interest rates. A more reliable payback period analysis would need to consider the risks associated with the fluctuations. A sensitivity analysis could be used and would be beneficial to customers in a cyclical economy. Therefore, it is highly recommended that construction professionals, in particular design professionals at the early design phase, should consider the implication of economic conditions to make a more beneficial decision among refurbishment alternatives and materials using a sensitivity analysis.

However, this research did not perform a sensitivity analysis because the main purpose of this payback period study is to identify if there are differences between a simple payback and discounted payback methods. Furthermore, the payback period is subjective decision making criterion or judgement for the customers as homeowners addressed their desire for payback period (See Section 3.5.2), and this is not mainly considered by construction professionals and customers for housing refurbishment planning.

8.2.2 Energy Efficiency and Environmental Impact

The LCA results also continue to increase as more insulation materials are installed as shown in Figure 8.11. In particular, the LCA using fibre glass continues to increase unlike the LCC. This is because more construction materials require more embodied CO_2 associated with the materials and construction works. The difference of LCA amounts between the fibre glass and the EPS are caused by the involvement of fossil fuels in the raw material. The raw materials in fibre glass - natural minerals and manufactured chemicals – involve less fossil fuel than the EPS, which is made of crude oil.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	17,832.75kg	21,979.66kg	26,078.54kg	28,469.16kg
EPS	19,141.02kg	23,692.26kg	28,442.9kg	31,017.7kg

Figure 8.11 LCA Comparison of Fibre Glass and EPS

If the amount of CO_2 related to construction works and transportation is considered, it can be financially and environmentally beneficial to adopt a higher energy standard from the beginning. This is because of less CO_2 and the costs associated with refurbishment when a higher energy standard is adopted at the beginning. Additional CO_2 and costs will be associated if house elements are upgraded at a later date.

Although the LCA continues to increase, Figure 8.12 indicates that the LCA for an existing house is higher than of a refurbished house. Therefore it can be considered that refurbishment is more environmentally-beneficial option than a new build, and a detached house is more environmentally beneficial if energy efficiency improvements are made.

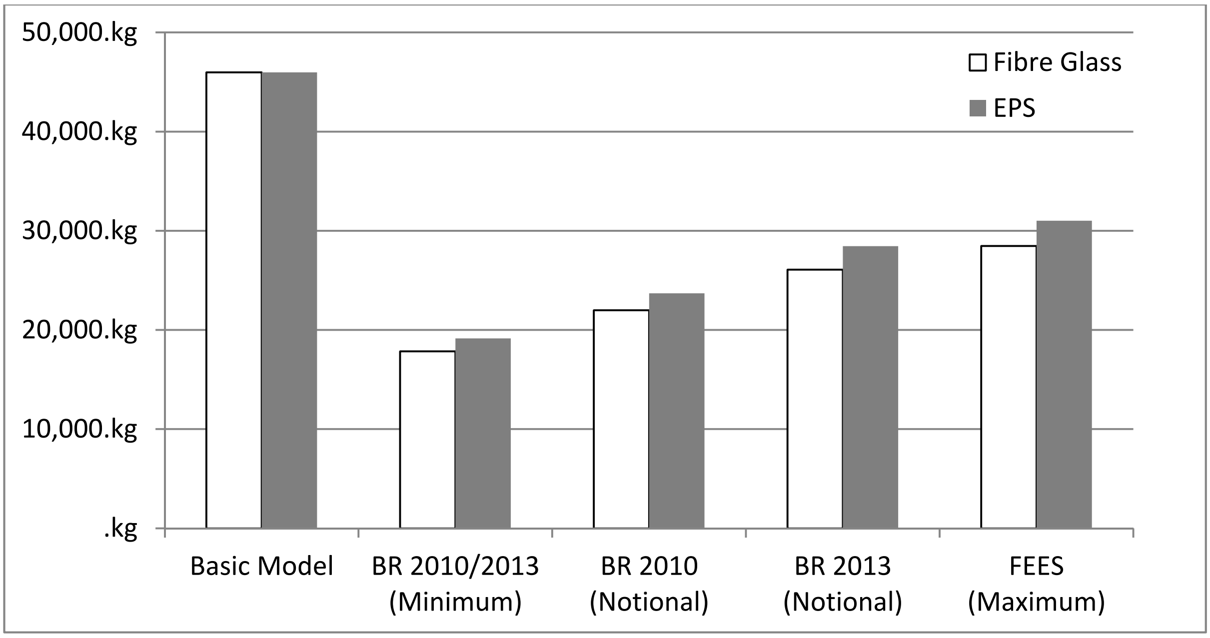


Figure 8.12 LCA Comparison between Existing House and Refurbished House

The amount of CO_2 emissions per year also continues to diminish as higher energy standards are adopted - see Figure 8.13 - although there is no significant CO_2 reduction after BR 2010 (Notional) adoption. The percentage of CO_2 reduction with the adoption of the FEES standard is 51% (10,985kg to 5,328.3kg), which is similar to the results of other research and practical experience. The maximum of 60% CO_2 reduction is achievable with whole-fabric refurbishment (Construction Production Association, 2014; Boardman et al., 2005).

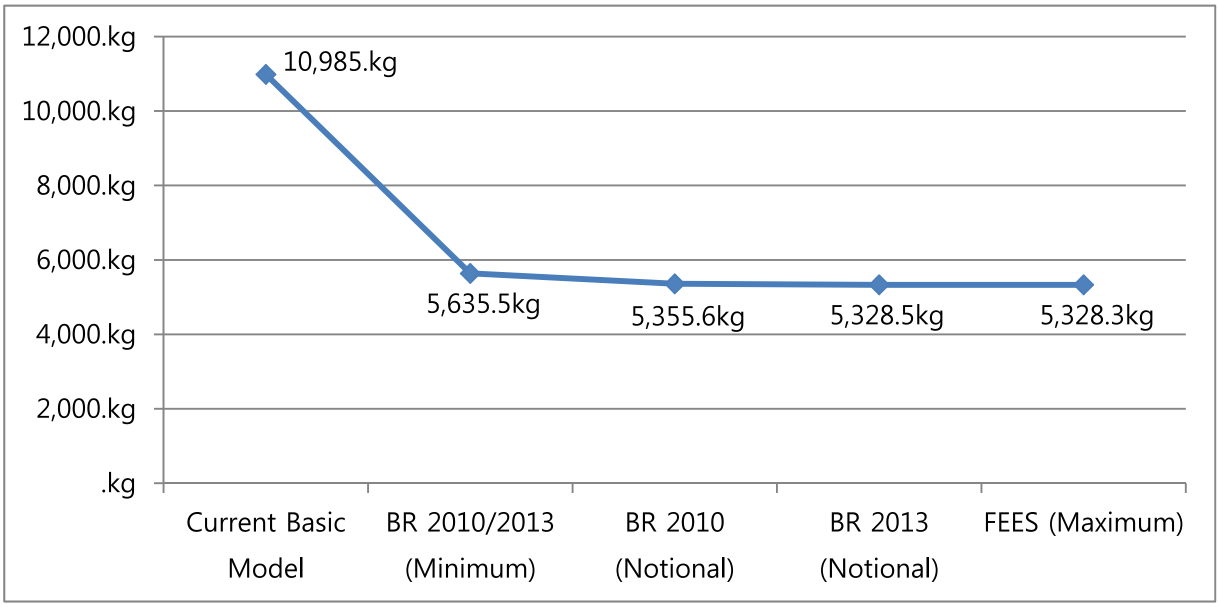
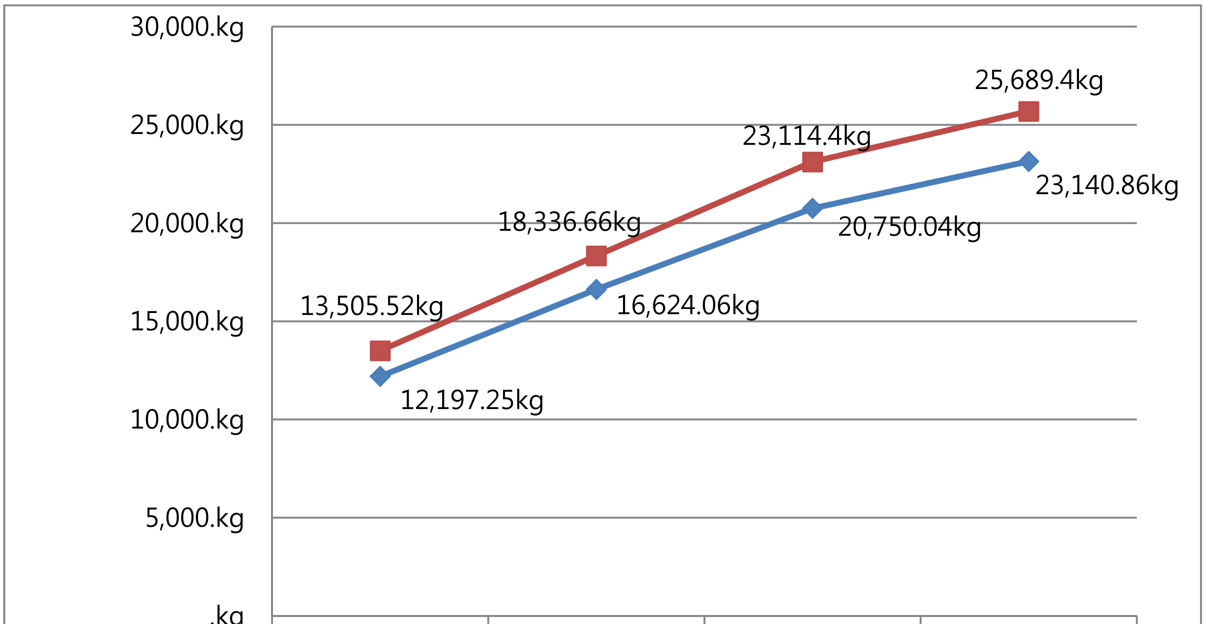


Figure 8.13 CO_2 Emission per year – Fibre Glass and EPS

The embodied CO_2 continues to increase as higher energy standards are applied for both fibre glass and EPS as shown in Figure 8.14. It is very obvious that more insulation materials render a larger amount of embodied CO_2, which is why LCA continues to increase although the operational CO_2 emission diminishes.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	12,197.25kg	16,624.06kg	20,750.04kg	23,140.86kg
EPS	13,505.52kg	18,336.66kg	23,114.4kg	25,689.4kg

Figure 8.14 Embodied CO_2 and CO_2 Emission - Fibre Glass and EPS

With the Government's target for zero-carbon homes, the use of recycled materials should be considered and promoted when refurbishment materials are chosen. Although construction professionals and customers pay little attention to recycled materials (See Section 6.3), they should be utilized to achieve a further reduction of embodied CO_2 and CO_2 emission.

The formula for the CO_2 payback period is shown in Equation B (Genchi et al., 2002) and Figure 8.15 shows the payback periods for different energy standards. The CO_2 payback period is a duration when the amount of operational CO_2 reduction after refurbishment compensates the embodied CO_2 invested in the refurbishment.

$$\frac{\text{Total amount of embodied CO2}}{\text{Annual CO2 emission reduction after refurbishment}} = \text{CO2 Payback Period} \qquad \text{(Equation B)}$$

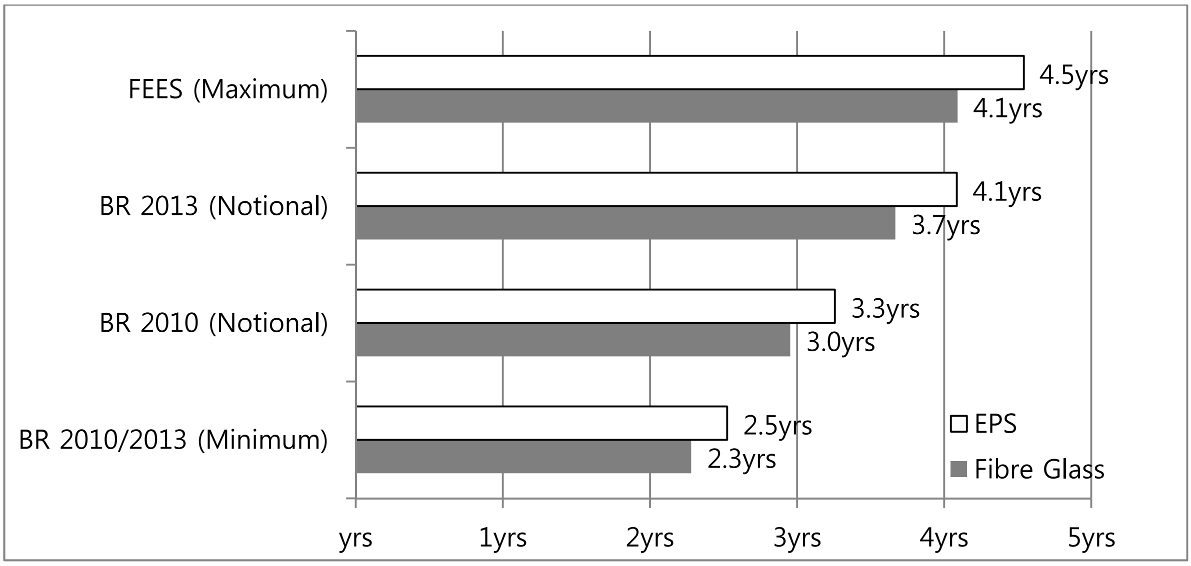


Figure 8.15 CO_2 Payback Period

The BR 2010/2013 (minimum) energy standard indicates the shortest CO_2 payback period among the other energy standards. However, it should be noted that the gap between the BR 2010/2013 (minimum) and the FEES (Maximum) is nearly two years for both the fibre glass and the EPS. If the CO_2 payback period is considered in conjunction with the embodied CO_2, the payback period for retrieving the embodied CO_2 by reducing CO_2 emissions is not significantly different among different energy standards.

As show in Figure 8.16, the construction costs for reducing 1kg of operational CO_2 emission continue to increase. The construction costs increase much rapidly when the EPS is used rather than fibre glass. As higher energy standards are adopted, the gap in construction costs between fibre glass and the EPS continue to increase.

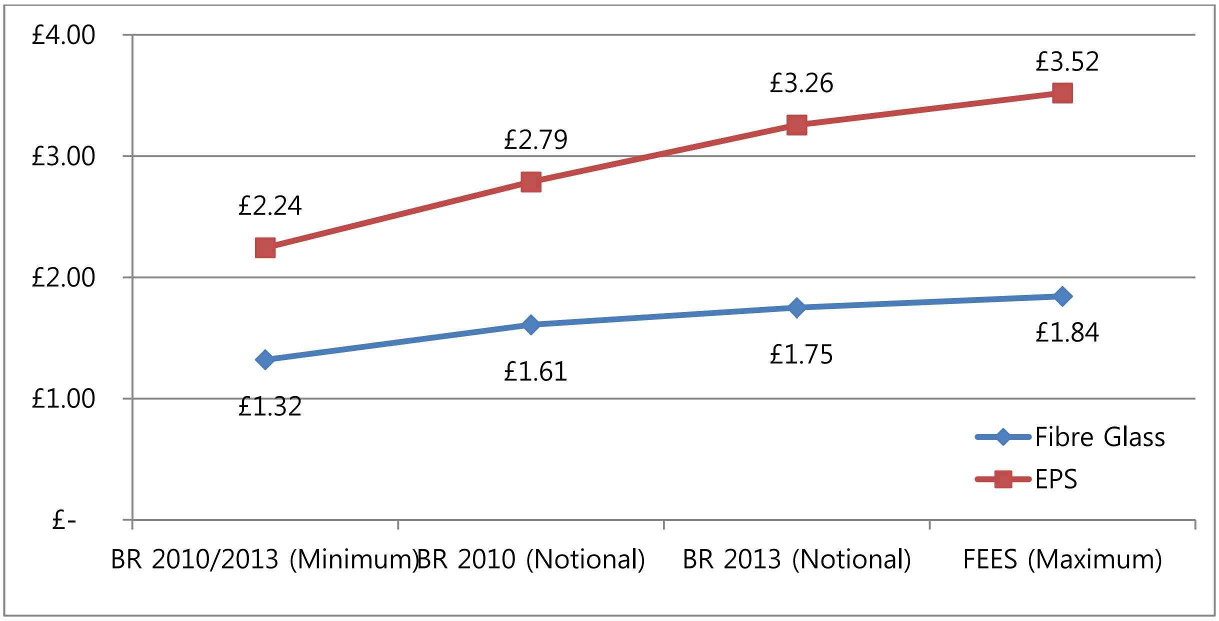


Figure 8.16 Construction Cost for Reducing 1kg of Operational CO_2 Emission

The two lines in Figure 8.17 show little difference in the rate of increase between the two types of insulation. There are no significant differences between the two materials when higher energy standards are adopted although the fibre glass (4.25kg/m^3) has lower embodied CO_2 than the EPS (12kg/m^3).

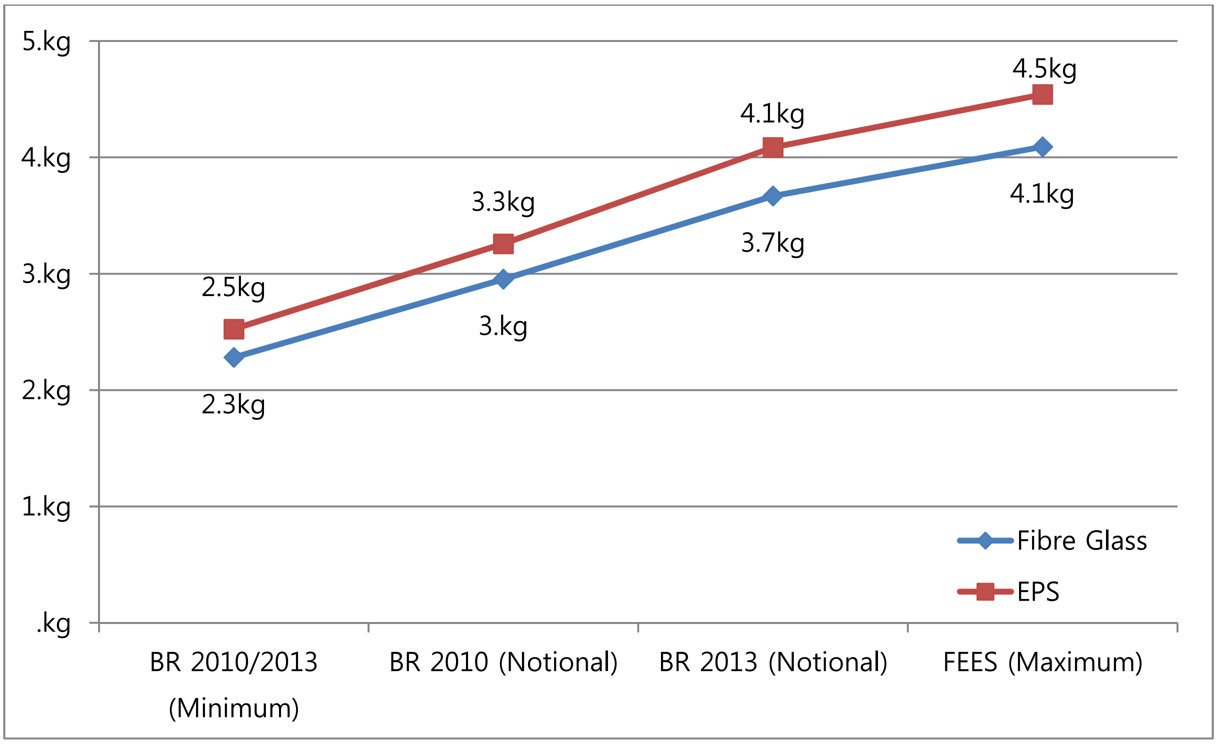


Figure 8.17 Embodied CO_2 for Reducing 1kg of Operational CO_2 Emission

8.3 Semi-Detached/End Terraced House Refurbishment Result

8.3.1 Energy Efficiency and Financial Impact

Figure 8.18 indicates that all the LCC results of a refurbished house with different energy standards are lower than the LCC for the existing house. Thus, it is economically beneficial for a semi-detached/end terrace solid-wall house to be refurbished to achieve energy efficiency improvement.

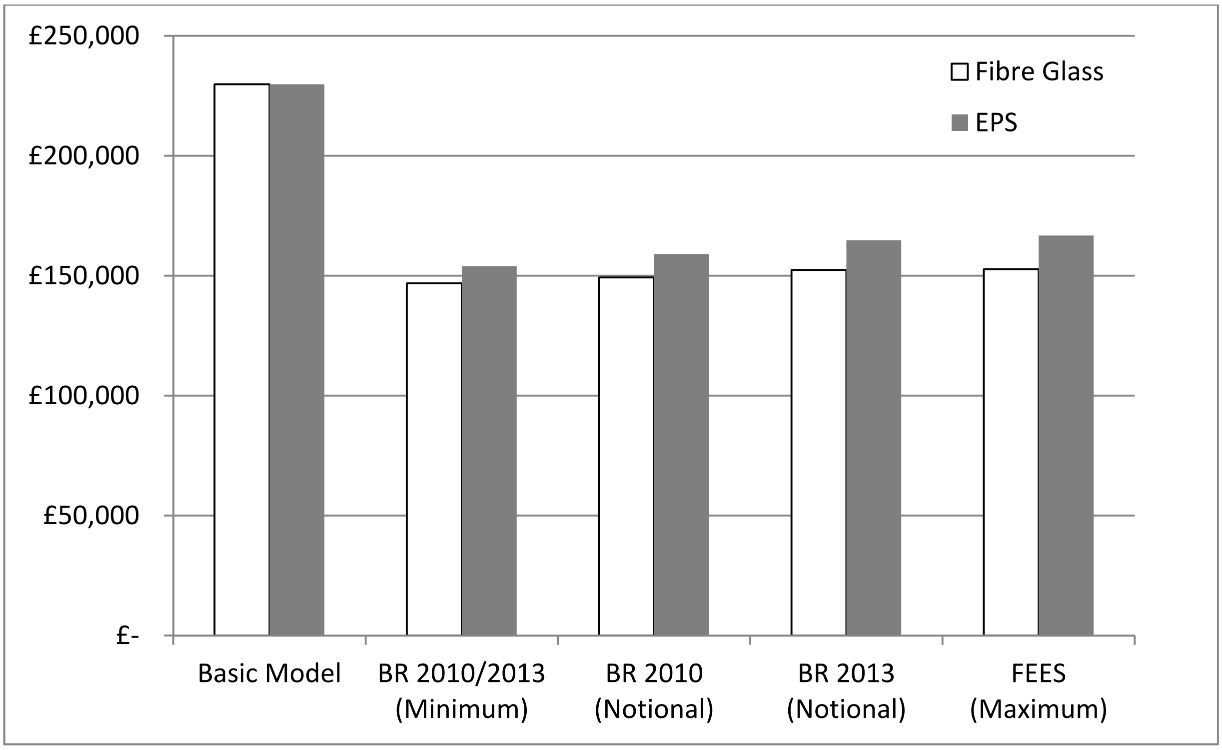


Figure 8.18 LCC Comparison between Existing House and Refurbished House

As shown in Figure 8.19, the LCC continues to increase as higher energy standards are adopted.

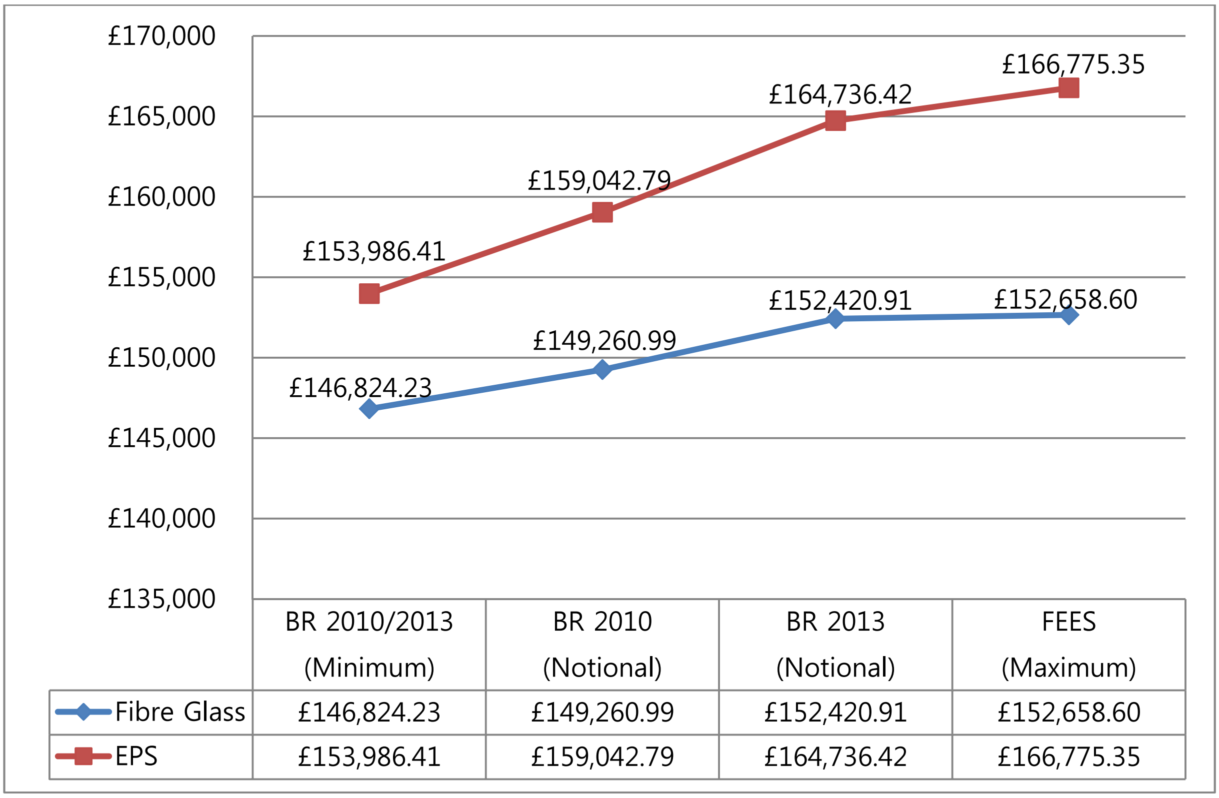


Figure 8.19 LCC Comparison of Fibre Glass and EPS

Figure 8.19 shows that the differences in life cycle costs for the fibre glass from the minimum energy performance requirements (BR 2010/13) to the maximum (FEES). The life cycle costs are much smaller when the fibre glass is used compared to the EPS. The total life cycle costs continue to increase, however the rate of increase continues to decrease as shown in Table 60. Based on this result, construction professionals can advise and persuade customers to adopt higher energy standard if they indicate their willingness to adopt high energy standards.

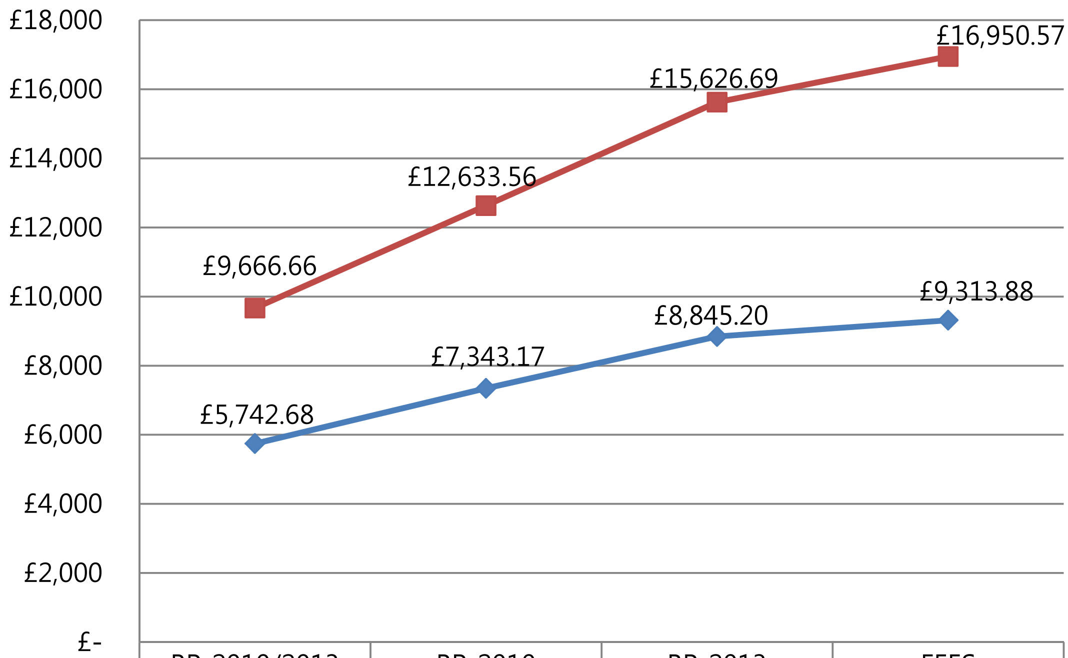
Table 60. LCC Increase Comparison for Upgrading Energy Standards

Insulation Materials	Upgrade A to B	Upgrade A to C	Upgrade A to D
Fibre Glass	£ 2,436.76	£ 5,596.68 (B to C = £ 3,159.92)	£ 5,834.37 (C to D = £ 237.69)
EPS	£ 5,056.38	£ 10,750 (B to C = £ 5,693.62)	£ 12,788.93 (C to D = £ 2,038.93)

Note: A: BR 2010/2013 (Minimum), B: BR 2010 (Notional),
C: BR 2013 (Notional), D: FEES (Maximum)

The costs in the parentheses indicate the increase in construction cost between the two energy standards. For example, B to C for fibre glass required an additional £603.09.
The life cycle costs for these options are investigated further through individual cost items; the construction cost and the operating costs include maintenance, operation and occupancy costs. The end of life costs are excluded.

Figure 8.20 indicates that construction costs for both material options continue to increase according to the different energy standards because more insulation materials are required to meet the higher energy standards in terms of the U-values of house elements and thickness of insulation materials. While the total construction cost increases, the rate of increase continues to decrease because the changes in U-values of house elements and thickness of insulation materials become less (See Subsection 7.4.4.1).

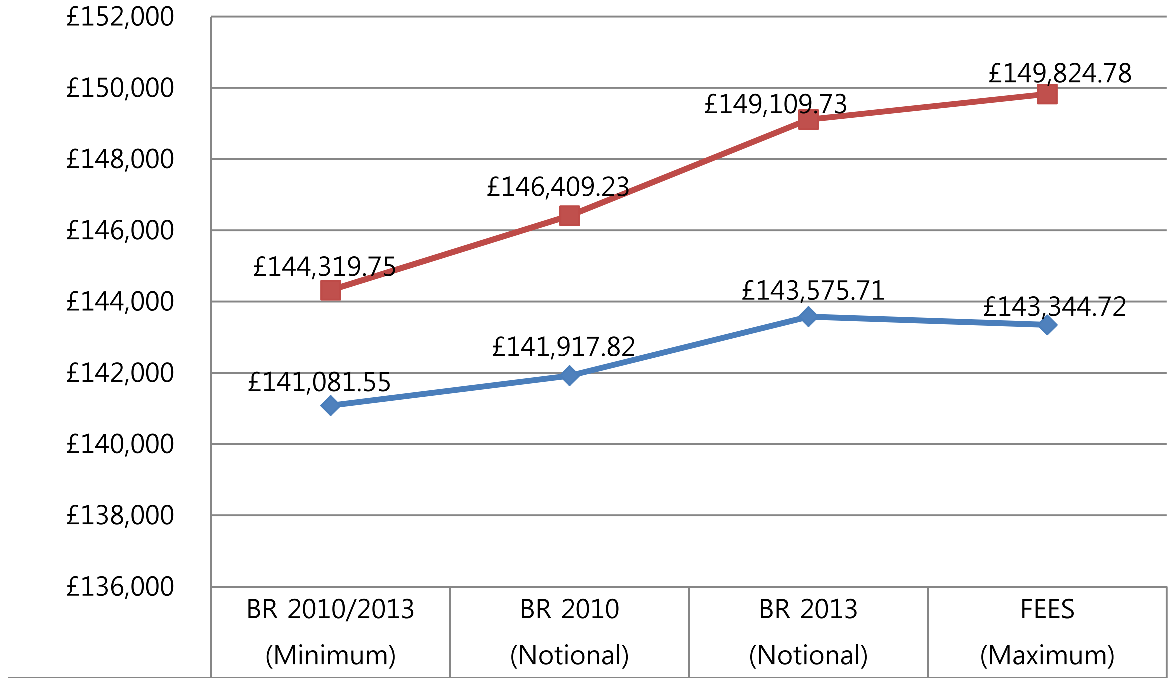


	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	£5,742.68	£7,343.17	£8,845.20	£9,313.88
EPS	£9,666.66	£12,633.56	£15,626.69	£16,950.57

Figure 8.20 Construction Cost Comparison between Fibre Glass and EPS

If only the construction costs are considered, the BR 2010/2013 (Minimum) energy standard should be adopted based on the customers' preferences as the initial cost for refurbishment is the most influential decision-making factor for housing refurbishment (See Section 6.3).

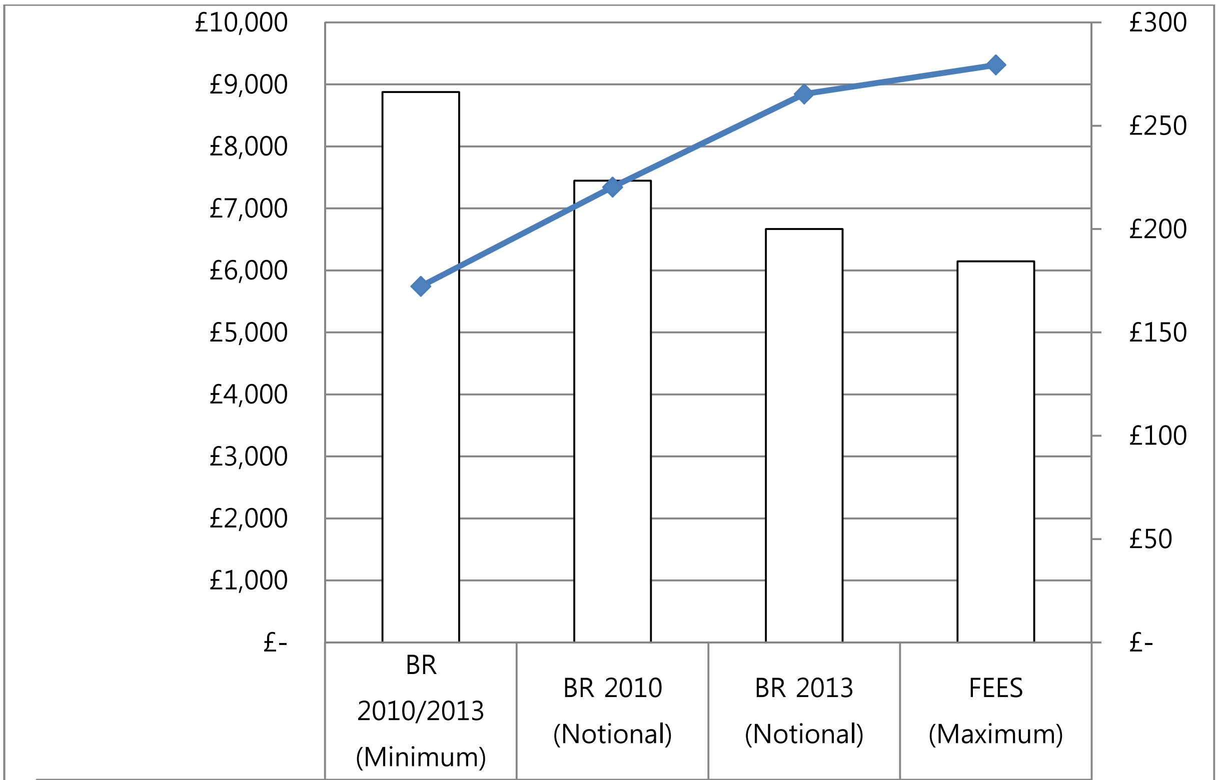
Figure 8.21 shows that the operating costs of the EPS follows the same pattern as the construction cost, while the operating costs of the fibre glass does not continuously increase. Even the operating costs with the FEES (Maximum) are less than the operating costs of the BR 2013 (Notional). Based on this result, construction professionals can advise customers that a higher energy standard such as FEES (Maximum) is more beneficial than BR 2013 (Notional), if they want to achieve high energy efficiency.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	£141,081.55	£141,917.82	£143,575.71	£143,344.72
EPS	£144,319.75	£146,409.23	£149,109.73	£149,824.78

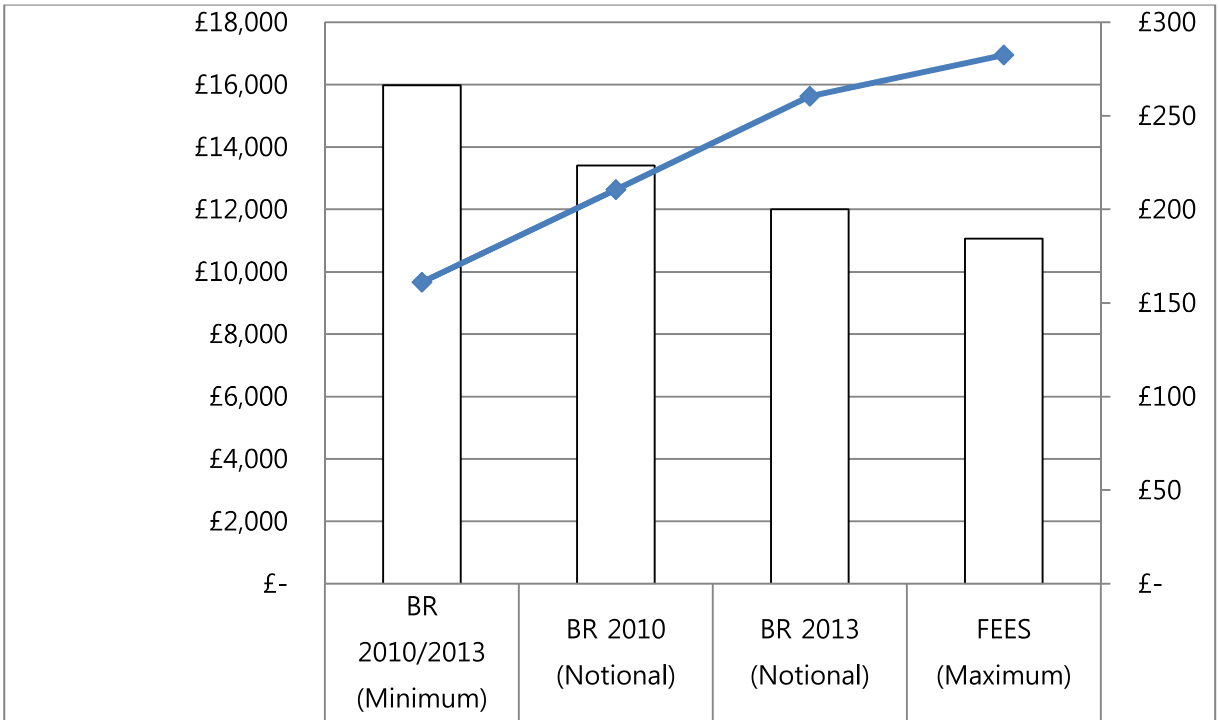
Figure 8.21 Operating Costs Comparison between Fibre Glass and EPS (NPV Applied 60 years)

The fluctuation of operating costs is caused by the relationship between construction cost and energy cost. The construction cost continues to increase when applying a higher energy standard, while the operating energy costs continue to decrease as energy performance improves as shown in Figures 8.22 and 8.23. The inverse proportion relationship is also confirmed based on this result for a semi-detached/end terrace house.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Cost	£266.30	£223.40	£200.00	£184.43
Construction Cost	£5,742.68	£7,343.17	£8,845.20	£9,313.88

Figure 8.22 Construction Cost and Energy Cost – Fibre Glass



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Energy Cost	£266.30	£223.40	£200.00	£184.43
Construction Cost	£9,666.66	£12,633.56	£15,626.69	£16,950.57

Figure 8.23 Construction Cost and Energy Cost – EPS

However, the operating energy costs reduction will reach a point where no further significant reduction can be achieved as shown in Figure 8.24. In this case, a maximum of 83% energy cost can be reduced by adopting FEES, which is 3% more reduction compared to a detached house.

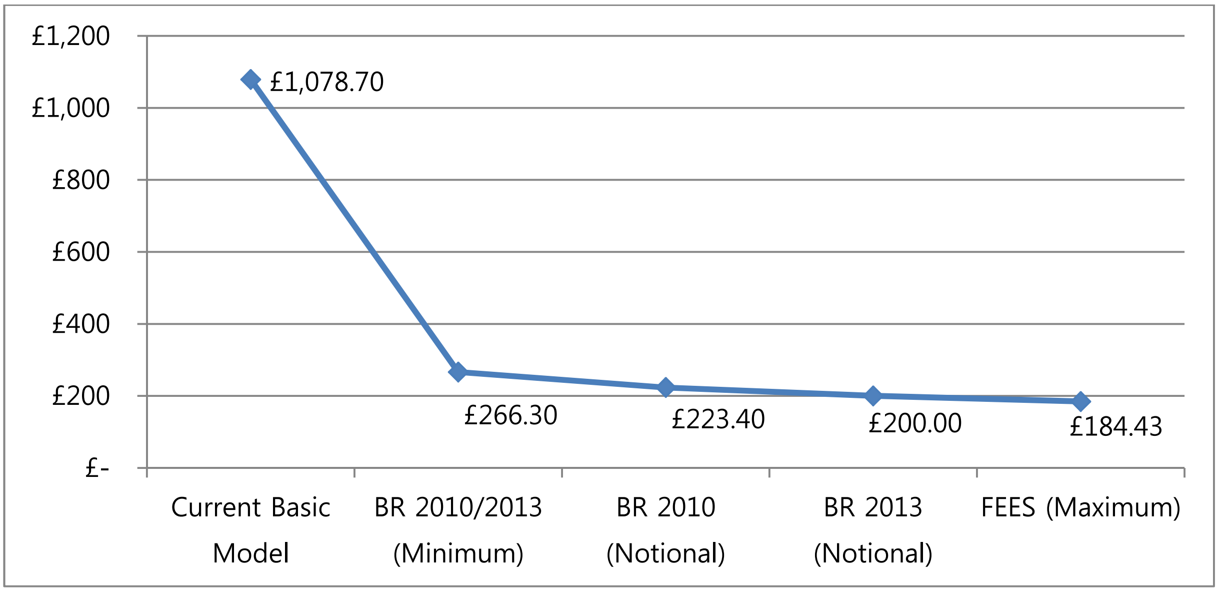


Figure 8.24 Energy Cost Reduction for Each Energy Standard

The construction cost for reducing £1 of the operating energy cost is shown in Figure 8.25. For example, the fibre glass costs £7.07 to reduce the operating energy cost by £1 while the EPS costs £11.90.

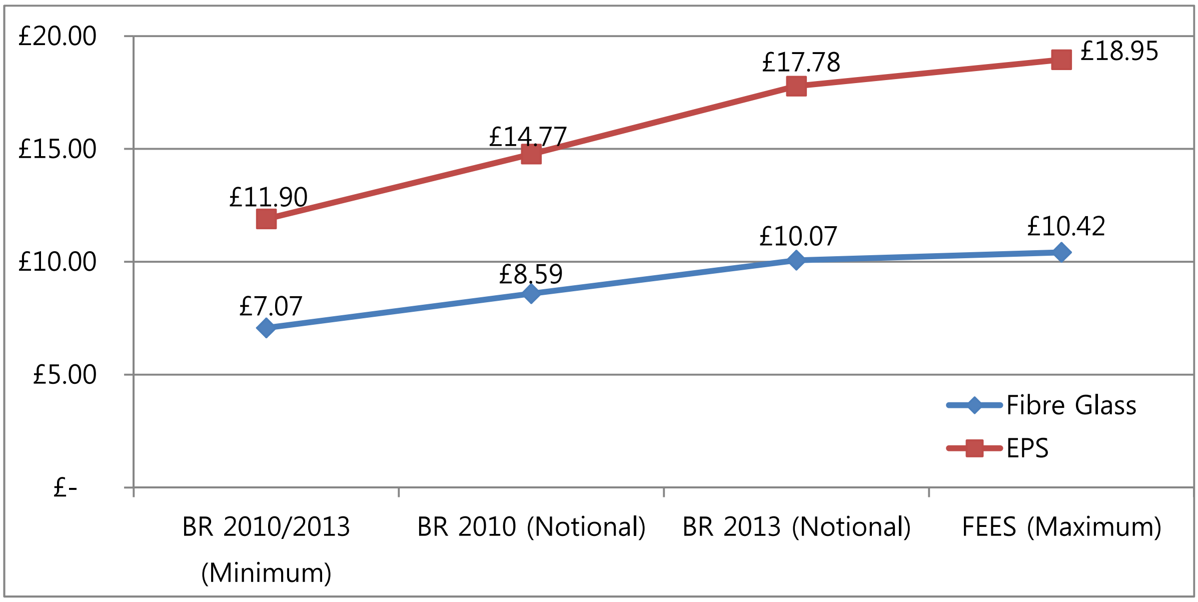


Figure 8.25 Construction Cost for Reducing £ 1 of Energy Cost - Fibre Glass and EPS

According to the customer preference, the BR2010/2013 (Minimum) energy standard with the fibre glass is the most economic option. Although the amount of construction costs increase with a higher energy standard, operating costs can be saved over the life cycle. As far as the unit price and savings are concerned, the fibre glass would be better option in this example.

Figure 8.26 identifies the differences between the simple and discounted payback methods for fibre glass. It shows that there is a maximum of one-year difference between two payback period methods.

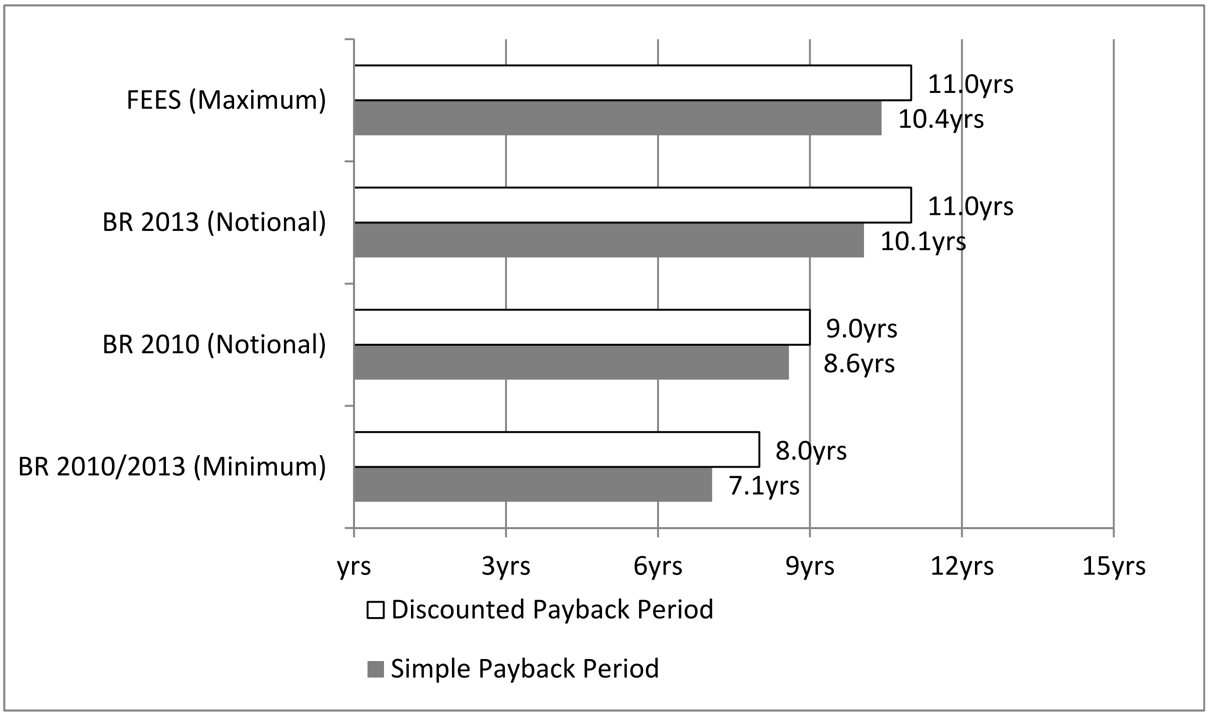


Figure 8.26 Simple Payback Period vs. Discounted Payback Period - Fibre Glass

This gap is much bigger with the EPS as there is at least a one-year difference and a maximum two-year difference as shown in Figure 8.27.

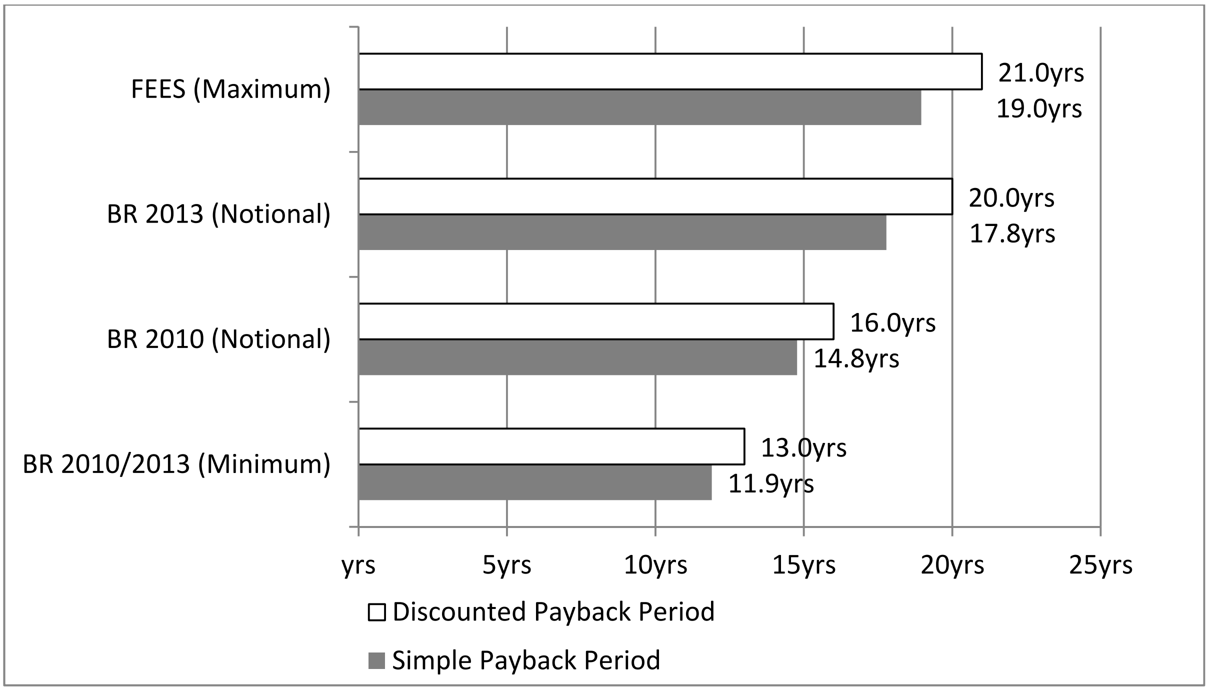
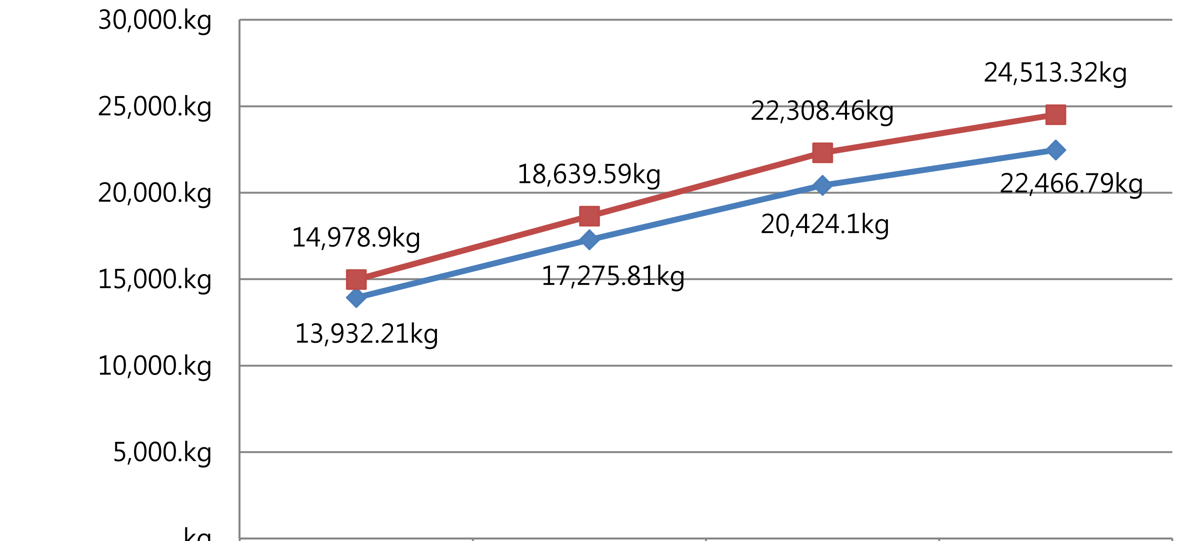


Figure 8.27 Simple Payback Period vs. Discounted Payback Period – EPS

8.3.2 Energy Efficiency and Environmental Impact

The LCA results also continue to increase as more insulation materials are installed as shown in Figure 8.28. This pattern is the same for the detached house.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	13,932.21kg	17,275.81kg	20,424.1kg	22,466.79kg
EPS	14,978.9kg	18,639.59kg	22,308.46kg	24,513.32kg

Figure 8.28 LCA Comparison of Fibre Glass and EPS

If the amount of CO_2 related to construction works and transportation is considered, it can be financially and environmentally beneficial to adopt the higher energy standard from the beginning. Although the LCA continues to increase, Figure 8.29 indicates that the LCA for an existing house is higher than the LCA of a refurbished house. Therefore, refurbishment is an environmentally more beneficial option than new build, and it is environmentally beneficial to refurbish a semi-detached/end terraced house to achieve energy efficiency improvement.

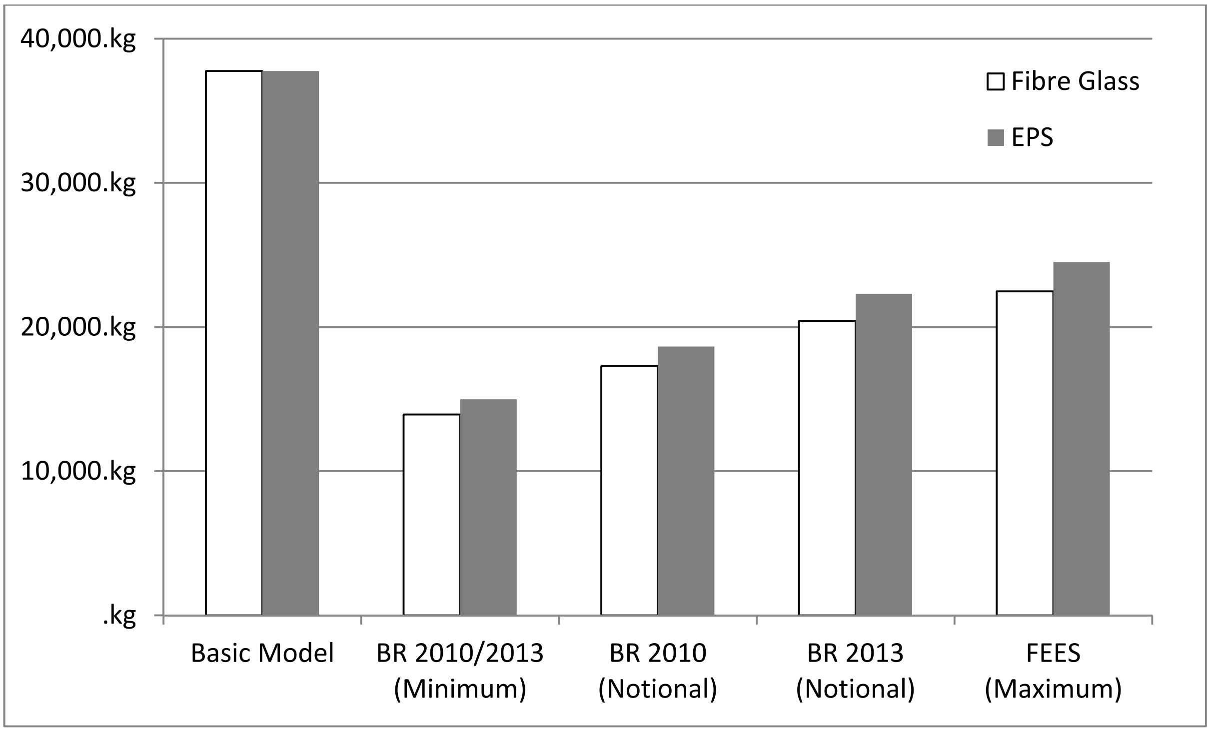


Figure 8.29 LCA Comparison between Existing House and Refurbished House

The amount of CO_2 emission per year also continues to diminish as higher energy standards are adopted - as shown in Figure 8.30. However, there is no significant CO_2 reduction if BR 2010 (Notional) is adopted. The percentage of CO_2 reduction with the adoption of FEES standard is 60% (9,454.8kg to 3,756.5kg).

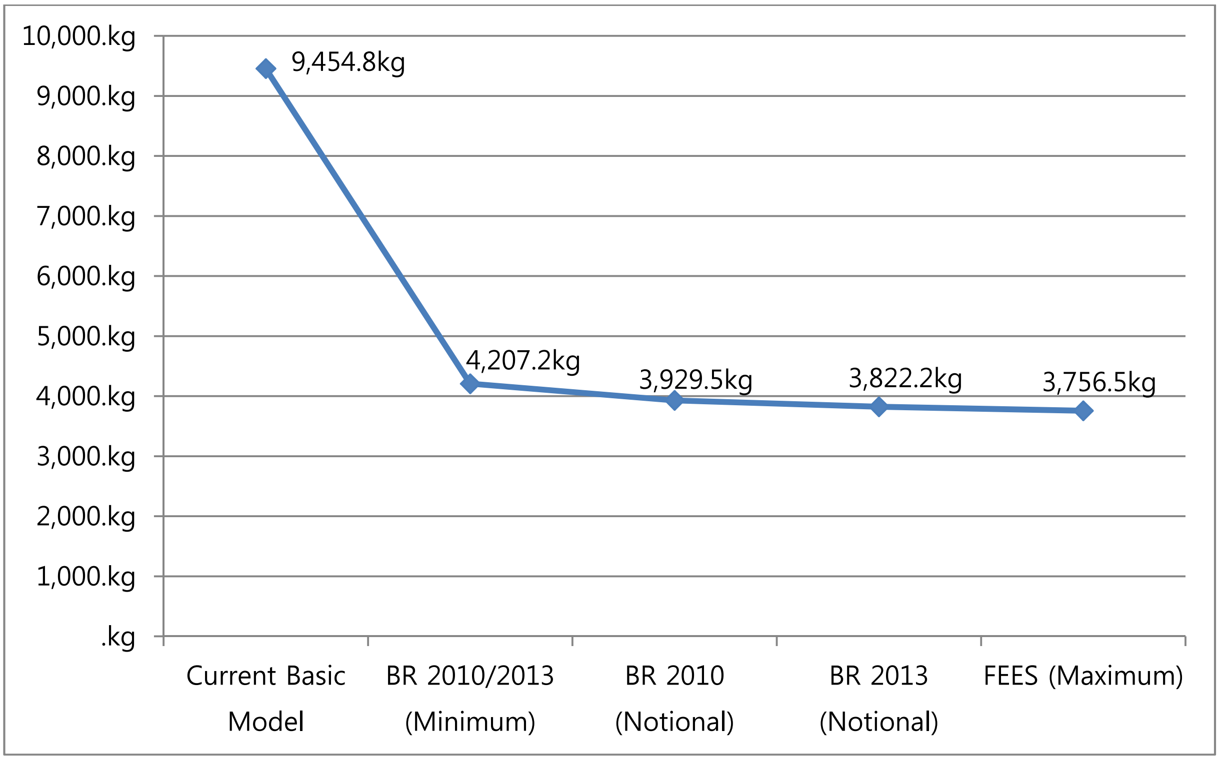
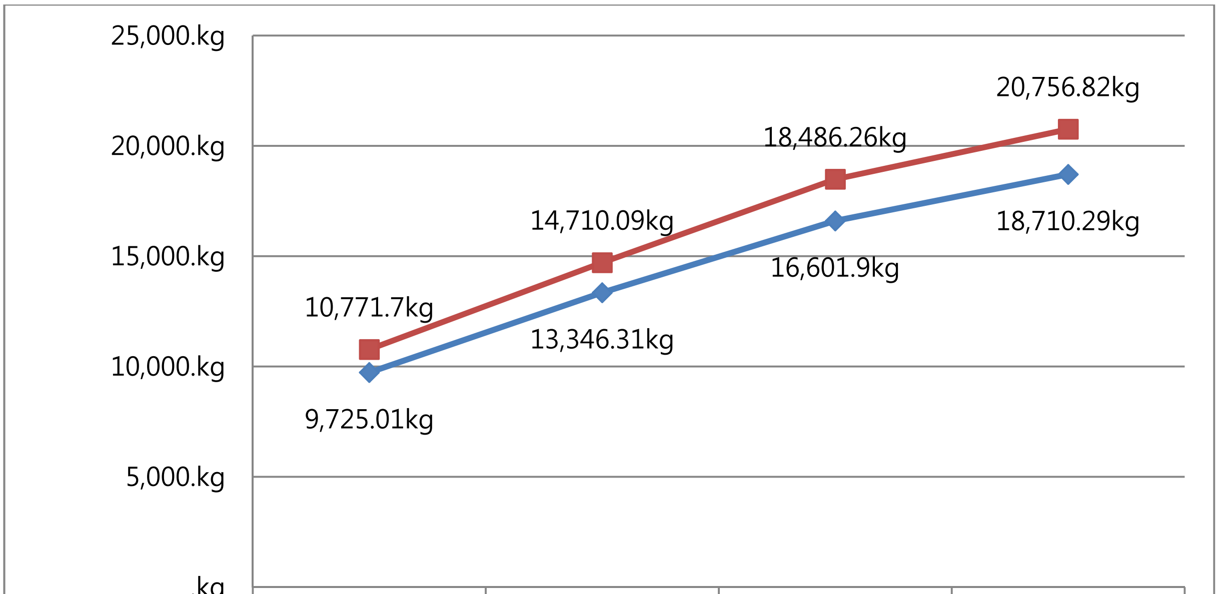


Figure 8.30 CO_2 Emission per year – Fibre Glass and EPS

Figure 8.31 indicated that the embodied CO_2 continues to increase as higher energy standards are applied for both fibre glass and EPS as it increases in the case of a detached house.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	9,725.01kg	13,346.31kg	16,601.9kg	18,710.29kg
EPS	10,771.7kg	14,710.09kg	18,486.26kg	20,756.82kg

Figure 8.31 Embodied CO_2 and CO_2 Emission - Fibre Glass and EPS

The CO_2 payback period is identified as shown in Figure 8.32.

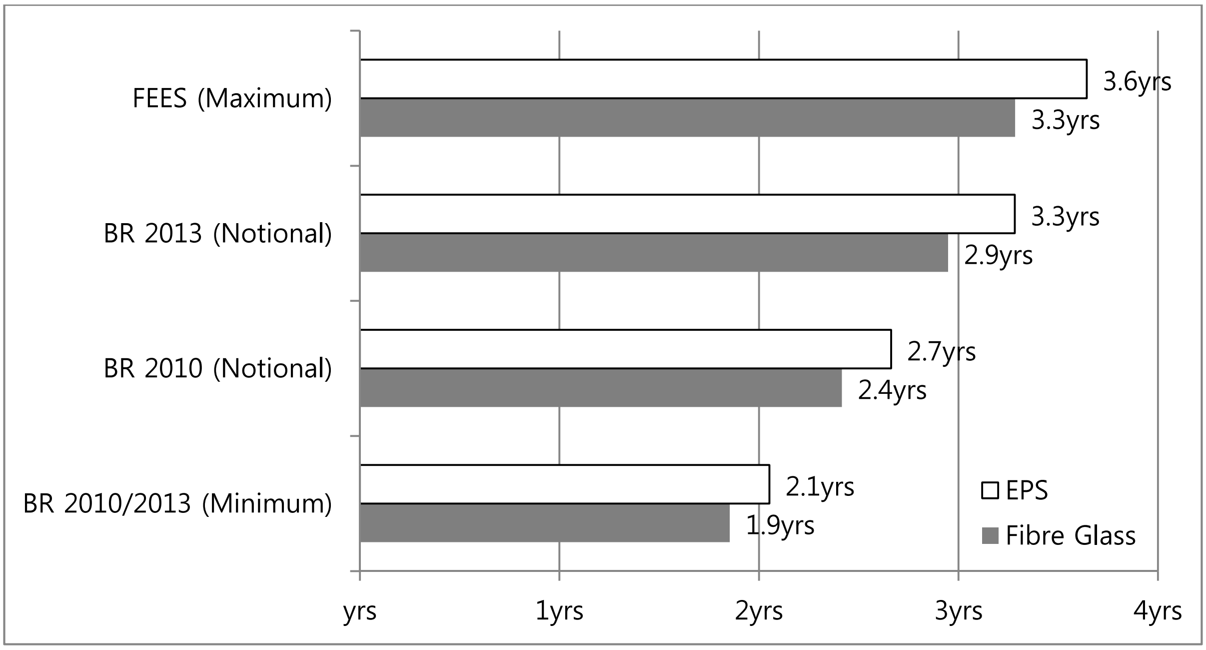


Figure 8.32 CO_2 Payback Period

It is obvious that the BR 2010/2013 (minimum) energy standard has the shortest CO_2 payback period of the other energy standards as shown in Figure 8.32. However, it should be noted that the gaps between the BR 2010/2013 (minimum) and the FEES (Maximum) are nearly two years for both the fibre glass and the EPS. If the CO_2 payback period is considered in conjunction with the embodied CO_2, it is revealed that the payback periods for retrieving the embodied CO_2 by reducing CO_2 emission are not significantly different among the different energy standards.

As show in Figure 8.33, the construction costs for reducing 1kg operational CO_2 emission continue to increase. The construction costs increase much more rapidly when the EPS is used than the fibre glass. As higher energy standards are adopted, the gaps of construction costs between the fibre glass and the EPS continue to increase.

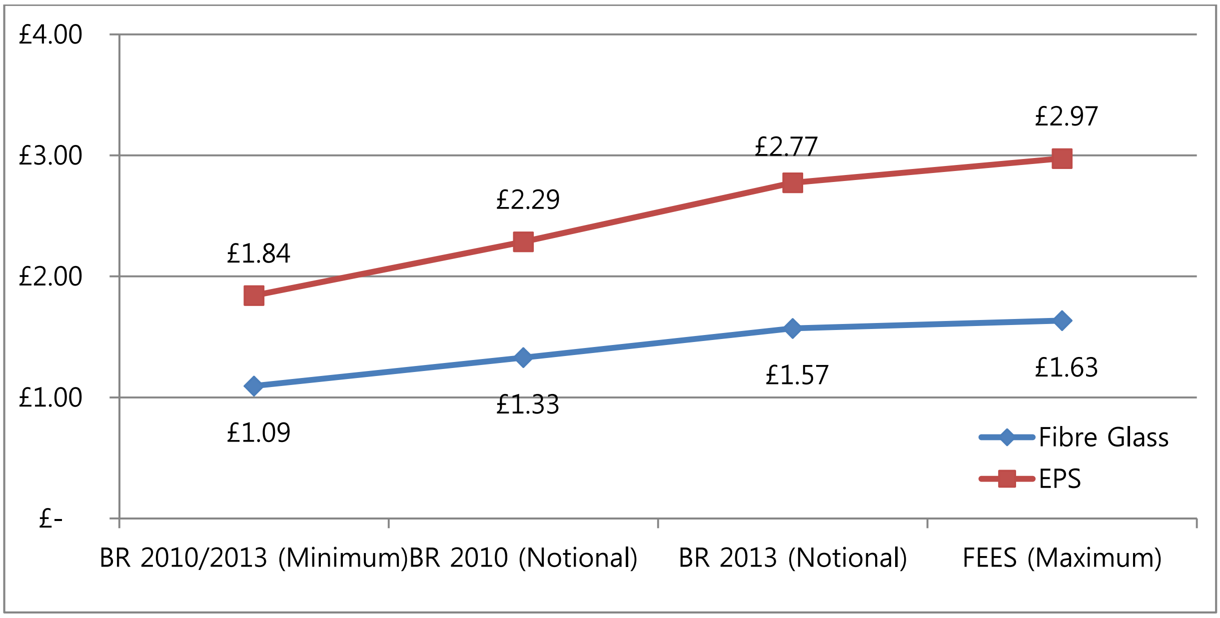


Figure 8.33 Construction Cost for Reducing 1kg Operational CO_2 Emission

However, the embodied CO_2 increase is almost the same between fibre glass and the EPS - see Figure 8.34. There are no significant differences between two materials as higher energy standards are adopted although the fibre glass (4.25kg/m^3) has a lower embodied CO_2 than the EPS (12kg/m^3).

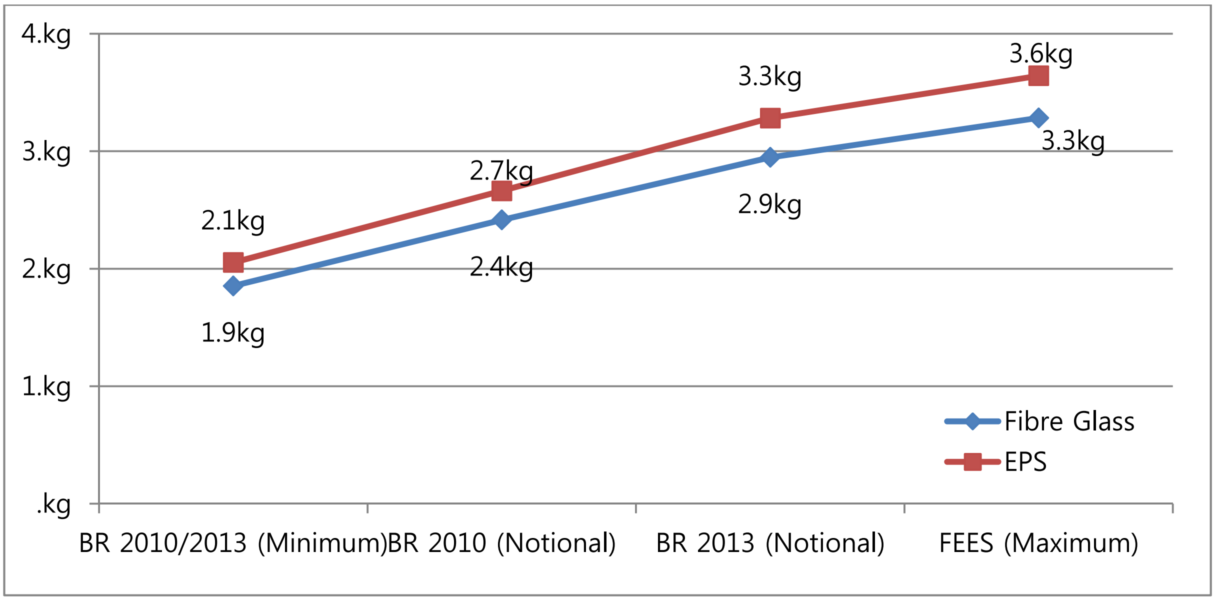


Figure 8.34 Embodied CO_2 for Reducing 1kg Operational CO_2 Emission

8.4 Terraced House Refurbishment Result

8.4.1 Energy Efficiency and Financial Impact

Figure 8.35 indicates that all the LCC results of a refurbished house with different energy standards are lower than the LCC of a refurbished house. Thus, it is economically beneficial to refurbish a solid-wall terraced house to achieve energy efficiency improvement.

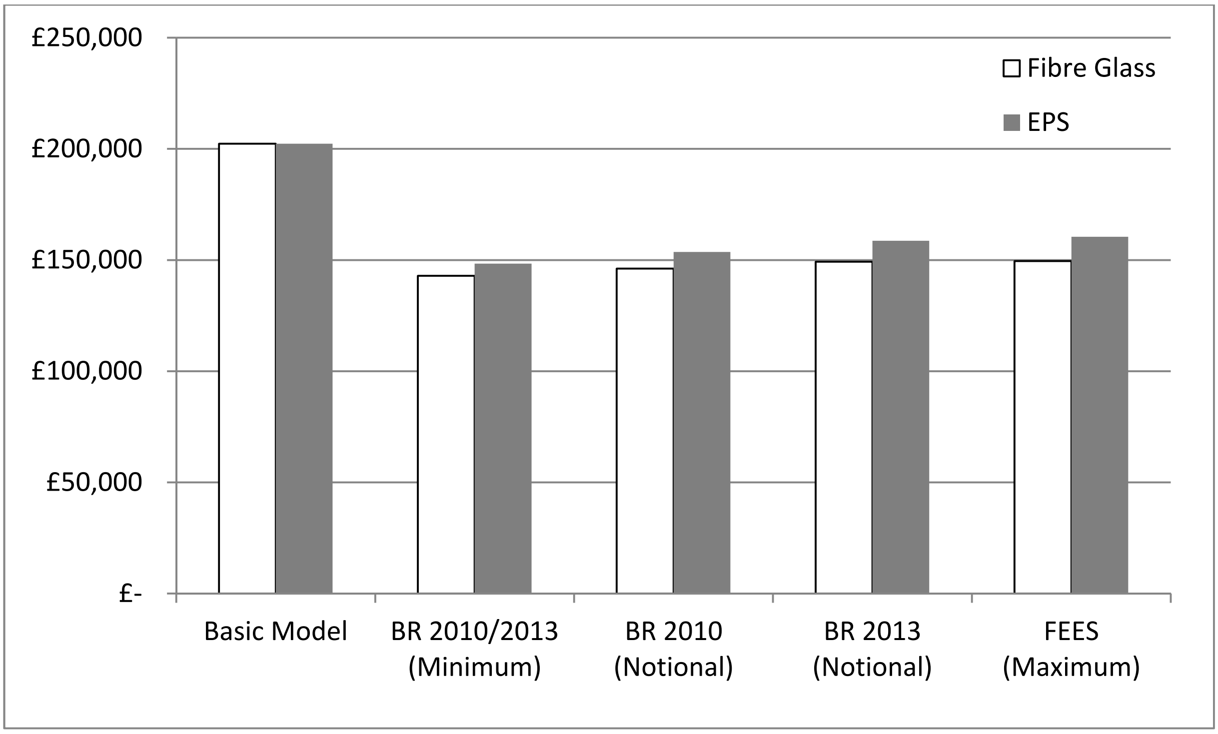


Figure 8.35 LCC Comparison between Existing House and Refurbished House

As shown in Figure 8.36, the LCC continues to increase as higher energy standards are adopted.

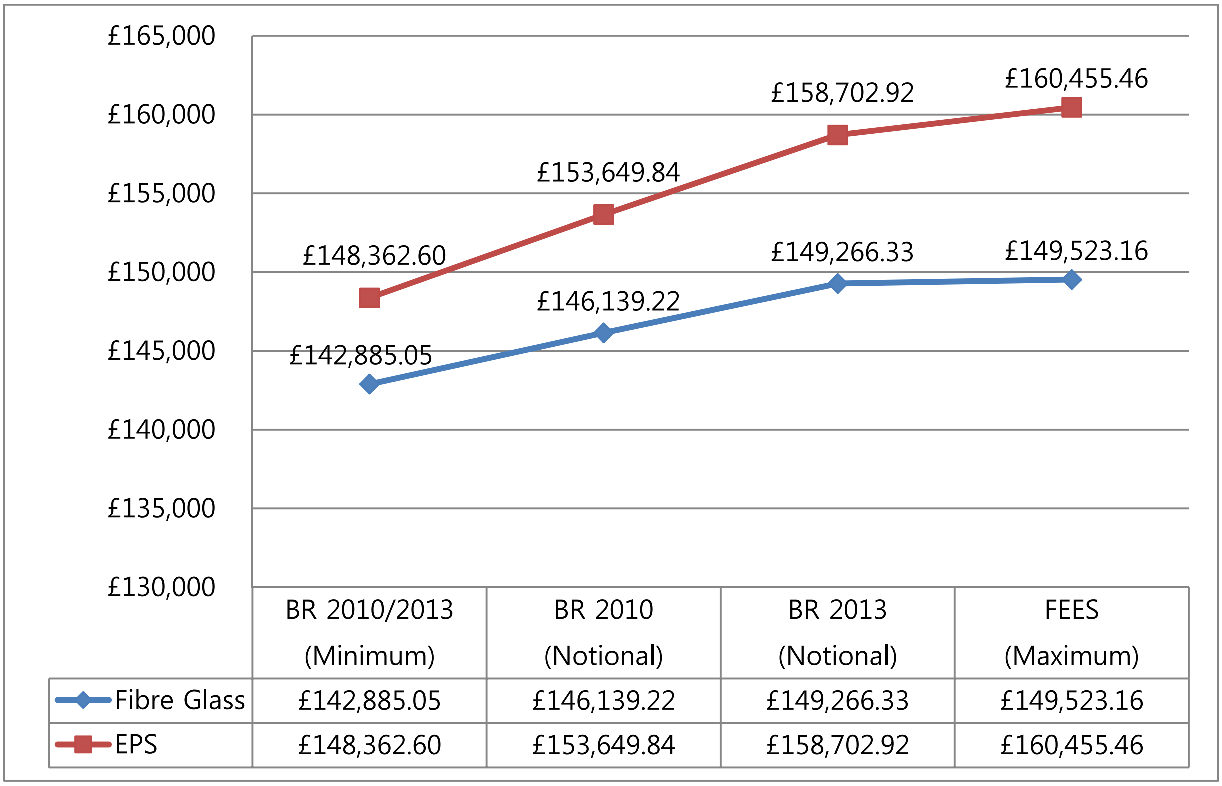


Figure 8.36 LCC Comparison of Fibre Glass and EPS

Figure 8.36 indicates the differences in life cycle costs for the fibre glass from the minimum energy performance requirements (BR 2010/13) to the maximum (FEES). The life cycle costs are much smaller when fibre glass is used compared to the EPS. The total life cycle costs continue to increase, however the rate of increase amount continues to fall as shown in Table 61. Based on this result, construction professionals can advise and persuade customers to adopt higher energy standard if want to adopt a high energy standard.

Table 61. Increasing Amount of LCC Comparison

Insulation Materials	**Upgrade A to B**	**Upgrade A to C**	**Upgrade A to D**
Fibre Glass	£ 3,254.16	£ 6,381.28 (B to C = £ 3,127.12)	£ 6,638.11 (C to D = £ 256.83)
EPS	£ 5,287.24	£ 10,340.32 (B to C = £ 5,053.08)	£ 12,092.86 (C to D = £ 1,752.54)

Note: A: BR 2010/2013 (Minimum), B: BR 2010 (Notional), C: BR 2013 (Notional), D: FEES (Maximum)

The costs in the parentheses indicate the increase amounts of construction cost between different two energy standards. For example, from B to C for the fibre glass indicates that additional £603.09. The life cycle costs options are investigated further for individual cost items such as: construction cost and operating costs, which include maintenance, operation and occupancy costs. The end-of-life costs are excluded (See Section 7.3.5).

Figure 8.37 indicates that construction costs for both material options continue to increase according different energy standards as more/different insulation materials are required in terms of the U-values of house elements and thickness of insulation materials. While the total construction cost increases, the rate of increase continues to fall as the changes in U-values of house elements and thickness of insulation materials become less (See Section 7.4.4.1).

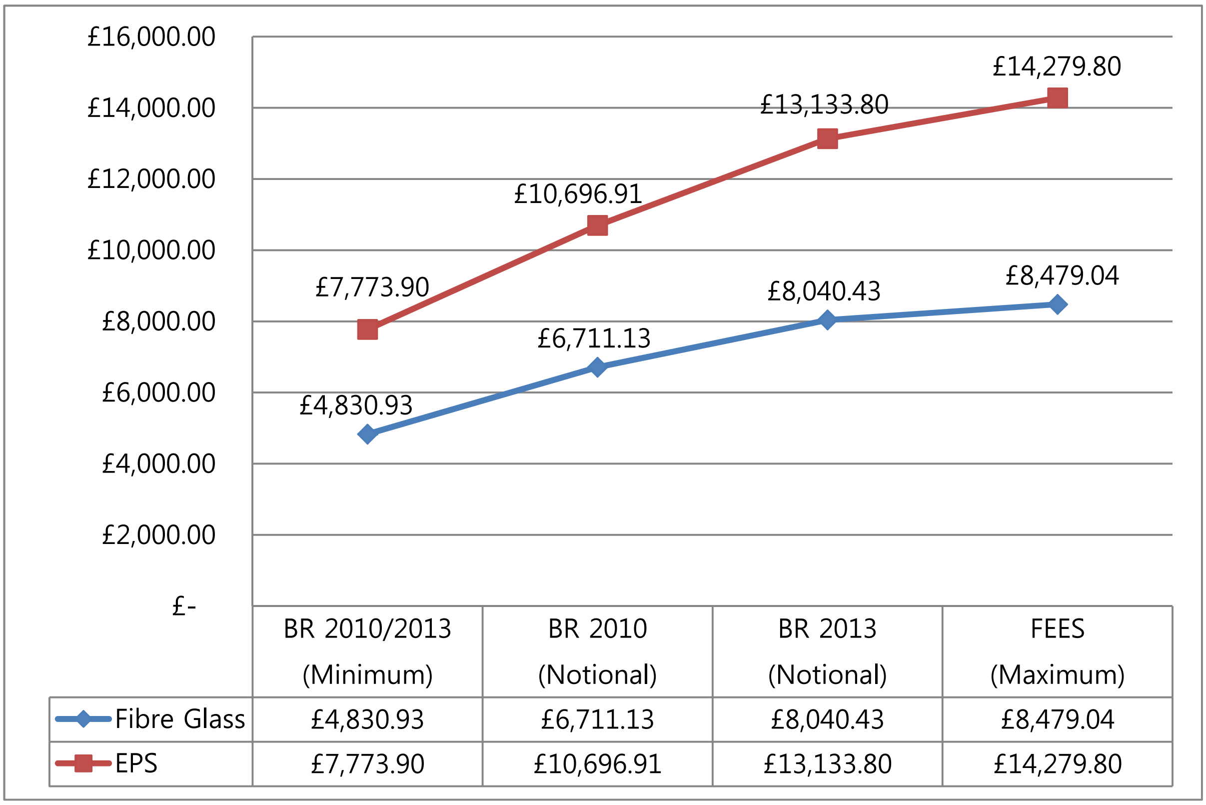
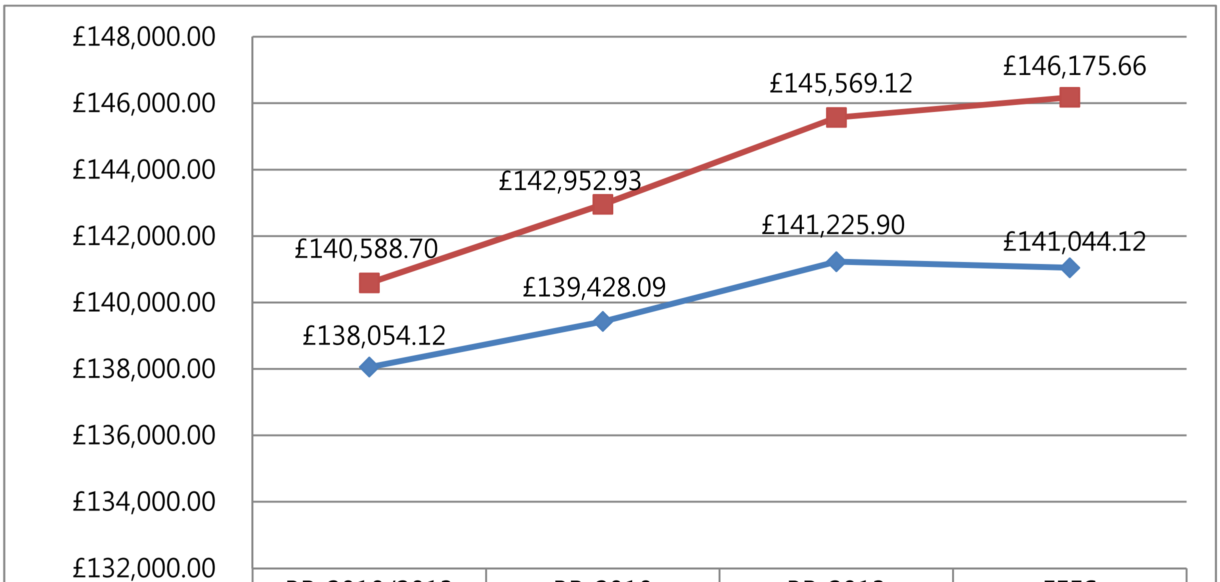


Figure 8.37 Construction Cost Comparison between Fibre Glass and EPS

If only the construction costs are considered, the BR 2010/2013 (Minimum) energy standard should be adopted based on the customers' preferences as the initial cost for refurbishment is the most influential factor in decision-making for housing refurbishment (See Section 6.3).

Figure 8.38 shows that the operating costs of the EPS has the same pattern as the construction cost, while the operating costs of the fibre glass does not have a continuous increase. Even the operating costs with the FEES (Maximum) are less than the operating costs with the BR 2013 (Notional). Based on this result, construction professionals can advise customers that a higher energy standard, such as FEES (Maximum), is more beneficial than BR 2013 (Notional) if the customer is seeking high energy efficiency.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	£138,054.12	£139,428.09	£141,225.90	£141,044.12
EPS	£140,588.70	£142,952.93	£145,569.12	£146,175.66

Figure 8.38 Operating Costs Comparison between Fibre Glass and EPS (NPV Applied 60 years)

The fluctuation in operating costs is caused by the relationship between construction cost and energy cost. The construction cost continues to increase when applying the higher energy standard, while the operating energy costs continue to decrease as energy performance improves - see Figures 8.39 and 8.40. The inverse proportion relationship is also confirmed, based on these results.

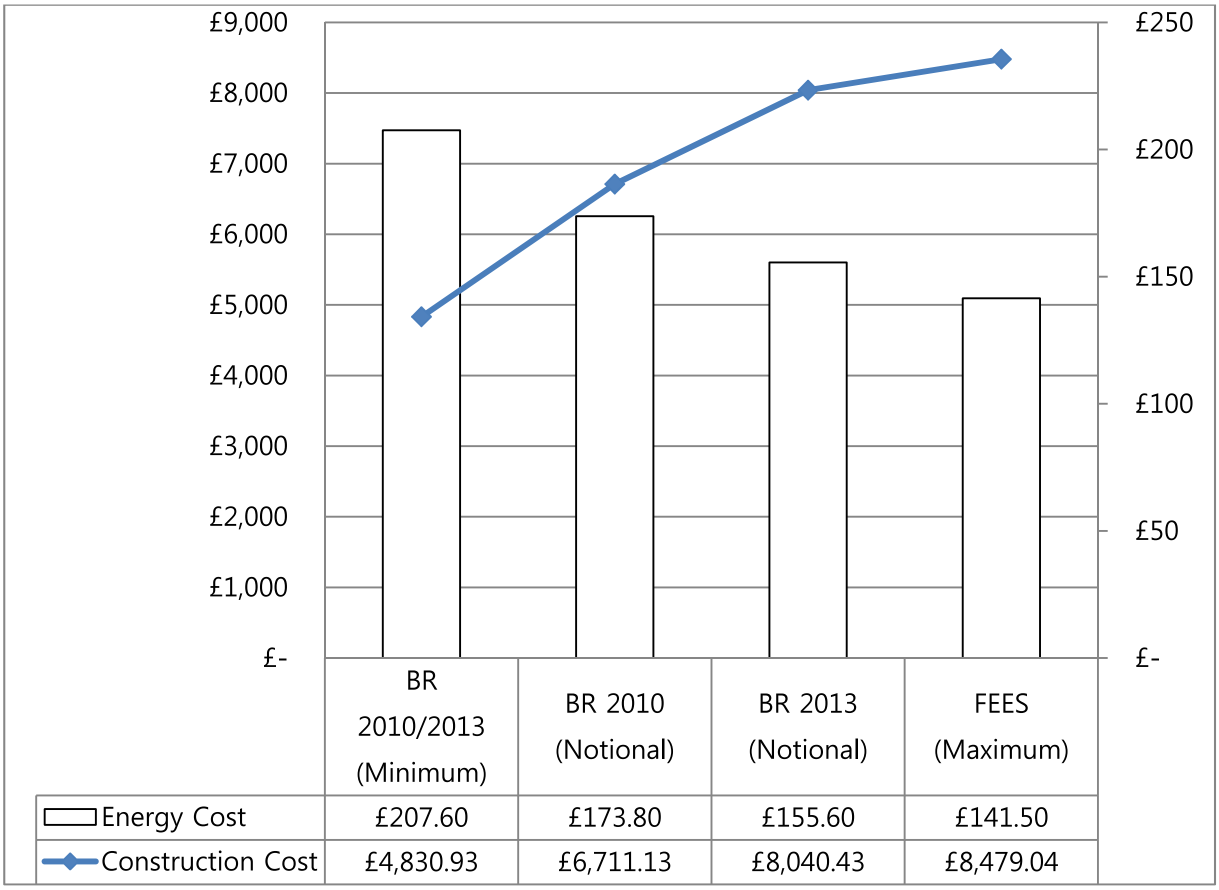


Figure 8.39 Construction Cost and Energy Cost – Fibre Glass

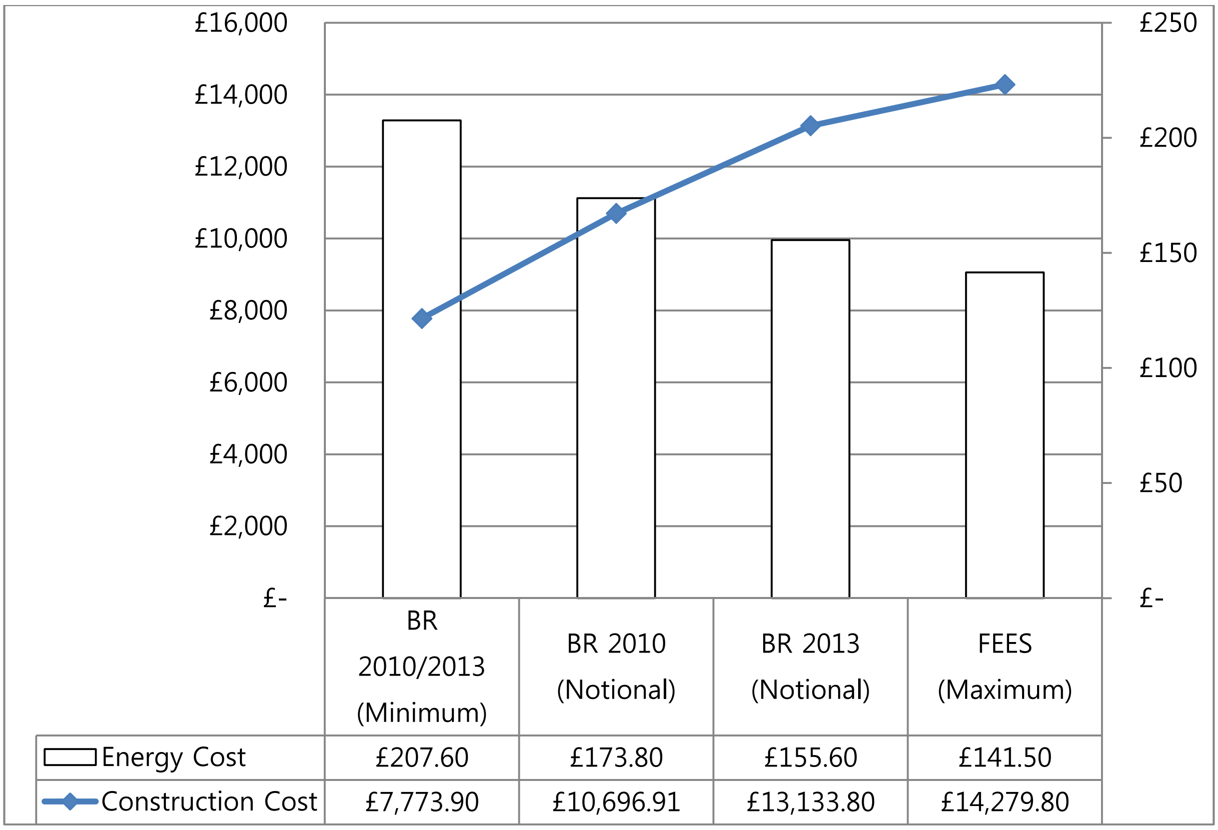


Figure 8.40 Construction Cost and Energy Cost – EPS

However, the operating energy costs reduction can reach a point where no significant reduction can be achieved, as shown in Figure 8.41. In this case, the maximum 82% energy cost can be reduced by adopting FEES, which is a 2% greater reduction compared to a detached house and 1% less than a semi-detached/end terrace house.

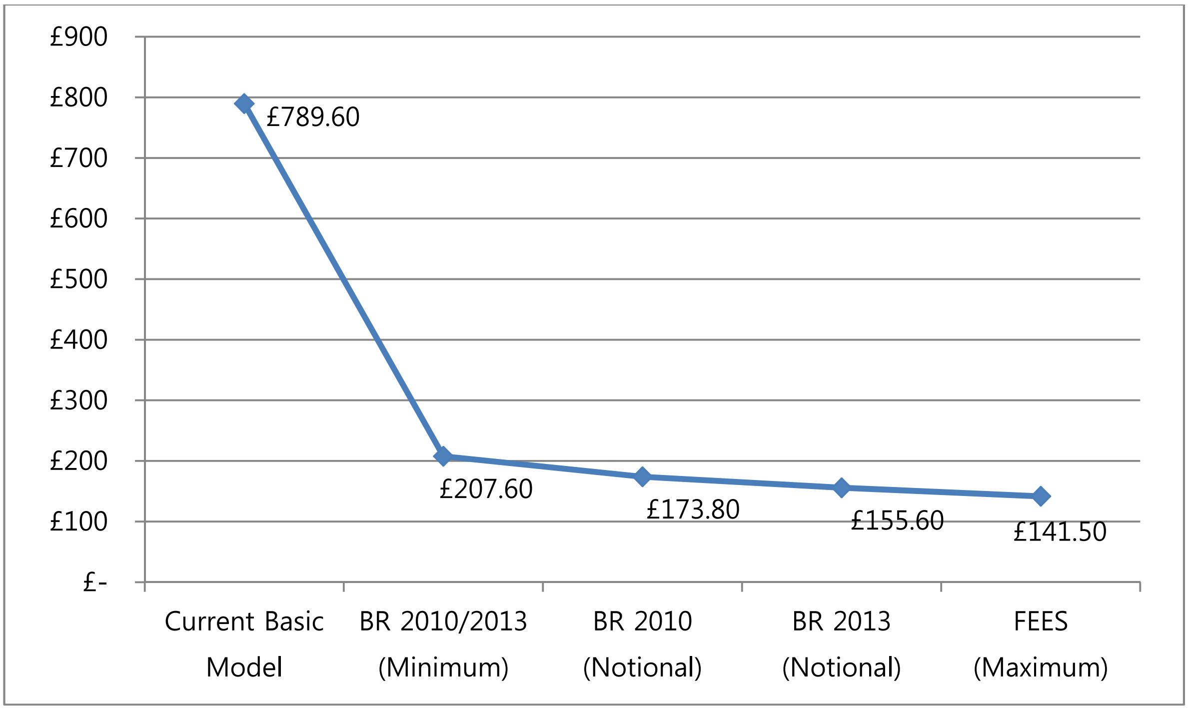


Figure 8.41 Energy Cost Reduction for Each Energy Standard

The construction cost for reducing £1 of operating energy cost is shown in Figure 8.42. For example, the fibre glass costs £8.30 for reducing £1 of the operating energy cost while the EPS costs £13.36.

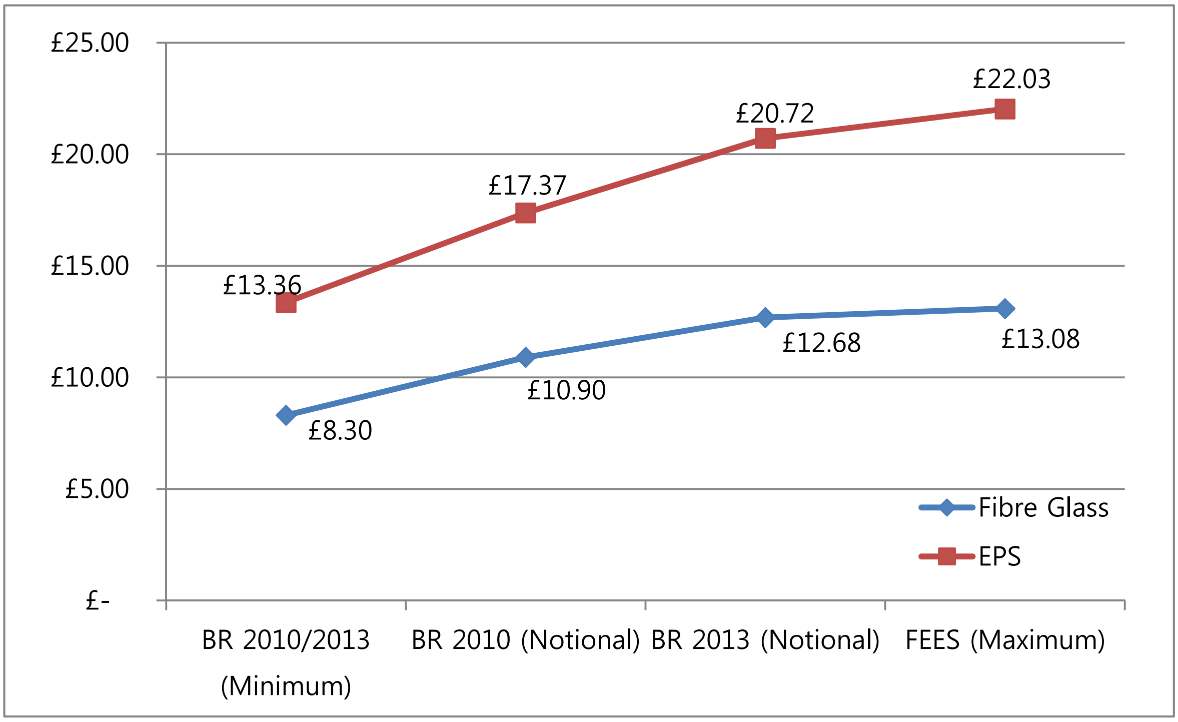


Figure 8.42 Construction Cost for Reducing £ 1 of Energy Cost - Fibre Glass and EPS

According to the customer's preference, the BR2010/2013 (Minimum) energy standard with the fibre glass is the most economic option. Although the amount of construction costs increase with the higher energy standard, operating costs can be saved over the life cycle. As far as the unit price and savings are concerned, fibre glass would be the better option in this example.

Figure 8.43 identifies the differences between the simple payback and discounted payback methods for fibre glass. It shows that there is a maximum of one year's difference between two payback period methods.

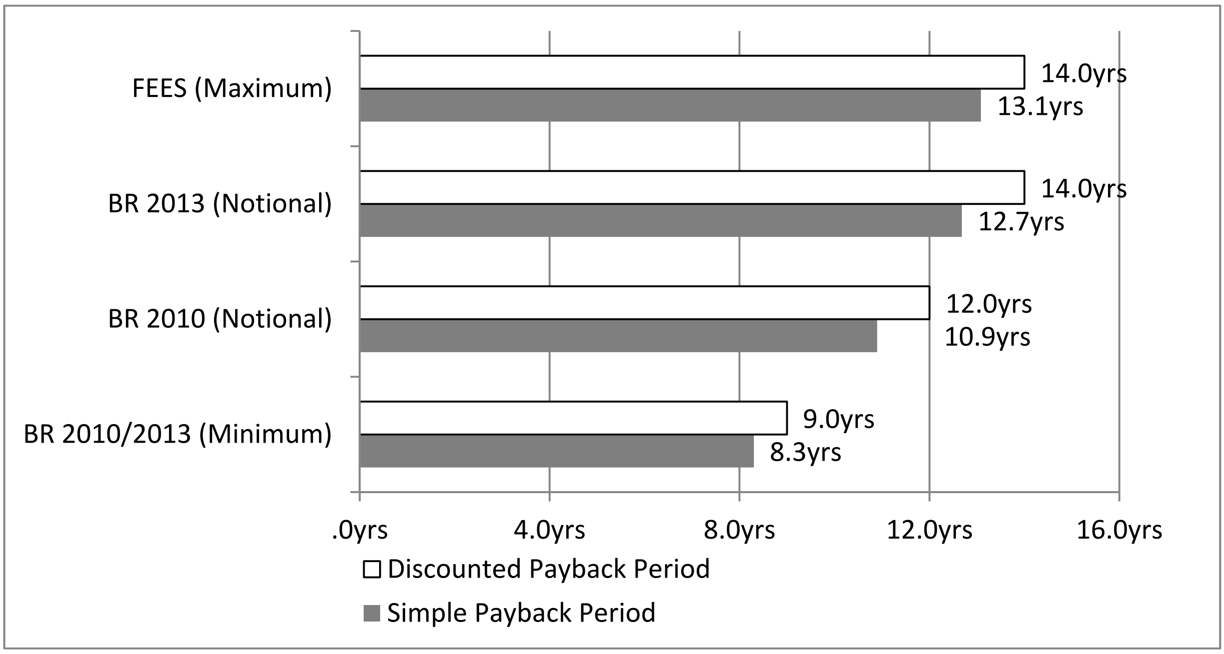


Figure 8.43 Simple Payback Period vs. Discounted Payback Period - Fibre Glass

This gap is much bigger in the EPS as there is at least a two-year difference (with a maximum three-year difference) as shown in Figure 8.44.

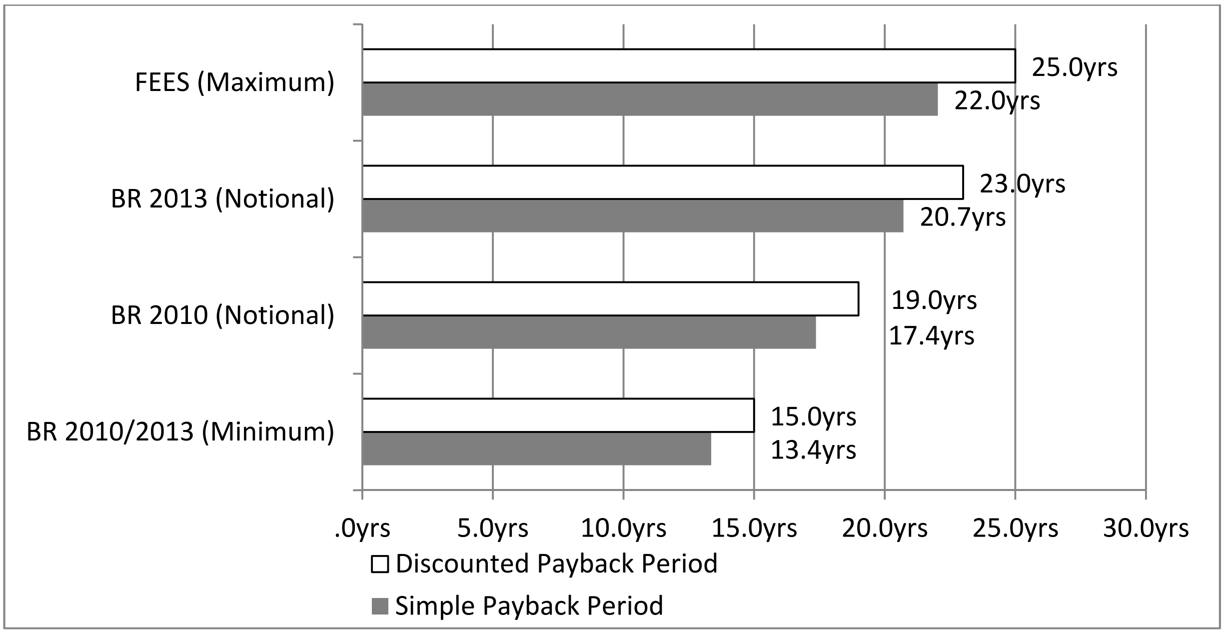
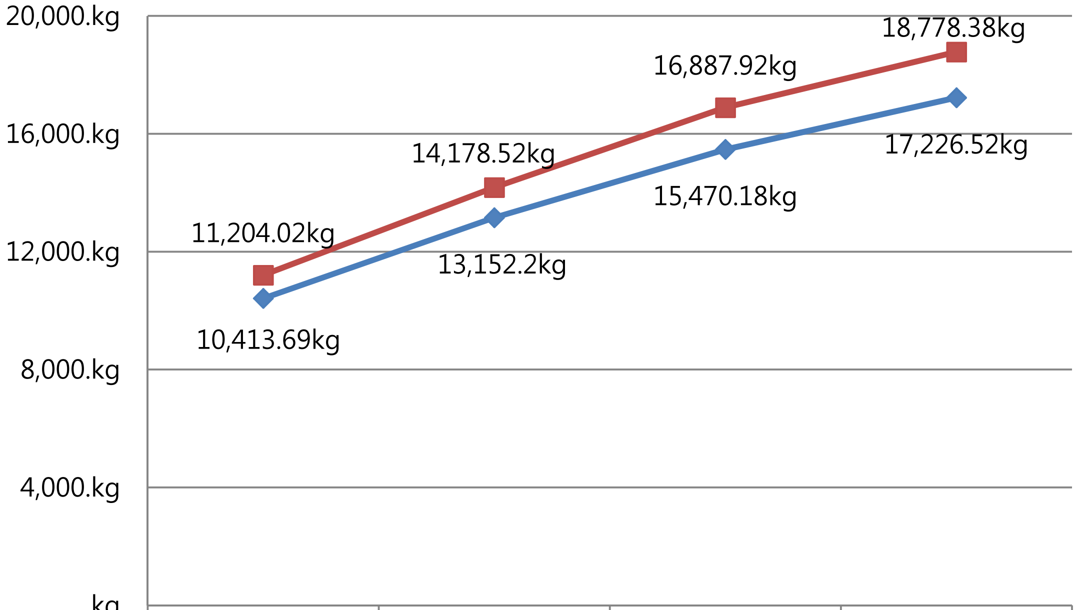


Figure 8.44 Simple Payback Period vs. Discounted Payback Period – EPS

8.4.2 Energy Efficiency and Financial Impact

The LCA results continue to increase as more insulation materials are installed as shown in Figure 8.45. This pattern is the same for the other types of houses.



	BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Fibre Glass	10,413.69kg	13,152.2kg	15,470.18kg	17,226.52kg
EPS	11,204.02kg	14,178.52kg	16,887.92kg	18,778.38kg

Figure 8.45 LCA Comparison of Fibre Glass and EPS

If the amount of CO_2 related to construction works and transportation is considered, it can be financially and environmentally beneficial to adopt the higher energy standard from the beginning.

Although the LCA continues to increase, Figure 8.46 indicates that the LCA of the existing house is higher than that of the refurbished house. Therefore refurbishment is a more environmentally-beneficial option than new build, and it is environmentally beneficial to refurbish a terraced house to make energy efficiency improvements.

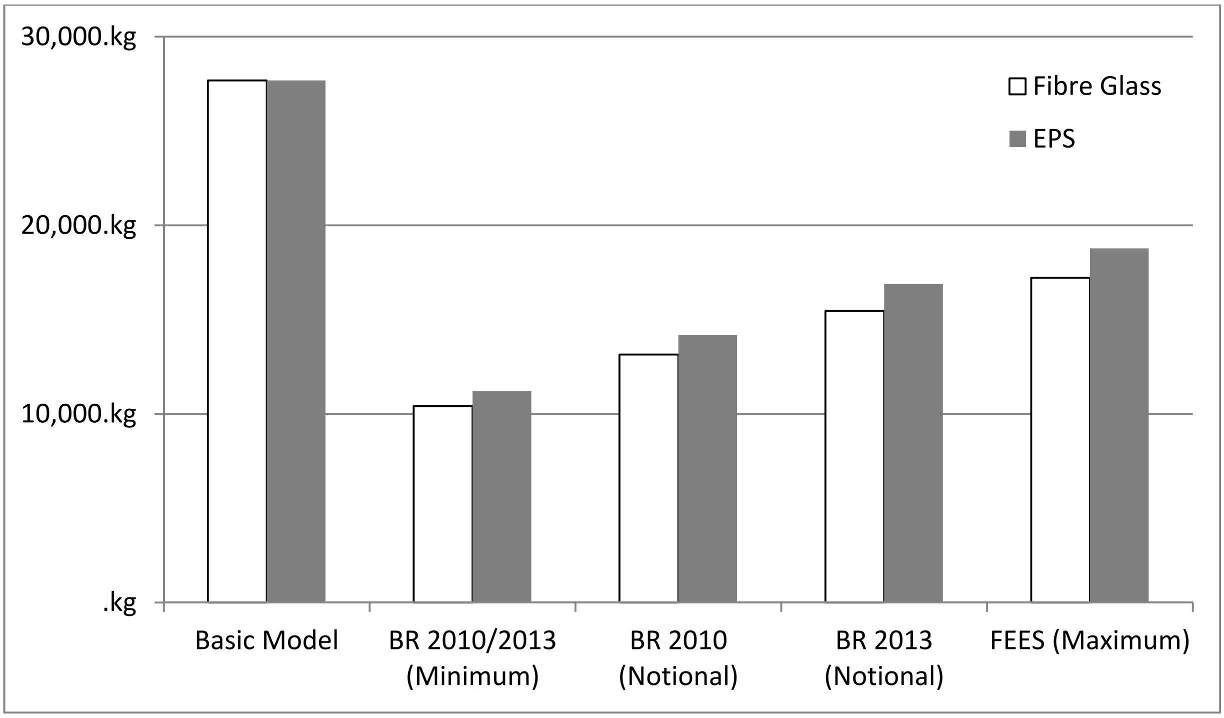


Figure 8.46 LCA Comparison between Existing House and Refurbished House

The amount of CO_2 emission per year also continues to diminish as higher energy standards are adopted as shown in Figure 8.47. However, there is no significant CO_2 reduction following BR 2010 (Notional) adoption. The percentage of CO_2 reduction with the adoption of FEES standard is 62% (6,716.2kg to 2,532.4kg).

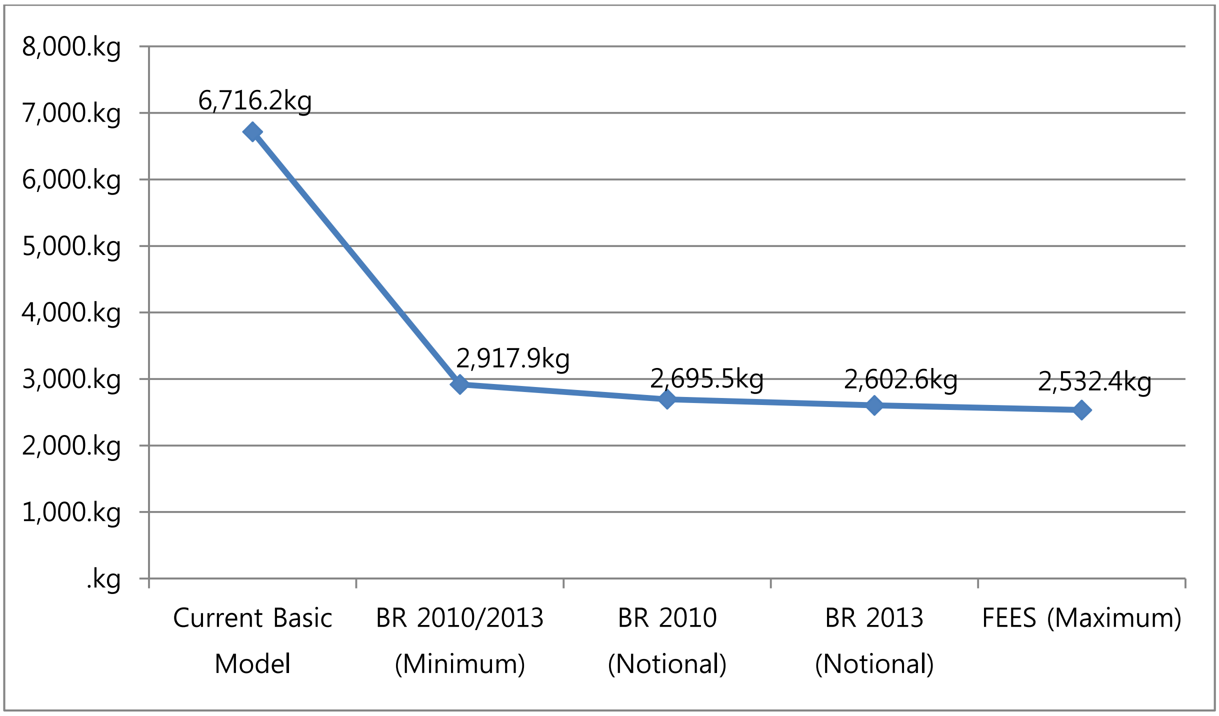


Figure 8.47 CO_2 Emission per year – Fibre Glass and EPS

Figure 8.48 indicated that the embodied CO_2 continues to increase as higher energy standards are applied for both fibre glass and EPS as it increases in other two types of houses.

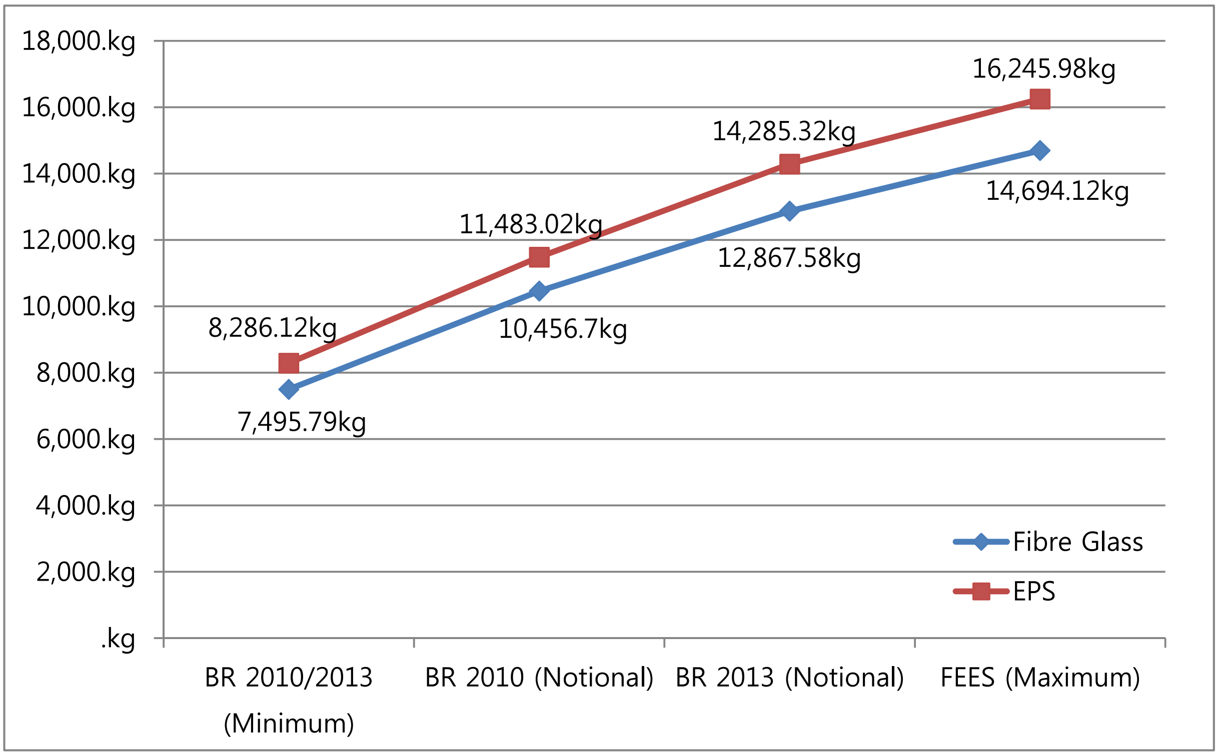


Figure 8.48 Embodied CO_2 and CO_2 Emission - Fibre Glass and EPS

The CO_2 payback period is identified as shown in Figure 8.49.

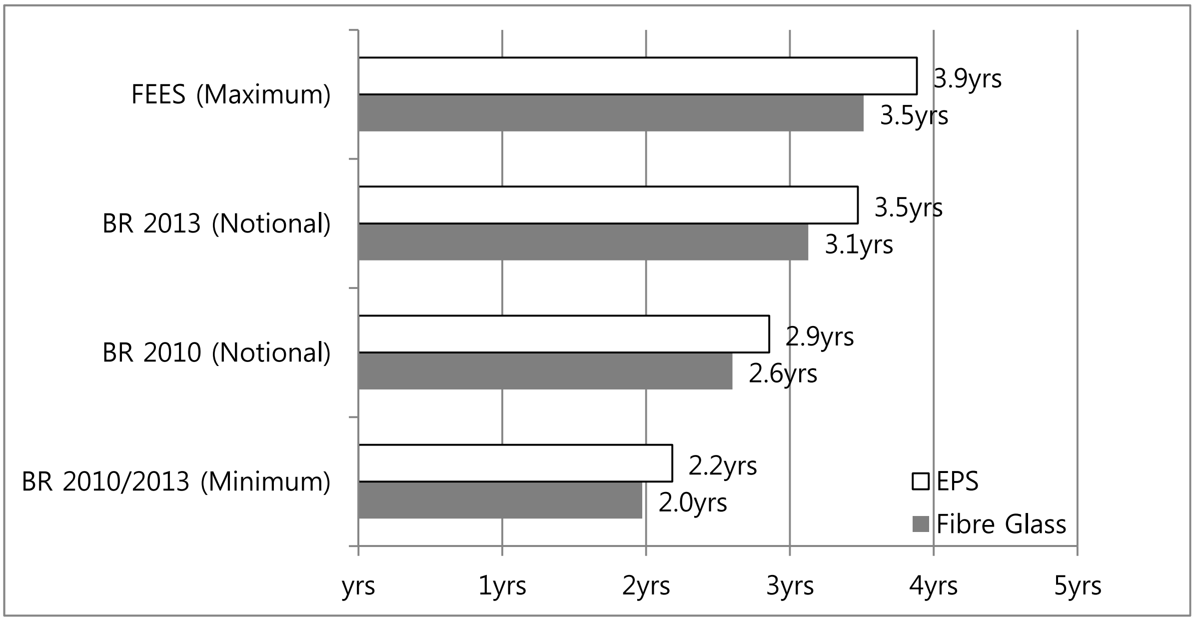


Figure 8.49 CO_2 Payback Period

It is clear that the BR 2010/2013 (minimum) energy standard gives the shortest CO_2 payback period when compared with other energy standards as shown in Figure 8.49. However, it should be noted that the gaps between the BR 2010/2013 (minimum) and the FEES (Maximum) is nearly two years for both fibre glass and the EPS. If the CO_2 payback period is considered in conjunction with the embodied CO_2, it is then the payback periods for retrieving the embodied CO_2 by reducing CO_2 emission are not significantly different among different energy standards.

As show in Figure 8.50, the construction costs for reducing 1kg operational CO_2 emission continue to increase. The rate of construction cost increase is more rapid when the EPS is used than fibre glass. As higher energy standards are adopted, the gaps in construction costs between fibre glass and the EPS continue to grow.

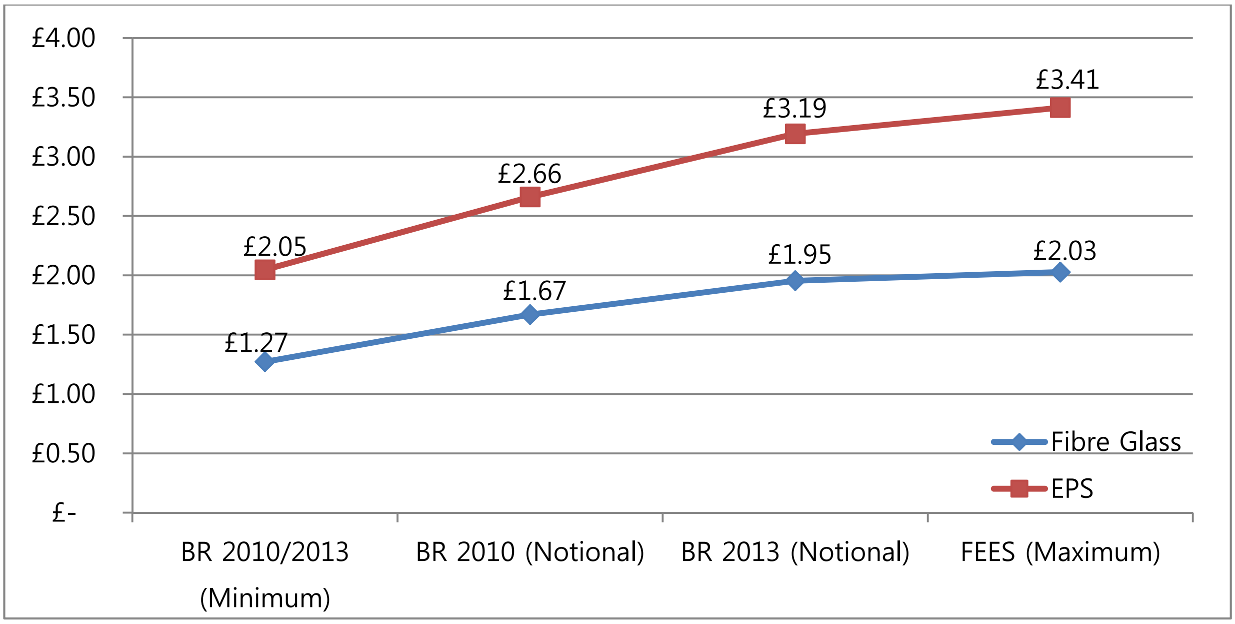


Figure 8.50 Construction Cost for Reducing 1kg Operational CO_2 Emission

There are no significant differences between two materials as higher energy standards are adopted although the fibre glass (4.25kg/m^3) has lower embodied CO_2 than the EPS (12kg/m^3). Their rate of increase is almost the same – see Figure 8.51.

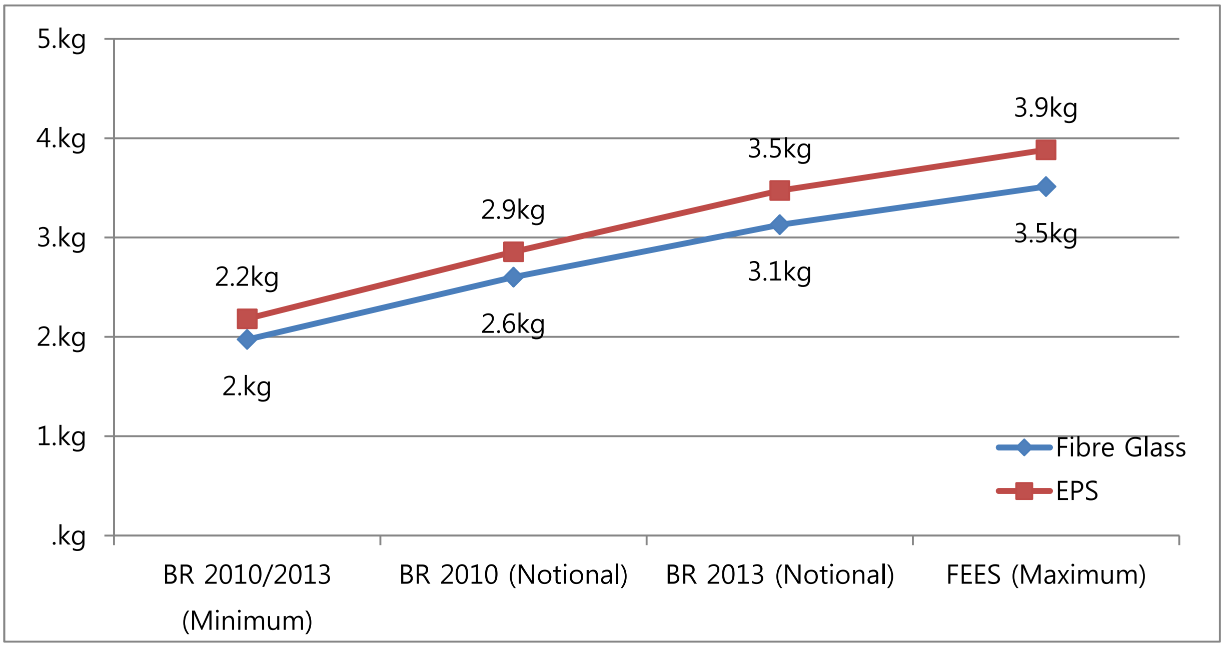


Figure 8.51 Embodied CO_2 for Reducing 1kg Operational CO_2 Emission

8.5 Comparative Whole Life Financial and Environmental Studies Among Different House Types

Figure 8.52 shows the comparison of construction costs for reducing £1 of energy cost across the three house types when fibre glass is used. The minimum energy standard (BR2010/2013) is the most economical refurbishment option for all three house types based on initial cost as a decision-making factor. The semi-detached/end terrace house shows the lowest construction costs for reducing £1 of energy cost. The gaps in construction costs between different types of houses continue to increase but stay in the same order with a terraced house being the highest and the semi-detached/end terrace being the lowest.

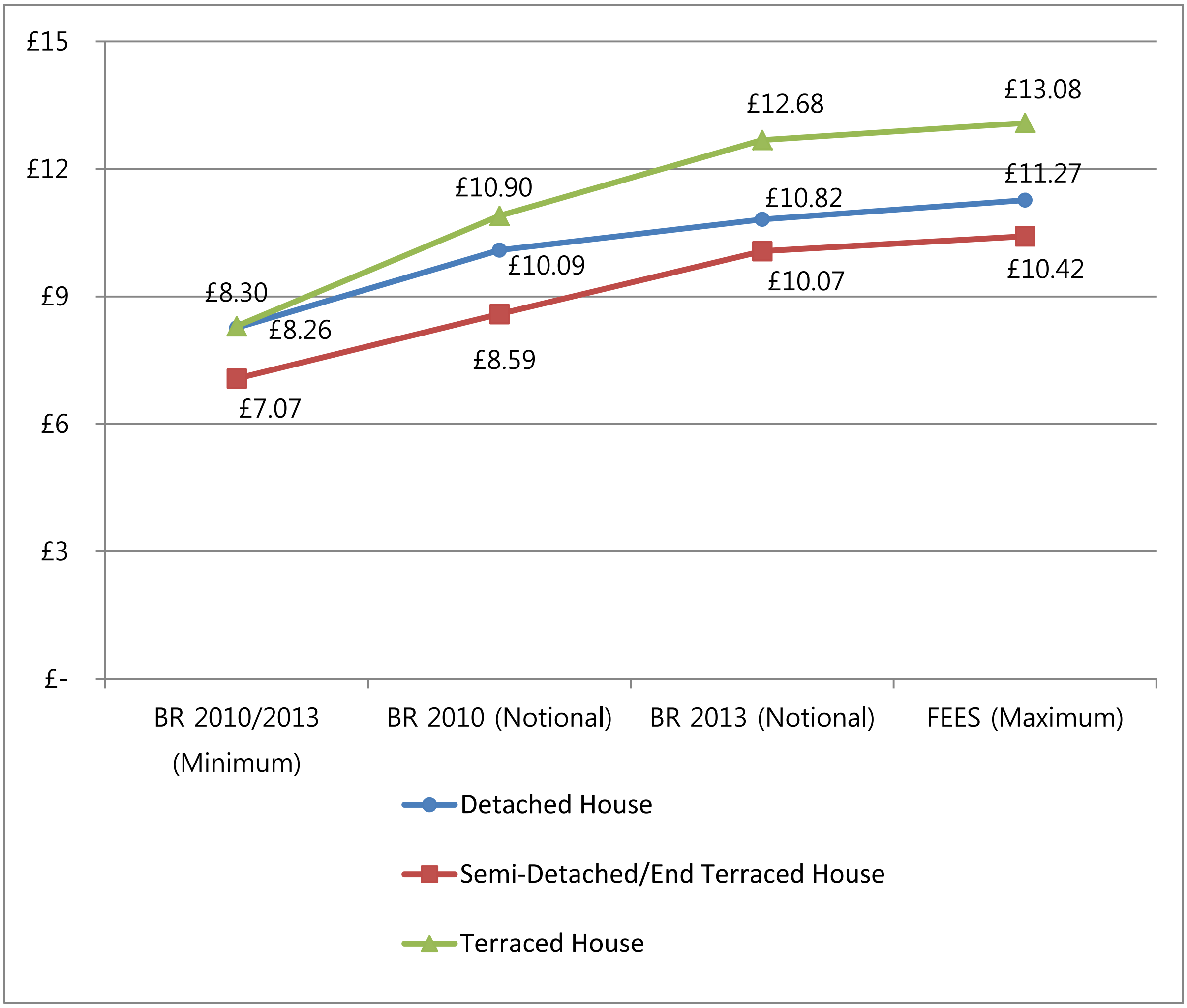


Figure 8.52 Construction Cost for Reducing £ 1 of Energy Cost - Fibre Glass

There is a difference in the use of fibre glass and EPS in terms of the construction costs. Furthermore, the construction costs for a detached house are larger than a terraced house when the minimum and BR 2010 energy standards are adopted as shown in Figure 8.53. The construction costs of a terraced house are always larger than a detached house.

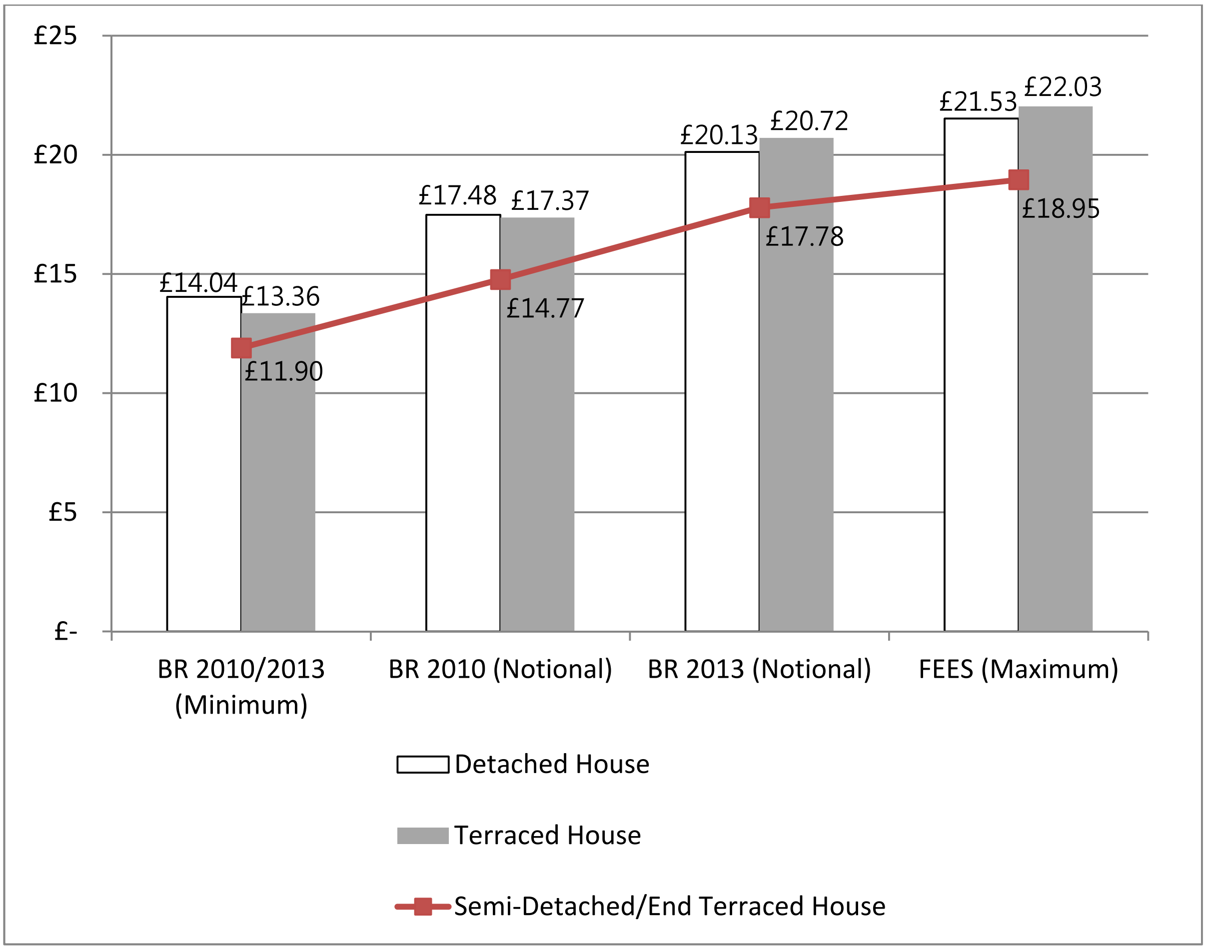


Figure 8.53 Construction Cost for Reducing £ 1 of Energy Cost - EPS

As a result, the minimum energy standard (BR2010/2013) is the most economical refurbishment option for all three house types when the EPS is used. However, the construction professional needs to consider that the application of EPS is more beneficial when higher energy standards are adopted in a detached house compared to the lower energy standards where the customer insists on the use of EPS for insulation material, but vice versa for a terraced house.

The construction costs for reducing 1kg CO_2 between different types of houses are identified as shown in Figure 8.54 and Figure 8.55. The terraced house is the most expensive house type to reduce 1kg of operational CO_2 when the fibre glass is used. The detached house is the most expensive when EPS is used. For both materials, the semi-detached/end terrace house is the most economical house type to achieve 1kg CO_2 reduction.

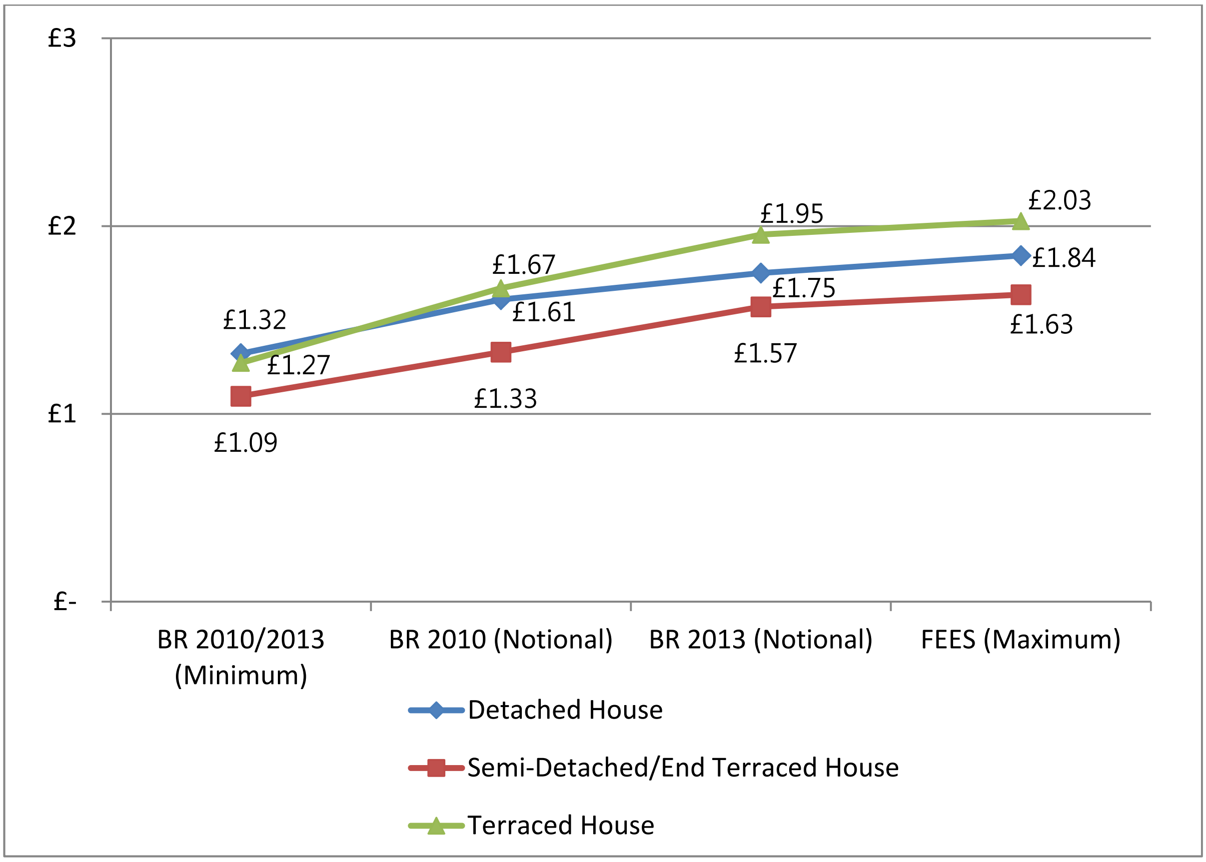


Figure 8.54 Construction Cost for Reducing 1 kg of Operational CO_2 – Fibre Glass

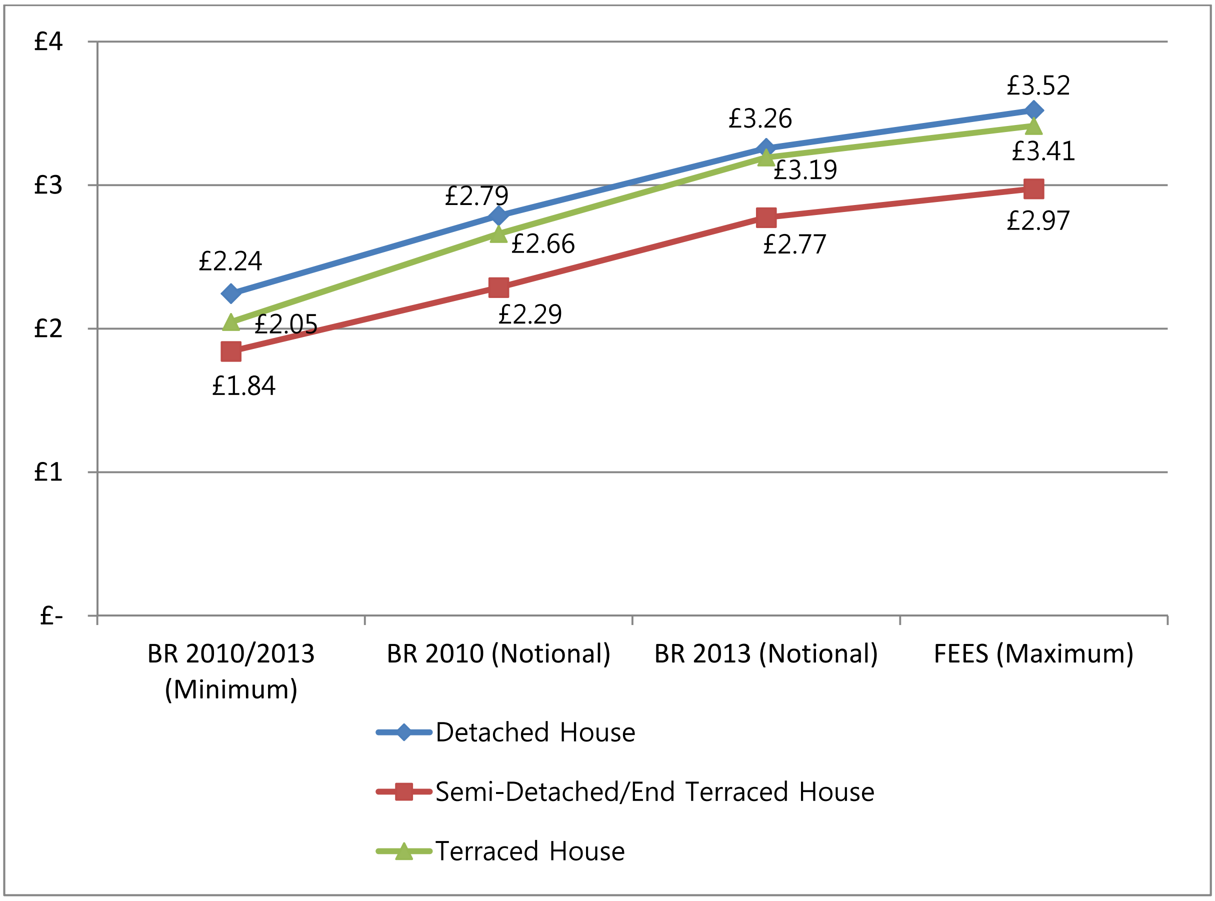


Figure 8.55 Construction Cost for Reducing 1 kg of Operational CO_2 – EPS

When the embodied CO_2 for reducing 1kg CO_2 is considered as a decision-making criterion for refurbishment, the minimum energy standard is the most economical option for all three types of houses as shown in Figure 8.56 and 8.57. In addition, the semi-detached/end terrace house is identified as the most economical house type, and the detached house is the most expensive when using fibre glass and EPS.

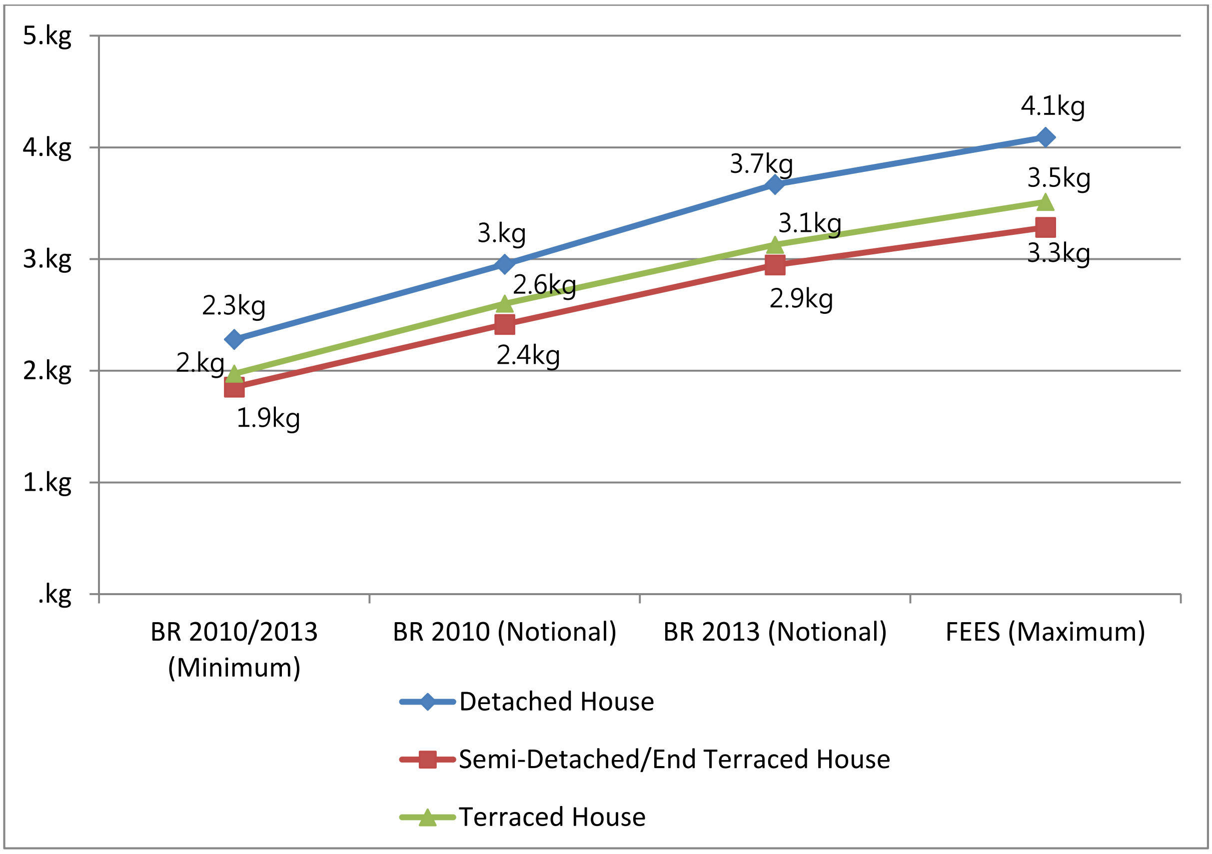


Figure 8.56 Embodied CO_2 for Reducing 1kg of Operational CO_2 – Fibre Glass

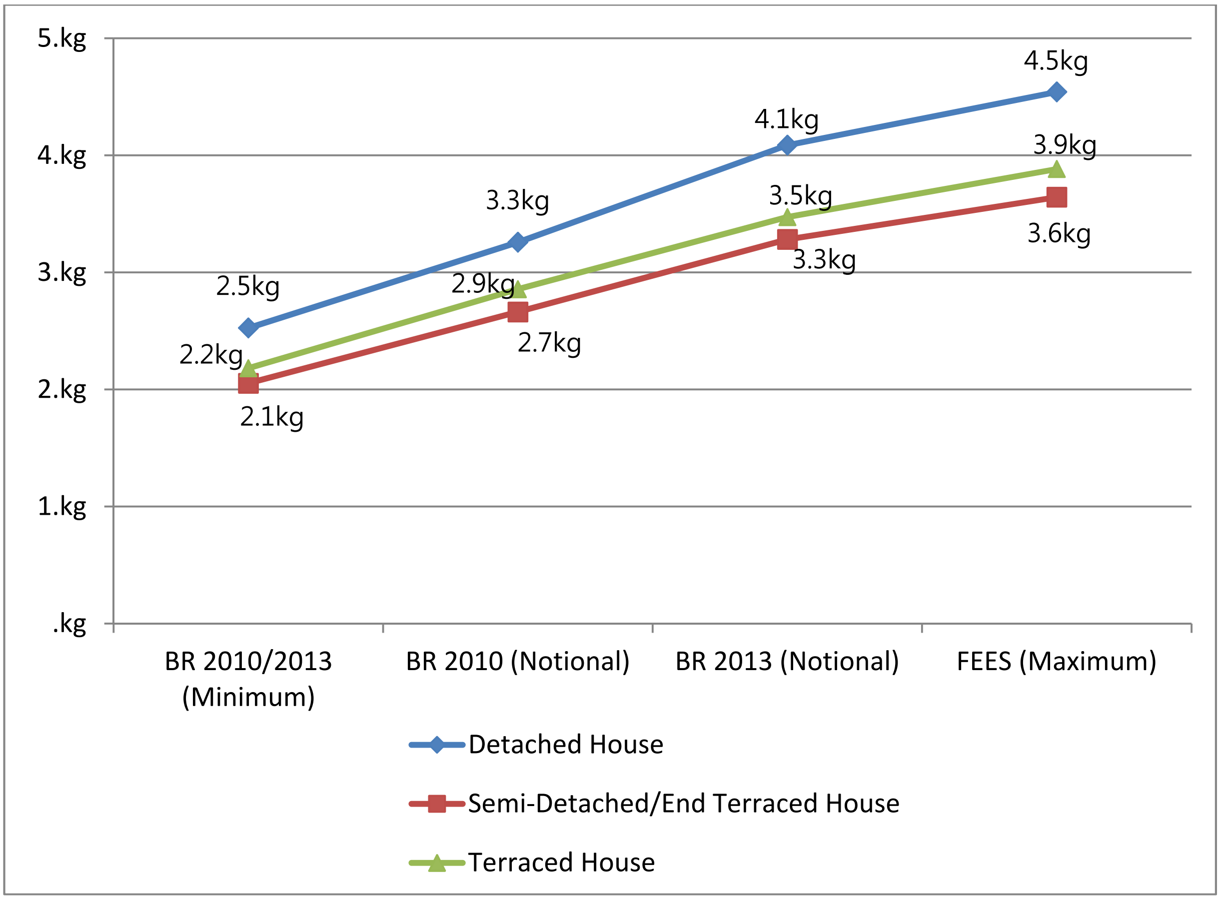


Figure 8.57 Embodied CO_2 for Reducing 1kg of Operational CO_2 – EPS

When fibre glass is used, the gaps in the payback period between the detached house and terraced house increases as higher energy standards are adopted as shown in Figure 8.58. In contrast to the fibre glass, the payback periods are the same for both detached house and terraced house between the minimum energy standard and BR 2010 when the EPS is used (Figure 8.59). In both cases, the semi-detached/end terrace house has the shortest payback period than other two types

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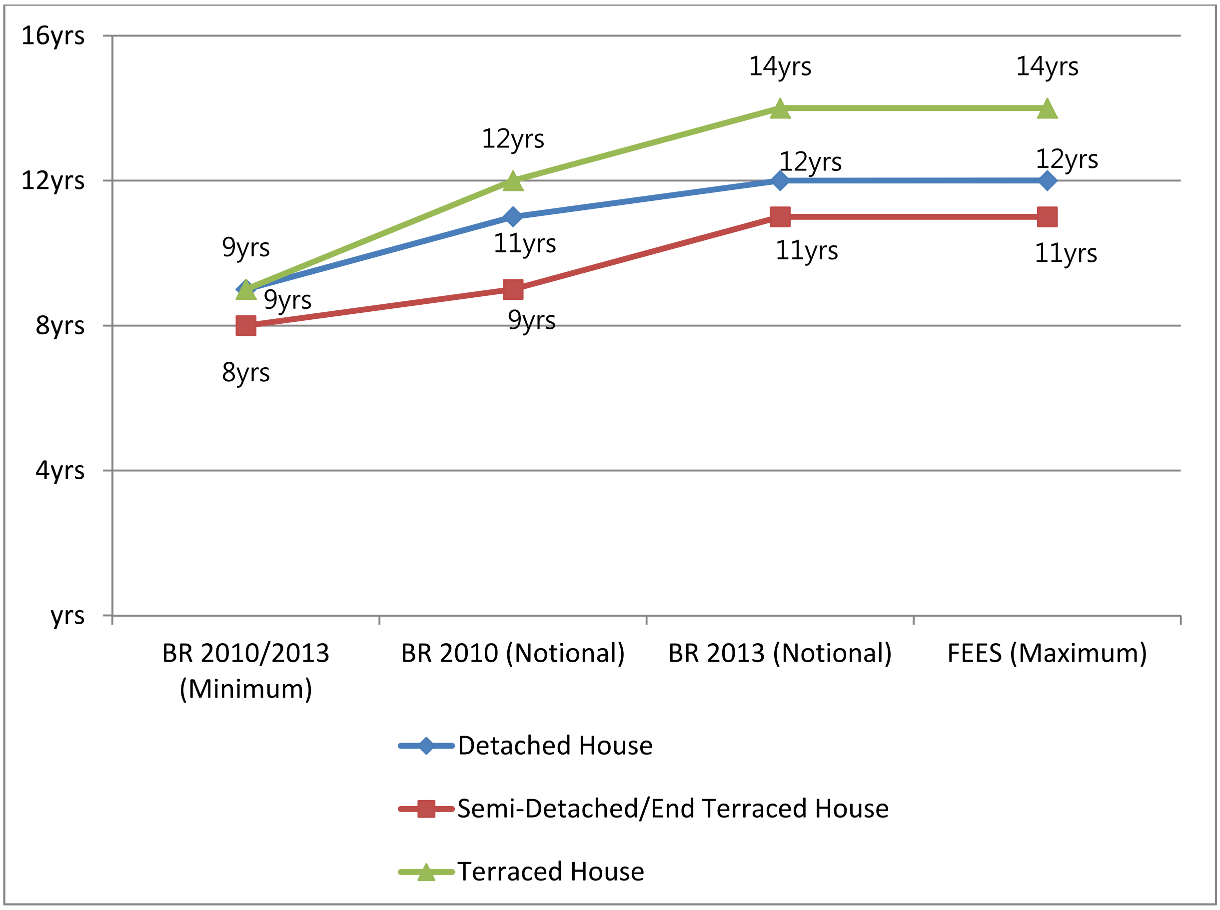

Figure 8.58 Discounted Payback Period – Fibre Glass

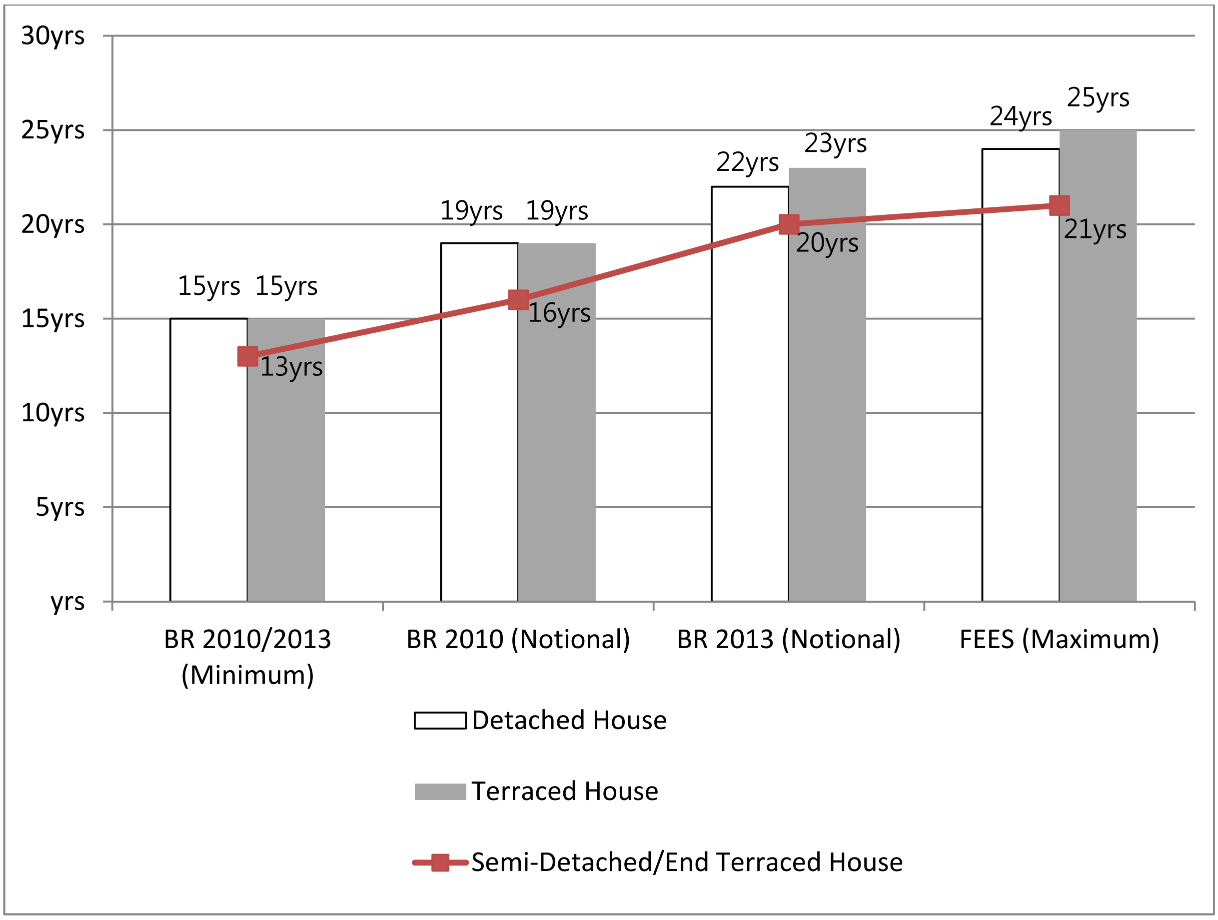

Figure 8.59 Discounted Payback Period – EPS

As shown in Figure 8.60 and 8.61, the CO_2 payback periods for all three types of houses are almost the same whether using fibre glass or EPS. The detached house indicates the longest CO_2 payback period, while the semi-detached/terraced house indicates the shortest CO_2 payback period, regardless of the insulation materials used.

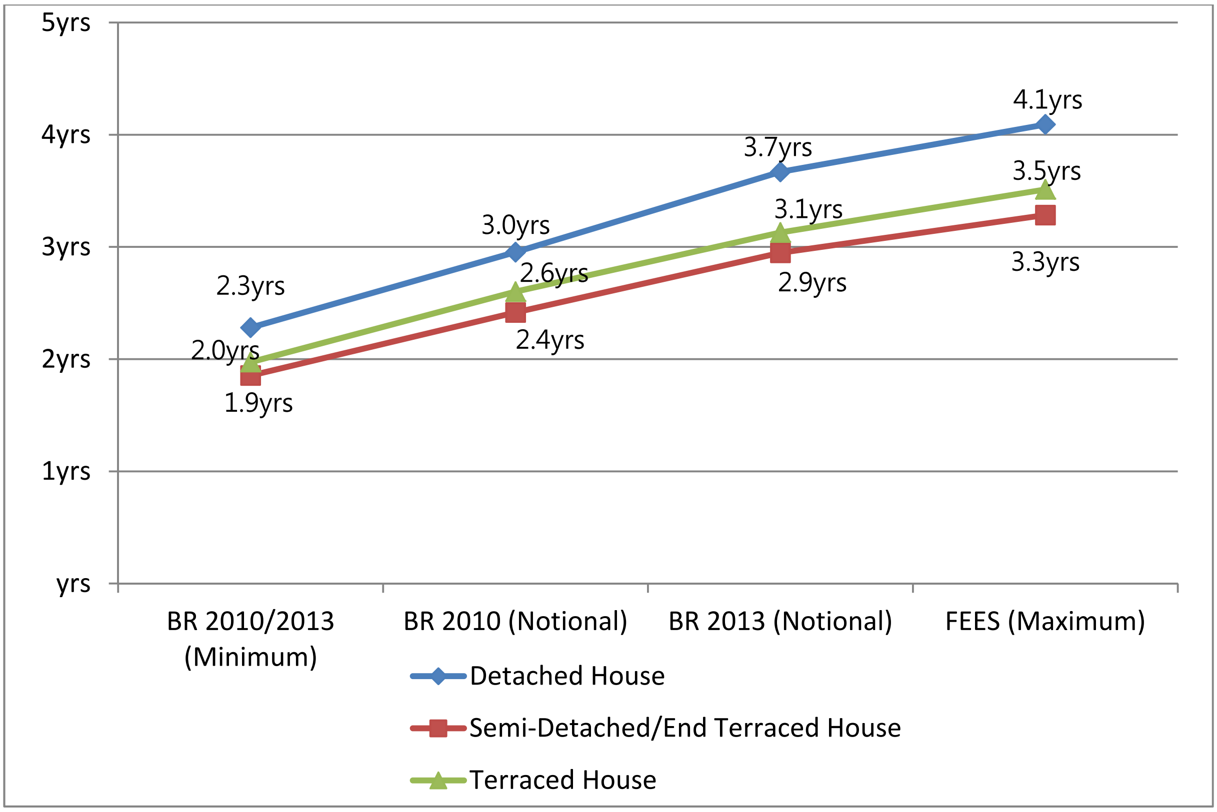

Figure 8.60 CO_2 Payback Period – Fibre Glass

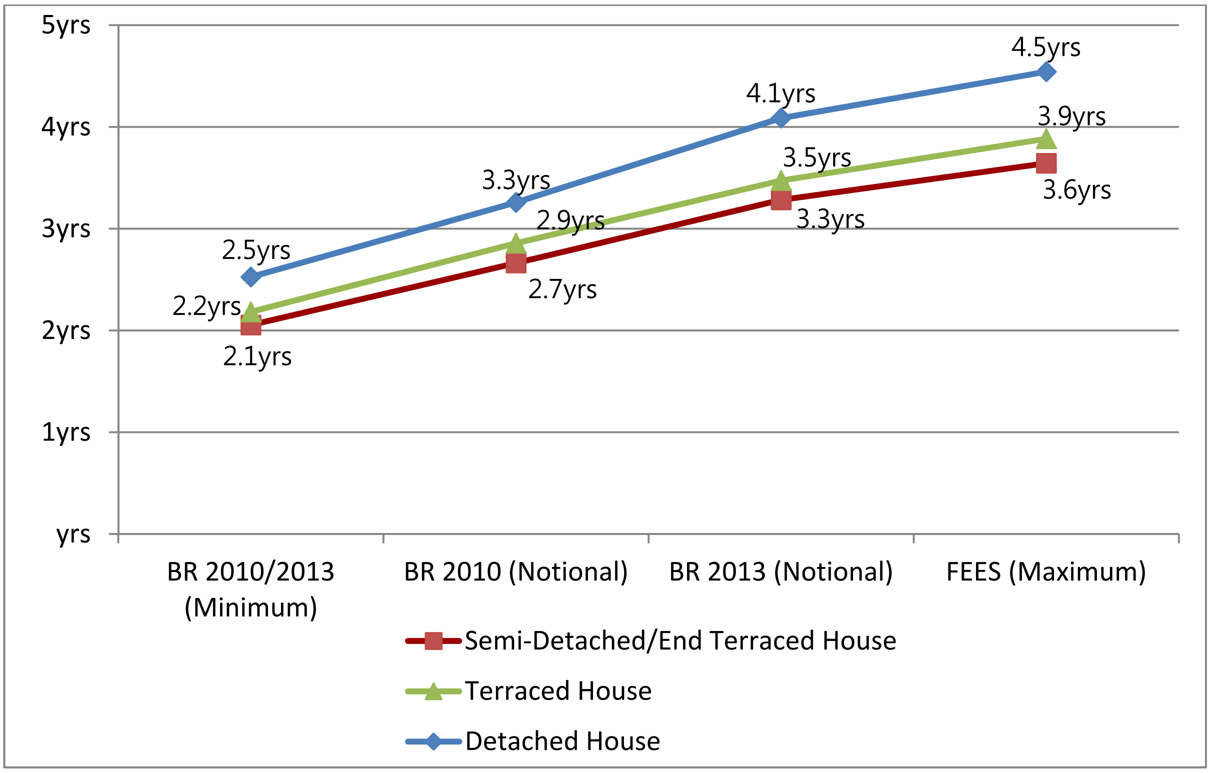

Figure 8.61 CO_2 Payback Period – EPS

8.6 Housing Information Modelling Framework Validation

The proposed framework was validated by four experts: two academics and two construction professionals. All of them were involved in a BIM-enabled project, and were currently managing a BIM project. They have been working for the average of 17 years in the construction industry, and are particularly actively involved in the housing sector and BIM. The aim of this validation was to consider whether or not the proposed framework is practical and could be used in the housing sector as a basis for housing information modelling framework. Therefore, they were selected as subject-matter experts, and expected to provide diverse professional and academic recommendations and feedbacks for further improvement of the proposed framework.

The four experts were asked to response the following questions (See Appendix 14):

1. Does the proposed framework suit for the housing refurbishment projects using BIM?
2. Is the proposed framework practical?
3. Are the outcomes of life cycle cost and life cycle assessment useful as a decision making criteria to determine affordable refurbishment solution regarding material(s) and energy standard(s)?

All of the reviewers provided constructive feedbacks and recommendations in the response to the questions. The followings are the summary of their feedbacks.

1. The proposed framework was found well thought out and applicable. The proposed framework should be useful for decision making throughout housing refurbishment life cycle.
2. The proposed framework was found practical. However, it might be impractical to implement it immediately because currently financial and environmental information in BIM system is not available.
3. The life cycle cost and life cycle assessment are useful as a decision making criteria to determine affordable refurbishment solution.

At the end of this survey, reviewers were asked to provide additional comments, and one reviewer suggested converting the LCC and LCA outcomes into more immediate indicators such as the net present value (NPV) of each measure or improvement package, or carbon cost effectiveness (CCE). Another reviewer recommended researching more deeply how to develop a BIM library with BIM objects containing proper financial and environmental information. In addition, a specific BIM library for housing refurbishment and a standardised coding for construction materials were recommended.

The proposed framework has been proven suitable for housing refurbishment, and proven practical to be utilized as an enabler for construction professionals to formulate a financially and environmentally affordable refurbishment solution in a systematic way.

8.7 Conclusion

This chapter conducted a whole life cycle financial and environmental impact study based on the LCC and LCA results formulated from the proposed BIM framework in Chapter 7. It can be concluded that the most financially affordable and environmentally responsible whole-house fabric refurbishment solution can be determined by comparing different construction materials and different energy performance levels through the proposed BIM framework. Through the whole life cycle studies, the followings are confirmed.

a. Regardless of housing types, the construction costs continue to increase in order to achieve higher energy standards and larger operational CO_2 reduction.
b. As the construction costs increase, the LCC and the embodied CO_2 increases.
c. As embodied CO_2 increases, the LCA increases.
d. In order to achieve larger operational energy cost savings, more construction costs and embodied CO_2 are required. Thus, It is inevitable to put more insulation materials and construction costs to achieve high energy efficiency in a house
e. Refurbishment material is the most critical factor to influence on the construction costs and embodied CO_2. In order to reduce the embodied CO_2, recycled materials should be considered for the insulation material.
f. When a customer wants high energy standards, it is beneficial to adopt the FEES (Maximum) energy standard. In the case of the detached house, the BR 2013 (Notional) is also beneficial in addition to the FEES (Maximum).
g. Currently, the Building Regulation is the best energy efficiency standard, which renders the most financially and environmentally feasible refurbishment solution. However, the FEES needs to be applied for achieving 60% CO_2 reduction through whole-house fabric refurbishment prior to any service or renewable energy installation.
h. The semi-detached/end terraced house has the shortest discounted payback period and CO2 payback period compared to detached and terraced houses, regardless of the construction materials used, in this case fibre glass and EPS.

However, it must be noted that there is always the possibility that the outcome can be chan ged as the input information is changed since this research used a hypothetical case study with the best possible information that is currently available. Therefore, it is worth emphasi sing that the outcome of this research should be used as a supporting tool for decision making, not as definitive decision making criteria.

Chapter 9 Conclusions and Recommendations

9.1 Introduction

This chapter provides the key findings and final conclusion of the research, and confirms if the aim and objectives of this research have been achieved. The research limitations, recommendations and future research aims are provided at the end of this chapter.

The research aim and objectives were established as follows.

- ✧ **Aim: Develop a BIM framework to formulate a financially and environmentally affordable whole-house refurbishment solution based on the life cycle costing (LCC) and life cycle assessment (LCA) methods simultaneously.**

The objectives are:

- ❖ **Theoretical studies through literature review to understand the housing sector in the UK.**
  - **Understand the current condition of the UK housing stock (Chapter 2)**
  - **Understand the current status of sustainable housing refurbishment (Chapter 3)**
  - **Understand the current status of BIM in the housing sector (Chapter 4)**
- ❖ **Conduct a BIM feasibility study for housing refurbishment projects. (Chapter 6)**
- ❖ **Identify homeowners' preferences for housing refurbishment. (Chapter 6)**
- ❖ **Develop a BIM framework to formulate a financially and environmentally affordable whole-house refurbishment solution. (Chapter 7)**
- ❖ **Conduct a hypothetical case study to implement and validate the developed framework for a housing refurbishment. (Chapter 8)**

9.2 Research Key Findings and Conclusions

This chapter reviews and summarizes the objectives and provides the relevant chapters and sections that can be referred to.

- ❖ **Understand the current condition of the UK housing stock (Chapter 2):** In order to achieve the aim of developing a BIM framework for housing refurbishment, the current condition of the UK housing stock has been studied in Chapter 2. It was revealed that there are 27 million homes in England, and refurbishment of 600,000 homes a year is required to achieve the 80% CO2 reduction by 2050. Currently, 78% of the UK housing stock was built before the 1980s when there was no mandated energy efficiency standard applied such as Building Regulation. This implies that 80% of UK housing stock was built with low energy efficiency, thus causing more energy consumption due to poor insulation than the housing stock built with modern energy efficiency standards. In particular, a solid wall house shows 50% more heat loss than an unfilled cavity wall house, as significant heat loss happens through housing fabrics such as walls, roof and windows. Solid wall housing alone occupies 29% of total UK housing; however only 3% of solid wall housing has been insulated, while 70% of cavity wall housing shows the uptake of refurbishment with proper insulation measure. Therefore, it is important to properly insulate a house based on the current energy standard, and particularly solid wall housing should be refurbished as a priority because a solid wall house can render a more effective impact on CO_2 reduction compared to other housing types.

- **Understand the current status of sustainable housing refurbishment (Chapter 3):** Currently, housing refurbishment focuses on adopting a measure approach such as loft insulation, cavity wall insulation and double glazing window installation that can achieve a limited percentage of heat loss reduction compared to a whole-house refurbishment approach. In order to achieve the 80% CO_2 reduction, a whole-house refurbishment needs to be adopted. However, there are three major barriers to adopting whole-house refurbishment in a sustainable and systematic manner that considers financial and environmental impacts simultaneously. The three major barriers are: a) A lack of understanding of homeowner's preferences for housing refurbishment, b) The complex decision making process for whole-house refurbishment, c) The absence of an effective way to generate and manage a whole-house refurbishment solution.

  a) A lack of understanding of homeowner's preferences for housing refurbishment: It was revealed that good experiences regarding housing refurbishment facilitate homeowners to adopt further refurbishment in the near future. Various researchers emphasized that a customer oriented housing refurbishment solution that considering customers' preferences and life styles can support the increase in uptake of housing refurbishment. However, homeowners' preferences for housing refurbishment have been rarely researched.

  b) The complex decision making process for a whole-house refurbishment: Whole-house refurbishment requires various stakeholders to consider all the possible refurbishment measures - building fabric, services and renewable energy systems - for formulating a financially feasible and environmentally responsible whole-house refurbishment solution. As various stakeholders are involved and a variety of construction information needs to be integrated, the decision making process is complex. It is crucial to secure a refurbishment project process that can integrate all the essential construction information from the outset of a project in a collaborative way amongst stakeholders to provide a financially and environmentally affordable refurbishment solution to customers. Furthermore, the life cycle costs and CO_2 performance are essential decision making factors to determine whether a refurbishment solution is affordable. Therefore, the life cycle costing (LCC) and life cycle assessment (LCA) methods for housing refurbishment are required to be considered from the outset of a project. However, the current decision making processes proposed by various researchers cannot accommodate the LCC and LCA methods from the outset of a project, and most of them do not consider the LCC and LCA simultaneously due to a lack of proper LCC and LCA dataset and the fragmented nature of the construction industry to retrieve the essential LCC and LCA data after project completion. As a result, the current refurbishment process has the challenge of identifying the life cycle financial and environmental implication of refurbishment solution.

c) The absence of effective way to generate and manage a whole-house refurbishment solution: Various researchers emphasize the importance of effective information management that enables project stakeholders to collaborate from the outset of a refurbishment project to formulate an affordable housing refurbishment solution. There are various sustainable refurbishment process models to manage diverse construction information efficiently and formulate an affordable refurbishment solution. However, none of these proposed models or processes considers the financial and environmental impacts of a refurbishment solution simultaneously by using the LCC and LCA together. Therefore, an effective and efficient refurbishment process model is required to formulate a refurbishment solution by considering the financial and environmental implications simultaneously from the early design stage, and also an adequate management tool to integrate and manage the construction information throughout a project life cycle.

- **Understand the current status of BIM in the housing sector (Chapter 4):** Currently, Building Information Modelling (BIM) is the most prevalent tool in the construction industry because various researchers and construction professionals recognized and recommended BIM as a tool to achieve effective and efficient integration of construction information and collaboration of various project stakeholders throughout a project life cycle. Furthermore, the UK government has mandated its use for public construction projects from 2016. However, the overall adoption rate of BIM in the construction industry is low at 39%, and it is only 25% in the housing industry. Currently, there are three major barriers to adopting BIM; a) business and legal problem, b) technical problem, and c) human/organizational problem. In order to tackle these barriers and achieve productivity in the construction industry, various standards and guidelines have been published such as

PAS 1192-2:2013, and BIM overlay to the RIBA Plan of Work. Although none of these are developed particularly for existing building refurbishment, they are identified through the literature review and can be used for a basis and guideline for housing refurbishment projects using BIM. In addition, various researchers have attempted to resolve the three barriers to adopting BIM for new build projects, and they concluded that a proper BIM process to develop a building design is required, and a proper dataset, i.e. a BIM library that enables project stakeholders to find out a best design by comparing various design alternatives from the outset of a project, need to be established. Despite these efforts, no studies have been done about BIM adoption for existing housing refurbishment.

- **Conduct a BIM feasibility study for housing refurbishment projects. (Chapter 5 and Section 6.2):** Consequently, this research conducted a BIM feasibility pilot study for housing refurbishment as an exploratory study (See Chapter 5) to investigate what the main barriers for BIM adoption are and whether BIM is feasible for housing refurbishment as a management tool. As a result, BIM is identified as feasible for housing refurbishment projects as a management tool, and it is revealed that it is timely to develop a BIM process or framework for housing refurbishment (See Section 6.2). As a critical step for BIM adoption in housing refurbishment, BIM training and education with an established BIM standard were identified (See Section 6.2).

- **Identify homeowners' preferences for housing refurbishment. (Chapter 5 and Section 6.3):** This research identified homeowners' preferences for housing refurbishment, and indeed it is essential to the understanding of customers' priorities and preferences for housing refurbishment such as refurbishment measures and materials from the brief stage to provide an affordable and satisfactory housing refurbishment solution to customers. Furthermore, it was revealed through the literature review (See Chapter 3) that construction professionals have a tendency to provide a refurbishment solution based on their priorities and preferences, which can lower customers' satisfaction. Thus, it is important to identify homeowners' and construction professionals' preferences to explore if there are any differences between them, and this research adopts a questionnaire survey to investigate the preferences of two groups (See Chapter 5). As a result, it was revealed that homeowners and construction professionals both prefer to refurbish the roof as the first priority and the floor as the fifth and lowest priority. Aside from the roof and floor, both groups indicate different priorities. For example, the second priority was window and external walls for homeowners and construction professionals respectively. In addition, both groups indicate that cost related decision making factors such as initial cost and payback period are the most important when they decide on refurbishment measures and materials (See Section 6.3).

- **Develop a BIM framework to formulate an affordable whole-house refurbishment solution, and implement the framework for a hypothetical housing refurbishment case study. (Chapter 7):** A theoretical BIM framework for housing refurbishment – the Housing Information Modelling (HIM) framework – was developed based on the grounded theory methodology (Chapter 5) by modifying standards and guidelines currently available for BIM enabled construction projects and housing refurbishment (Chapter 3 and 4). The framework was developed by combining generic construction project processes and refurbishment specific processes based on the BIM standards. This research integrated essential project phases and processes for developing a housing refurbishment specific framework. In addition to the standards and guidelines, knowledge obtained from professional training specifically designed for whole-house refurbishment was incorporated into the framework to obtain more realistic and practical viewpoints about whole house refurbishment using BIM.

  The developed BIM framework was examined through a hypothetical housing refurbishment case study. It was revealed that BIM could be used to improve the energy efficiency of a house for its whole life cycle by formulating various refurbishment alternatives and determining the best refurbishment solution among the alternatives based on the LCC and LCA result. It was also revealed that there are limitations to fully utilizing BIM, such as a lack of a standardised dataset of BIM object library, technical interoperability issues between different BIM software tools, and a lack of LCC and LCA dataset for housing refurbishment.

- **Conduct a whole life cycle financial and environmental impacts study based on a hypothetical housing refurbishment case study, and validate the developed framework. (Chapter 8):** Whole life cycle financial and environmental impacts studies were conducted based on the LCC and LCA results formulated from the proposed BIM framework in Chapter 7. It can be concluded that the most financially affordable and environmentally responsible whole-house fabric refurbishment solution can be determined by comparing different construction materials and different energy performance through the proposed BIM framework. In addition, the Building Regulation Part La is the most affordable energy efficiency standard for a whole-house refurbishment solution based on LCC and LCA studies. However, the Fabric Energy Efficiency Standard (FEES) is recommended in order to maximise CO_2 reduction through whole-house fabric refurbishment, which is 60% CO_2 reduction; and in addition, this standard is the most beneficial to adopt when customers are willing to refurbish their houses with high energy efficiency standards. Furthermore, construction material is highly influential on the LCC and LCA results.

After the LCC and LCA analysis, this research conducted a questionnaire survey to validate the developed BIM framework. In order to obtain various aspects and feedback, the validation was conducted amongst two academics and two construction professionals. As a result, all the reviewers provide positive feedback that the framework is suitable for housing refurbishment projects using BIM, and practical in its use although there are barriers and limitations to adopting BIM. Also, all the reviewers agreed that the LCC and LCA methods are appropriate to evaluate an affordable housing refurbishment solution. In addition, reviewers pointed out that a more specific and standardised dataset for BIM objects and BIM object libraries should be prepared in order to formulate more reliable and affordable housing refurbishment solutions.

As shown in these conclusions, all seven objectives were achieved, and finally, the main aim of this research has been achieved through studying theoretical backgrounds, designing a theoretical BIM framework, implementing the framework to a hypothetical case study and validating the framework by academics and construction professionals.

9.3 Contribution to Knowledge

The important contributions of this research are, as in the following, to:

- **Provide a systematic BIM framework to formulate sustainability and financial viability for a whole-house refurbishment solution.**

The developed BIM framework is capable of formulating an affordable refurbishment solution with considering the LCC and LCA simultaneously, and also capable of managing and integrating construction information throughout the whole life cycle of a construction project and a house. A particular challenge directly associated with this research is that there has been no preceding research or studies about using BIM for housing refurbishment projects, and consequently, there is no BIM framework for such projects. Thus, this research has the unique opportunity to provide a substantial contribution to using BIM for housing refurbishment by developing a BIM framework. This framework can support construction professionals to understand the big picture of a refurbishment project in a BIM enabled environment, and facilitate sharing the right information at the right time with the right sequences among key stakeholders throughout a project life cycle. As a result, construction professionals can suggest a financially and environmentally affordable housing refurbishment solution to customers more productively and without unnecessary reworks. Furthermore, this research may provide a guideline for construction professionals who consider adopting BIM for housing refurbishment, and enlighten manufacturers and suppliers about the importance of preparing and establishing BIM objects with cost and environmental information about construction materials.

- **Reveal limitations and challenges in the current environment of the construction industry to utilize BIM framework.**

The hypothetical case study using the BIM framework identifies the limitations and challenges that must be resolved in order to fully utilize BIM for housing refurbishment projects as well as any other construction project. In order to undertake housing refurbishment projects using BIM in an integrated manner, it is essential to resolve the issues revealed in this study such as the need for a more specific dataset of LCC and LCA, and a BIM object library with proper financial and environmental information. The limitations and challenges identified through this research can be an integral foundation for future research and other related studies such as BIM library development and life cycle dataset development. Thus, this research contributed to identifying the current limitations of the BIM system as a tool to manage housing refurbishment projects more productively. Furthermore, this research will contribute to the construction industry to improve the current BIM maturity to the next level.

- **Identify the implication of LCC and LCA trade-off relationships of a whole-house fabric refurbishment solution based on the different energy efficiency standards.**

There are no mandatory energy efficiency standards for housing refurbishment, although there is the Building Regulation Part La, which focuses on new builds. Currently, various energy efficiency standards, i.e. many different U-values of housing element are applied to housing refurbishment without considering the implication of financial and environmental impacts. This research revealed that the energy efficiency standard recommended by the Building Regulation Part La is the most financially and environmentally beneficial option at present, based on the LCC and LCA studies. In addition, when customers would like to adopt higher energy efficiency standards than the Building Regulation Part La, it is recommended to adopt the Fabric Efficiency Energy Standard (FEES) because this standard renders the lowest operation and maintenance costs than other energy standards based on the LCC and LCA study.

- **Investigate homeowners' preferences for housing refurbishment to develop essential BIM input data for a housing refurbishment project.**

Construction professionals should be able to provide essential information that can fulfil homeowners' preferences about housing refurbishment such as initial costs of refurbishment and forecasting energy performance of a refurbished house. This essential information is important because customers should be able to make an informed decision about proposed refurbishment solutions based on their preferences. In order to achieve this, the initial BIM input data with proper information such as costs and energy performance is crucial to provide proper refurbishment information to customers. Thus, this research investigated homeowners' preferences for housing refurbishment, and contributes to the establishment of a basis for developing essential BIM input data and BIM objects with proper cost and environmental datasets. Although the preferences cannot be generalised because each individual has different needs and wants, this research attempted to identify how most homeowners think about housing refurbishment.

9.4 Limitations of Research

The limitations of this research are as follows:

❖ **Limited Location for Homeowners' Preferences Survey**

For the initial BIM input data, homeowners' preferences from 112 responses were collected and analysed. However, the locations of respondents were mainly from Midlands (59%), while small portions of Northern (15%) and Southern (26%) regions were collected. Although the collected data cannot draw definitive conclusions about homeowners' preferences, this research attempted to identify how most homeowners think about refurbishment. Furthermore, due to the difference of weather between the different locations, preferences from the Northern and Southern regions could be different from the Midlands. Therefore, the findings about homeowners' preferences should be treated with caution and more research about preferences from Northern and Southern regions is required to identify if there is any difference amongst the different locations.

❖ **Limited Consideration of Refurbishment Measures and Phases in the BIM framework**

This research focused on the whole-house fabric refurbishment approach, and provided further explanation about the assessment and design phases only. Although the whole-house fabric should be considered first, the developed a BIM framework can provide more various refurbishment alternatives and more realistic LCC and LCA information if services and renewable energy systems are included. In addition, more detailed explanation about the framework was limited to the assessment and design phases, although this research developed the BIM framework for the entire refurbishment project life cycle. This is because development of detailed framework for the construction and use phases of a housing refurbishment is beyond one individual researcher's capability, time and resources. Furthermore, there is limited literature regarding how to utilize BIM for the construction and use phases, although these two phases should be included and further researched in order to understand the full benefits of BIM throughout the entire project life cycle and a whole life cycle of a refurbished house.

❖ **No Previous Research of Housing Refurbishment using BIM**

Currently, BIM has been researched and studied amongst various researchers and construction professionals for how to adopt and utilize BIM effectively and efficiently. However, BIM has been rarely researched for housing refurbishment projects, and as a result, previous studies and experiences of housing refurbishment using BIM are limited. Although this research attempted to collect as realistic data as possible for a hypothetical case study, the developed BIM framework would achieve better practicality and effectiveness if previous research results about BIM use for housing refurbishment were incorporated into the BIM framework.

9.5 Recommendations for Future Research

The following are recommendations for future research based on the conclusions and limitations from this research. Future research focuses on enhancing the developed BIM framework and researching how to develop a BIM library and objects with the proper cost and environmental information.

❖ **Enhancement of the BIM Framework by Developing Detailed Process Map**

The developed BIM framework has focused on whole-house fabric refurbishment and the assessment and design phases of a refurbishment project, although entire refurbishment project phases should be focused and further developed. Future research should further develop the current BIM framework into a more specific and detailed process map by researching more deeply about the relationships between processes and activities for each stage and phase throughout the entire project life cycle.

❖ **Development of BIM Objects and BIM Library with LCC and LCA Information**

Due to the limitation of datasets in BIM objects, only two construction materials were used for energy simulation to formulate a refurbishment solution. In order to effectively utilize BIM to determine the best refurbishment solution by analysing LCC and LCA results of various refurbishment solutions with different construction materials, it is essential to develop BIM objects with proper LCC and LCA information. Once BIM objects with proper information are developed, a BIM library specifically developed for housing refurbishment could be developed.

❖ **Research of Asset Management Using BIM During the Use Phase**

In order to formulate more realistic and affordable refurbishment solutions, real data from the existing house should be collected, such as the dimensions of the house, floor plan and thermal performance information. In order to utilize real data collected from existing housing, research is required on how to use and maintain built asset information using BIM. Recently, a standard of how to use and maintain build asset information during the use phase, PAS 1192-3, was developed by BSI. In addition, the COBie has been encouraged for construction professionals, in particular facility managers and maintenance teams, to use for the operation of existing assets, and the UK BIM task group released a COBie template for effective sharing of existing building information in a BIM system. Thus, future research will be conducted to further research how to utilize BIM for managing a built asset based on these standards and templates.

❖ **Research of Relationship between 3D Visualization of Refurbishment Solution and Customers' Satisfaction**

Construction professionals pointed out that BIM provides 3D visual aids that can offer easier explanations about project plans and designs to their customers than 2D based paper drawings. Furthermore, it was identified that customers are reluctant to refurbish their homes because they cannot always clearly understand the proposed refurbishment solutions that construction professionals suggest. Thus, it could be worth researching about the relationship between BIM 3D visual aids and customers' satisfaction to reveal if the 3D visualization of proposed refurbishment solution can improve customer satisfaction.

The future research points listed above should contribute to improving the productivity of BIM use for whole-house refurbishment, and should provide a guideline for the construction industry to adopt and utilize BIM more effectively and efficiently.

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Appendices

Appendix 1. BIM Feasibility Study Questionnaire

BIM Feasibility for Housing Refurbishment

Exit this survey

1. How long is your experience in construction?

1-5 years

6-10 years

11-16 years

16-20 years

21-25 years

26+ years

2. What type of company do you represent? (Check all that apply)

Public Client

Private Client

Architect

Building Surveying

Quantity Surveying

Civil Engineering/Infrastructure

Structure Engineering

Facilities Management

Project Management

Tier 1 Contractor

Specialist Contractor

Other

Other, please specify

*** 3. What is the level of BIM awareness/desire amongst your clients?**

None

Low

Medium

High

Very High

*** 4. Are you aware that the UK Government mandates BIM use for construction**

projects from 2016?

Yes

No

5. Are you aware of the BIM adoption strategy devised by UK government (Level 0 - Level 3)?

Yes

No

6. Does your company adopt and/or use BIM?

Not use

Just adopt and start to use

Use for small size projects

Use for every project

Plan to adopt

Other

Other, please specify

7. What is the stage of BIM utilization in your company?

Not use

Just adopt and use BIM for pilot projects

Visualization Stage - 3D modelling for communication with project team

Technical Analyze & Prediction Stage - Whole life cycle cost calculation, CO2 performance

Fully Integrated Stage - Project schedule & cost and bill of material for procurement generated from BIM

Other

Other, please specify

*** 8. For what type of buildings does your company use BIM?**

Retail

Offices

Residential

Education

Prisons

Courts

Healthcare

Industrial

Specialised buildings assessed under the BREEAM Bespoke method

Other

Other, please specify

9. Where do you think BIM need to be adopted?

None

New Build

Refurbishment

Both (New Build and Refurbishment)

Other

Please explain the reason briefly.

10. What do you see as the main benefits of BIM use for housing refurbishment? (Check all that apply)

Cost-benefit analysis amongst refurbishing alternatives

Reduce risks and improve health & safety

Easy explanation of refurbishment alternatives to customer

Increase efficiency and profit

No benefit

Other

Please explain the reason briefly.

* 11. What kind of source do you use to obtain BIM data from existing housing?

Not use BIM

2D Drawing

3D Drawing

3D Laser Scanning

Other

Please explain the reason briefly.

*** 12. In your opinion, what is the most feasible housing type for refurbishment in terms of cost and time?**

Terraced House

Semi-detached House

Detached House

Bungalow

Converted Flat

Please explain the reason briefly.

*** 13. In your opinion, what is the most feasible built year of housing for refurbishment in terms of cost and time?**

Pre 1919

1919-1944

1945-1964

1965-1980

1981-1990

Post 1990

Please explain the reason briefly.

*** 14. What are barriers to adopt BIM for housing refurbishment? (Check all that apply)**

Initial investment cost

Lack of client demand

Lack of amended forms of construction contracts

Uncertainties over ownership of data and responsibilities

Lack of training/education

Lack of Standards

Other

Please explain the reason briefly.

***15. What do you think the most critical step/action to adopt BIM in housing refurbishment?**

Financial support for initial BIM adoption cost

Establish housing refurbishment standard/guidance

Establish BIM standard/guidance

BIM Training/education

Other

Please explain the reason briefly.

***16. Do you think BIM adoption for housing refurbishment is timely?**

Too early

Early

Timely

Late

Too late

Please explain the reason briefly and any additional comments

Appendix 2. Pilot Study Result of Housing Refurbishment Preference Questionnaire

	Initial Question (Pilot Study)	Updated Questions (Main Questionnaire) and Reason (Feedbacks from the Pilot Survey)
Survey Title:	Preference Survey for Housing Refurbishment	UK Housing Refurbishment Preference for Improving Energy Efficiency Reason: 1. The meaning of Refurbishment is received differently by respondents. Painting walls or replace wall can be both regarded as refurbishment. Therefore, the title should address that refurbishment is for energy efficiency improvement. 2. Since the questionnaire survey will exposed to various people from various country via online, it should be indicated that UK housing refurbishment is the target for this survey.
Section 1	Background of a Respondent, 1 questions	Background of a Respondent, 2 questions Reason: One additional question has been added to collect respondents' location in the UK, since the questionnaire survey will exposed to various people from various location in the UK.
Section 2	Basic Information of a Respondent's Home, 2 questions	Basic Information of a Respondent's Home, 2 questions Reason: There is minor change in wording. Initial question was "Built Year", but it was corrected as "Year Built"
Section 3	Basic Preference of Housing Refurbishment, 2 questions	Basic Preference of Housing Refurbishment, 2 questions Reason: There is minor change in the order of listing choices. Initial question listed the choices for questions randomly, but it was listed in the alphabetical order to minimise the influence on selection of choices.
Section 4	Detailed Preference of Housing Refurbishment, 3 questions	Detailed Preference of Housing Refurbishment, 3 questions Reason: 1. A picture of a house is removed since it is redundant to explain the components of a house, and could cause visual confusion. 2. A question asking budget for housing refurbishment is removed since pilot survey respondents addressed a lack of knowledge about refurbishment measures and costs.

		3. The 9 scale Likert scale was substituted with 5 scale Likert scale since the pilot survey respondents expressed difficulties to answer the question since the 9 scale is too wide and complicated. In addition, since the 5 scale Likert scale is the most popular method, this research adopted this.

Initially, the section 4 questions were designed to obtain relative importance between two factors. The expected outcome of these questions were designed to analysed using normalized value by using AHP method. However, there are common feedbacks on the section 4 that the questions are very difficult to understand how to answer the questions in the viewpoints of respondents. Furthermore, the design of question itself causes confusion. As a result, the main questionnaire adopted the Likert scale to minimise misunderstanding and increase the easiness of questions.

Appendix 3. Homeowners Preference Survey Questionnaire

UK Housing Refurbishment Preference for Improving Energy Efficiency

Exit this survey

1. Please indicate your location

Scotland

North West

North East

Yorkshire & Humberside

West Midland

East Midland

East

London

South West

South East

Wales

EU

US

Other Countries

*2. Please select as applicable

	Age	Occupier	Home Ownership
Household			

*3. Please tell us about your home

	Type	Year Built	Orientation	Number of Bedrooms
House				

*4. Please indicate the construction type of your home

	Floor	Wall	Roof	Window
Construction Type				

5. Do you plan to refurbish your home?

If Yes, please select all the reasons why from below. If No, please go to next question.

	Very Important	Important	Neutral	Unimportant	Not considered
Aesthetics (Appearance)					
Energy Cost Saving					
CO2 Reduction					
Energy Efficiency					
Increasing Market Value					
Indoor Air Quality					
Thermal Comfort					

Other (please specify)

6. If you do not want to refurbish your home, please select all the reasons from below.

	Very Important	Important	Neutral	Unimportant	Not considered
No Need					
Disruption caused by Refurbishment					
Initial Cost					
Lack of Information about Refurbishment Options					
Mistrust of Builders					
Payback Period					

Other (please specify)

***7. If you want to improve the energy efficiency of your home, where do you prefer to refurbish most? Please rank the following in order, where the 1st is Most Important and the 5th is Least Important.**

	1st	2nd	3rd	4th	5th
Roof					

Wall - Inside of House
Wall - Outside of House
Floor
Window/Door

***8. Which factor do you consider most important when you plan to refurbish your home for energy efficiency? Please indicate the importance of the following.**

	Very Important	Important	Neutral	Unimportant	Not Considered
CO2 Reduction					
Disruption caused by Refurbishment					
Initial Cost					
Low Maintenance (Durability)					
Payback Period (Energy Cost Saving)					
Thermal Performance					

Other (please specify)

***9. Please indicate the importance of decision making factors for selecting construction materials for refurbishment.**

	Very Important	Important	Neutral	Unimportant	Not considered
Aesthetic (Finished Look)					
Low Maintenance (Durability)					
Health and Safety (Non-toxic Materials)					
Initial Cost					
Life Cycle Cost					
Manufacturers' Reputation					
Recycled Materials (CO2 Reduction)					
Thermal Performance					

Other (please specify)

Appendix 4. Interview Results with Construction Professionals

Interviewee 1: Architect

Location: Nottingham, UK

1. Experience (years) + Background

: 13 years, Architect (RIBA Part 3 Education)

2. What are the common processes/steps for housing refurbishment? How do you think BIM would affect the housing construction practices? (Any difference between new build and refurbishment?)

: Normally I followed RIBA Plan of Work, but more loosely follow the process. For example, condition assessment is the first step normally taken for housing refurbishment.

3. If a homeowner wants to refurbish whole house, how do you work with other builders?

: Mainly 2D drawings. In particular, the product information is mainly documents.

4. Currently, I am conducting homeowners' preference for housing refurbishment. Do you have any relevant data or historic records for homeowners' preference? For example, the combination of options: wall only, wall + roof insulation, and so on.

: I have done a whole-house refurbishment project recently. Name: …

There is not specific combination of refurbishment measures, but usually external wall insulation turns out the best outcome in terms of thermal performance and damp. There are various reasons for people to select refurbishment measures such as non-monetary factors.

However, even if the refurbishment solution can be justified, the budget for refurbishment could not be prepared often time. For example, the Green Deal often excludes reasonable refurbishment measures due to the Golden Rules.

I personally recommend the Passive House standard for my customers.

5. What do you think possible benefits/barriers of using BIM for housing refurbishment might be?

(except clash and error detection and accurate schedule. I think these benefits are more related to new build rather than refurbishment. Do you think these benefits can be applied to refurbishment?)

: CAD, 3D CAD and Energy Modelling (SAP Modelling).

6. Do you think it is economically feasible for small-medium size home builders to adopt BIM for refurbishment?

: Not heard of BIM (Is it 3D CAD?).

7. Could you tell me what the current state of COBie for housing sector is? Actually they are using it? I noticed that COBie is way too complicated to use.

: Not heard about people who use COBie.

COBie is recommended by the government. But, so far I have not seen any guideline or standard what information sets need to be exchanged among project stakeholders.

Is there any COBie completed for a new house build or refurbishment?

Do you have any insight how COBie might be used for housing refurbishment?

Do you think if it is possible that BIM used for new build can apply to refurbishment? I mean if that is possible, we can use the same dataset or information for refurbishment.

8. What do you think the most important thing to be done for increasing uptake of BIM in the housing sector?

: Cannot answer to this question.

9. What is the required information for each phase of housing refurbishment project? (Next page)

: Planning Permission should be considered as the refurbishment measures are chosen.

10. Is NRM2 used for housing refurbishment? (If yes, how to apply?)

: Never heard of NRM2, Better talk with programme manager or project management people.

Interviewee 2

Title: Architect

Location: Milton Keynes, UK

1. Experience (years) + Background

: 30 years (Retrofit 10 years), Architect, Ph.D

2. What are the common processes/steps for housing refurbishment? How do you think BIM would affect the housing construction practices? (Any difference between new build and refurbishment?)

: No existing BIM model for generic houses.

3. If a homeowner wants to refurbish whole house, how do you work with other builders?

: Package of Drawings. Tendering, Contract: Builder and Homeowners.

4. Currently, I am conducting homeowners' preference for housing refurbishment. Do you have any relevant data or historic records for homeowners' preference? For example, the combination of options: wall only, wall + roof insulation, and so on.

: Nothing fixed. Everyone has different tastes and priorities. Fabric First approach since it can secure 40 to 60% energy/CO_2 savings. Mechanical and house service system is expensive and extra care is required. Additionally, there is diminishing returns applied to refurbishment measures.

5. What do you think possible benefits/barriers of using BIM for housing refurbishment might be?

(except clash and error detection and accurate schedule. I think these benefits are more related to new build rather than refurbishment. Do you think these benefits can be applied to refurbishment?)

: Facility Management (social housing) wants to manage assets properly through life cycle of a building. Additionally, the government mandates it. The problem is the communication between the construction sector and management side. BIM will take a while to be adopted by the housing sector. Even the existed data for housing condition about SAP and EPC is not correct, even lots of them are missing and poorly recorded.

6. Do you think it is economically feasible for small-medium size home builders to adopt BIM for refurbishment?

: No, unless there is an existing BIM model for generic houses.

7. Could you tell me what the current state of COBie for housing sector is? Actually they are using it? I noticed that COBie is way too complicated to use.

COBie is recommended by the government. But, so far I have not seen any guideline or standard what information sets need to be exchanged among project stakeholders.

Is there any COBie completed for a new house build or refurbishment?

Do you have any insight how COBie might be used for housing refurbishment?

: Too much information in COBie. It should keep it simple.

Do you think if it is possible that BIM used for new build can apply to refurbishment? I mean if that is possible, we can use the same dataset or information for refurbishment.

8. What do you think the most important thing to be done for increasing uptake of BIM in the housing sector?

: Currently, it is happening in the new build sector. Architect hand over the BIM data to housing association.

9. What is the required information for each phase of housing refurbishment project? (Next page)

: BIM model for housing should be ready first. In term of dataset, new build housing is much easier to obtain data. In particular, BIM is currently used for big scale projects. Multiple residential houses.

Assessment and Modelling is expensive. Should compromise between cost and accuracy. First, take time to assess the housing for accuracy. However, 3D laser scan for 3D modelling but it is expensive.

Most problematic situation is fragmented practice in the construction sector. Planning and builder don't communicate well. Always discover unforeseen and hidden condition of house later on. It cause delay, additional cost and risk.

Decanting cost a lot of money.

Builder has shortage of skill to install the products, and also manufacturer don't produce material without consideration of project. For example, VIP (vacuum insulated panel) cannot be cut and be fitted to place requiring insulation. However, there is only one fixed size is produced by manufacturer. Even installation is successful, later on while occupancy, people drill a hole for hanging a picture or something. Then, the vacuumed panel is broken and lose its insulation material character.

Technical failure and human behaviour is the two major failure factors for refurbishment.

10. Is NRM2 used for housing refurbishment? (If yes, how to apply?)

: Contractors have their own cost estimating system. NRM is not always applied.

Interviewee 3

Title: Master Builder

Location: London

1. Experience (years) + Background

: 12 years, Start with floor insulation in German, then start whole-house refurbishment in UK

2. What are the common processes/steps for housing refurbishment? How do you think BIM would affect the housing construction practices? (Any difference between new build and refurbishment?)

: RIBA Plan of work, but not follow exactly as it is. Modified and used. Existing house condition – change options – final result – construction, Never heard of BIM. 2D drawings are the common tool.

3. If a homeowner wants to refurbish whole house, how do you work with other builders?

: Contractors have their own crew or other contractors with good relationship. Most of time, they communicate with package such as drawings and spreadsheet.

4. Currently, I am conducting homeowners' preference for housing refurbishment. Do you have any relevant data or historic records for homeowners' preference? For example, the combination of options: wall only, wall + roof insulation, and so on.

: I don't have data for preference.

5. What do you think possible benefits/barriers of using BIM for housing refurbishment might be?

(except clash and error detection and accurate schedule. I think these benefits are more related to new build rather than refurbishment. Do you think these benefits can be applied to refurbishment?)

: The problem is the barrier in the whole-house refurbishment. The mentality of people is huge barrier since they only want cheap materials and refurbishment measures. Also, there is no tool to calculate sustainability. Currently, contractors use U-value calculation and Wufi software. Then, contractors work with energy consultant for energy load, energy consumption and savings.

6. Do you think it is economically feasible for small-medium size home builders to adopt BIM for refurbishment?

: Current market does not reflect the importance of sustainability aspects. The sustainability is not really connected to the market value of a house. Whether you refurbish your house with sustainable way, it does not increase value of your home.

7. Could you tell me what the current state of COBie for housing sector is? Actually they are using it? I noticed that COBie is way too complicated to use.

COBie is recommended by the government. But, so far I have not seen any guideline or standard what information sets need to be exchanged among project stakeholders.

Is there any COBie completed for a new house build or refurbishment?

Do you have any insight how COBie might be used for housing refurbishment?

Do you think if it is possible that BIM used for new build can apply to refurbishment? I mean if that is possible, we can use the same dataset or information for refurbishment.

: The most important thing is communication. When you do the whole-house refurbishment, communication is very difficult among different builders (different element). Even not qualified builders do the job, especially VIP. The unqualified builders don't know how to handle materials. As a result, there are always repair and rework associated.

Proper training and education should be provided by the government like German.

8. What do you think the most important thing to be done for increasing uptake of BIM in the housing sector?

: Most of people consider the cost is the most important. They don't care what is behind the wall. If builder use cheap materials and install them in an inappropriate way, there are always problems such as condensation, mould growing.

9. What is the required information for each phase of housing refurbishment project? (Next page)

10. Is NRM2 used for housing refurbishment? (If yes, how to apply?)

: Never heard of NRM. Builder has own way to calculate the fee.

Before energy assessment, builder can recommend initial refurbishment measures. However, it cannot be charged. If customer decided to proceed further, then builder can come up with refurbishment solution and charge them. But, people often try other builders who provide cheaper solution. Electrician and plumber can charge initial assessment and they deduct from the entire house repair or maintenance.

At the construction phase, it is very important to have a watchman who can direct and make decision about construction. Also, refurbishment project sequence should be well planned.

Interviewee 4

Title: BIM Manager

Location: York

1. Experience (years) + Background

: 9 years, 2007 Architect Part 3 completion, from 2009, start engaged in BIM

2. What are the common processes/steps for housing refurbishment? How do you think BIM would affect the housing construction practices? (Any difference between new build and refurbishment?)

: Depending the scope of work. However, generally, assessment (time, cost, delivery quality) – stakeholder involvement – QS involvement – ROI calculation – Design – Construction – Handover

3. What are the common processes for housing refurbishment project? IS there any standardised process for housing refurbishment project?

: Not at the moment. Currently, BIM is used for 3D visualization for clients meeting. Drawing is completed in 2D manner first, then the 2D drawings are either converted to 3D in BIM or keep using 2D if clients don't require. However, it is very beneficial to use 3D for the viewpoint of cost estimation. The cost estimation can be done quickly at the briefing stage with clients, they can estimate the total cost and calculate the ROI. No need to QS get involved.

Q4. How do you integrate the refurbishment process and BIM process?

Since I get involved in the design stage and only involve in 3D realization, It is hard to tell how to integrate them. What I can tell you though is the most challenging situation using BIM for refurbishment projects or other construction projects. There are various requirements for in-situ design and construction, however it is difficult to design at the beginning with BIM because there is no standardised material or model which can be used for BIM. Since there are no standardised components, objects or materials, each designer or builder make their own model with various data source. I know there is NBS BIM library, but it is not quite useful since there are so many missing objects and information like cost, dimensions and u-value. So, the standardised BIM library is very important, and this support should be provided.

Q5. How do you calculate environmental impacts (CO_2/embodied CO_2/Energy Efficiency) of housing refurbishment? (method/software/ tool)

The sustainability is not checked all the time unless clients request. Currently, I use ECOTECT and online tool green building studio. The environmental impacts should be calculated by level of change such as small refurb does not necessarily need that kind of work, but big refurb such as whole envelope changes may get some benefits to use software.

Q6. In which phase (or process) do you calculate environmental impacts?

When architect consider the u-value of components. Architect requires u-value to manufacturer, and when manufacturer recommend material A, architect consider the recommendation and change designs if necessary.

Q7. Do you use life cycle costing for housing refurbishment? (method/software/ tool) No

Q8. In which phase (or process) do you calculate life cycle cost? No

Q9. What kind of data do you need to calculate the Q5 & Q7 using BIM, and how you can obtain data?

3D scanner or Quantity Surveyor

Q10. Is NRM2 used for cost estimating of housing refurbishment project?

No, usually, Architect ask QS the cost estimation and convert that into 3D BIM. (Not aware of NRM)

Q11. What do you think possible benefits of using BIM for housing refurbishment?

Cost estimation may be done quicker

Q12. What do you think the important things to do for using BIM in housing refurbishment?

Not sure, BIM library

Would you make any other comments?

Appendix 5. Current Whole-House Refurbishment Practices for Solid Wall Housing

Referred to TSB Funded Retrofit for Future Projects (www.lowenergybuildings.org.uk/projectbrowser.php) and EST Housing Refurbishment Best Practices

	Location	House Type	Refurbishment Measure Wall	Refurbishment Measure Roof	Refurbishment Measure Floor
1	South Yorkshire, Doncaster	Mid-Terrace Victorian	Internal wall	Loft Insulation - 100mm Top-up layer	Joist Insulation with junction seal
2	South Bristol	End-Terrace		Loft Insulation - 200mm mineral wool Top-up roof	Joist Insulation 150mm mineral wool
3	Redland, N. Bristol	Semi-Detach	Internal wall	Loft Insulation - 200mm mineral wool Top-up	Joist Insulation 200mm Knauf Roll44
4	Thornbury, S. Gloucestershire	Detached	External		
5	Norfolk	Cottage	Internal wall		Chipboard Top-up Insulation - Thin layer aerogel laminated chipboard
6	Belfast, N. Ireland	Mid-Terrace	Internal wall		Chipboard Top-up Insulation - 25mm Phenolic Insulation
7	Cambridge	Semi-Detach	External	Loft Insulation - 350mm mineral fiber quilt Top-up	Chipboard Top-up Insulation - 25mm nanogel blanket
8	Lancashire	End-Terrace	Internal wall	Roof Rafter and joist - Warm Roof	
9	Brixton	Mid-Terrace	External		
10	Cambridge	Semi-Detach	Internal wall		Chipboard Top-up Insulation - Thin layer aerogel laminated chipboard
11	Queens Park	Mid-Terrace			Chipboard Top-up Insulation - Thin layer aerogel laminated chipboard
12	Lancashire	Mid-Terrace	Internal wall	Roof Rafter and joist - Warm Roof	
13	Isle of Wight	Semi-Detach	External		
14	West Sussex	End-Terrace	External		Top-up Insulation - Thin layer aerogel laminated chipboard

15	West Sussex	Mid-Terrace	External		Chipboard Top-up Insulation - Thin layer aerogel laminated chipboard
16	Lancashire	End-Terrace	Internal wall	Roof Rafter and joist - Warm Roof	
17	London				Joist Insulation Celluose insulation + Wood Fibre Top-up board
18	East Sussex	Mid-Terrace		Loft Insulation - 300mm insulation	Joist Insulation - 240mm PU below screed
19	London	Mid-Terrace	External	Loft Insulation - 300mm insulation	Solid floor Insulation
20	Herefordshire	Detached	External		
21	Essex	End-Terrace			Joist Insulation - Mineral Wool
22	Birmingham	Mid-Terrace			
23	Tyne&Wear	End-Terrace	Internal wall		Chipboard Top-up Insulation - VIP, EnergyFlo Dynamic insulation
24	Leicester	Mid-Terrace	Internal wall	Roof Rafter and joist - Warm Roof	Dig out solid floor and insulate
25	Liverpool	Mid-Terrace		Roof Rafter and joist - Warm Roof (Spray Foam)	
26	London	Mid-Terrace	Internal wall		Inject graphite-coated sticky bead EPS insulation
27	London	Mid-Terrace	Internal Front		
28	Nottinghamshire	Semi-Detach	Internal	Loft Insulation - 500mm insulation	Remove current floor
29	Oxfordshire	End-Terrace	Internal Front	Loft Insulation - 250mm polyurethane	Chipboard Top-up Insulation - VIP
30	Surrey	Semi-Detach	Internal	Phenolic insulation + Aerogel	Chipboard Top-up Insulation - VIP
31	Norfolk	Mid-Terrace	Internal	Loft Insulation - 350mm mineral fibre quilt	Chipboard Top-up Insulation - 25mm nanogel blanket
32	London	Semi-Detach	Internal	Loft Insulation - 350mm mineral fibre quilt	Joist Insulation - 150mm phenolic foam
33	West Yorkshire	Mid-Terrace	External	Top-up Insulation – 100mm Warmcel	Joist Insulation - 200mm Misapor granular foamed glass
34	Nottinghamshire	Mid-	External	Loft Insulation -	Chipboard Top-up

		Terrace		300mm Thermafleece	Insulation - 10mm Spacetherm
35	Hampshire, Petersfield	Semi-Detach	External	Loft Insulation - 300mm mineral wool Topup	Chipboard Top-up Insulation - 50mm extruded polystyrene (XPS) wtih Junction (Edge Floor) insulation
36	16 Roxburgh St., Scotland	Terrace	Internal		
37	Drummond St. Scottish	Flat, 2nd Floor	Internal		
38	Marshall St. Scotland	End-Terrace	Internal		
39	2 Roxburgh St., Scotland	Flat, 2nd Floor	Internal		
40	Edinburgh, Scotland		Internal	Loft Insulation - Sheep's wool, 280 mm	Joist Insulation - 80 mm wood fibre
41	Culross, Scotland	Detached Cottage	Internal	Loft Insulation - 275mm hemp wool insulation	
42	Glasgow, Scotland		Internal		
43	South Uist, Scotland	Detached Cottage	Internal	Rafter and Joist Insulation - 100mm wood fibre behind existing timber lining	Chipboard Top-up Insulation - 30mm aerogel board
44	Cupar, Scotland	Detached Cottage	Internal	Loft Insulation - 270mm hemp batts between and over joist	Joist Insulation - Hemp fibre batt + Floorboard Insulation
45	Cumnock		Internal	Loft Insulation - 250mm sheep wool insulation	Solid Concrete Screed Replacement

Appendix 8. Construction Costs and Embodied CO_2 (Cradle to Site) Calculation – Basic Detached House

Detached House Basic

							SMM7	Univ. of Bath	m2	m3	Black Book		kg				
NRM Code	Element	Assembly Code (Autodesk Revit)	Level	Family	Family and Type	Material: Name	Construction Costs (Material + Labor)	Material: Embodied CO2 (Cost)	Material: Area	Material: Volume	Construction Embodied CO2	Total Cost	Total Embodied CO2	Reference			
1	Substructure													CO2	Black Book	Cost	SMM7
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	67	1.47	2.42	£ 1,645.52	162.9338	423p	K111308D	sec 15 p10	K20002
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer, 75x225	£ 8.78	0.71	67	15.07	3.045	£ 588.26	214.7147	354p	G202102F	sec 12 p6	G20052
						Floor member 200 & 250 median					Total	£ 2,233.78	377.649kg				
2	Superstructure																
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	67	1.47	2.42	£ 1,645.52	162.9338	423p	K111308D	sec 15 p10	K20002
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£ 8.78	0.71	67	15.07	3.045	£ 588.26	214.7147	354p	G202102F	sec 12 p6	G20052
2.2.1	Upper Floor	B1010375	Ground Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	65	0.78	29.044	£ 1,822.60	1888.1564	400p	K100110E	sec15 p1	K10002
2.2.1	Upper Floor	B1010375	First Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	65	0.78	29.044	£ 1,822.60	1888.1564	400p	K100110E	sec15 p1	K10002
											Total	£ 5,878.98	4153.961kg				
						SMM7 Pitched roof members including ceiling joist, Revit does not include celing joist and Carbon book also does not include											
2.3.1	Roof Structure	B1020400	Loft	Floor	Floor: Roof Ceiling Joist	Structure, Timber Joist/Rafter Layer 100x150		0.71	67	6.7	4.058	£ -	276.643	355p	G202911S		
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Wood Strutt 50x150	£ 6.61	0.71	90	2.26	2.184	£ 594.90	198.1646	356p	G203152D	sec12 p7	G20057
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter Layer	£ 12.49	0.71	90	13.56	4.058	£ 1,124.10	374.8476	355p	G202911S	sec12 p6	G20055
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing, Tile 65mm lap 100mm gauge	£ 58.40	0.45	90	3.43	37.56	£ 5,256.00	3381.9435	141p	8020101A	sec 13 p13	H60151
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing Felt	£ 6.83	0.41	90	0	5.22	£ 614.70	469.8	151p	8090203A	sec14 p3	J21018
											Total	£ 7,589.70	4701.399kg				
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common cement mortar 1:3	£ 87.59	0.23	54	11.43	98.017	£ 4,729.86	5295.5469	323p	F100102B	sec11 p1	F10002
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	54	1.08	3.29	£ 581.58	177.7896	72p	4010303A	sec 17 p9	M20090
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	42	9.11	98.017	£ 3,678.78	4118.8093	323p	F100102B	sec11 p1	F10002
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	42	0.85	3.29	£ 452.34	138.282	72p	4010303A	sec 17 p9	M20090
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	49	10.34	98.017	£ 4,291.91	4805.2112	323p	F100102B	sec11 p1	F10002
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	49	0.98	3.29	£ 527.73	161.3276	72p	4010303A	sec 17 p9	M20090
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	39	8.43	98.017	£ 3,416.01	3824.6019	323p	F100102B	sec11 p1	F10002
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	39	0.78	3.29	£ 420.03	128.4036	72p	4010303A	sec 17 p9	M20090
											Total	£ 18,098.24	18649.972kg				
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372	110p	6010109D	sec16 p1	L10002
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284				
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372				
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284				
2.6.1	External windows	B2020100	Ground Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Glass	£ 92.70	0.86	1	0.01	20.86	£ 92.70	20.8686				
2.6.1	External windows	B2020100	Ground Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Window Frame		0.71	2	0.02		£ -	0.0142				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372				
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284				
2.6.1	External windows	B2020100	First Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Glass	£ 92.70	0.86	1	0.01	20.86	£ 92.70	20.8686				
2.6.1	External windows	B2020100	First Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Window Frame		0.71	2	0.02		£ -	0.0142				
											Total	£ 1,027.86	334.959kg				
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Panel 44mm	£ 93.59	0.71	4	0.06	23.915	£ 93.59	95.7026	476p	L201830G	sec16 p12	L20103
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Frame/Mullion	£ -	0.71	3	0.04		£ -	0.0284				
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Architrave		0.71	2	0.01		£ -	0.0071				
2.6.3	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Handle			0	0		£ -	0				
											Total	£ 93.59	95.738kg				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		5	0.36		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	10	0.12	29.044	£ 280.40	290.4856	400p	K100110E	sec15 p1	K10002
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		5	0.38		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	10	0.13	29.044	£ 280.40	290.4894				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		8	0.63		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	17	0.21	29.044	£ 476.68	493.8278				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		6	0.45		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	12	0.15	29.044	£ 336.48	348.585				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		17	1.28		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	34	0.43	29.044	£ 953.36	987.6594				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		12	0.88		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	23	0.29	29.044	£ 644.92	668.1222				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		17	1.28		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	34	0.43	29.044	£ 953.36	987.6594				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		7	0.55		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	15	0.18	29.044	£ 420.60	435.7284				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		12	0.88		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	23	0.29	29.044	£ 644.92	668.1222				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		10	0.73		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	19	0.24	29.044	£ 532.76	551.9272				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		10	0.73		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	19	0.24	29.044	£ 532.76	551.9272				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		7	0.54		£ -	0				
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	14	0.18	29.044	£ 392.56	406.6844				
											Total	£ 6,449.20	6681.218kg				
											Grand Total	£ 41,371.35	34994.8961				

Insulation Materials	Material Cost	SMM7	Embodied CO_2	
EPS 50mm	£ 9.88	sec19 p1	12	BRE Green Guide Specification
Fibre Glass 100mm	£ 5.25	sec19 p2	4.25	BRE Green Guide Specification

Appendix 9. Construction Costs and Embodied CO_2 (Cradle to Site) Calculation – Basic Semi-Detached/End Terraced House

Semi-Detached/End Terraced House Basic							SMM7	Univ. of Bath	m2	m3	Black Book		kg
NRM Code	Element	Assembly Code (Autodesk Revit)	Level	Family	Family and Type	Material: Name	Construction Costs (Material + Labor)	Material: Embodied CO2 (Cost)	Material: Area	Material: Volume	Construction Embodied CO2	Total Cost	Total Embodied CO2
1	Substructure												
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	48	1.05	2.42	£ 1,178.88	116.727
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer, 75x225	£ 8.78	0.71	48	10.76	3.045	£ 421.44	153.7996
											Total	£ 1,600.32	270.527kg
2	Superstructure												
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	48	1.05	2.42	£ 1,178.88	116.727
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£ 8.78	0.71	48	10.76	3.045	£ 421.44	153.7996
2.2.1	Upper Floor	B1010375	Ground Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	46	0.55	29.044	£ 1,289.84	1336.233
2.2.1	Upper Floor	B1010375	First Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	46	0.55	29.044	£ 1,289.84	1336.233
											Total	£ 4,180.00	2942.993kg
2.3.1	Roof Structure	B1020400	Loft	Floor	Floor: Roof Ceiling Joist			0.71	47	4.73	4.058	£ -	194.0843
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Wood Strutt 50x150	£ 6.61	0.71	64	1.59	2.184	£ 423.04	140.9049
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter Layer	£ 12.49	0.71	64	9.54	4.058	£ 799.36	266.4854
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing, Tile 65mm lap 100mm gauge	£ 58.40	0.45	64	2.42	37.56	£ 3,737.60	2404.929
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing Felt	£ 6.83	0.41	64	0	5.22	£ 437.12	334.08
											Total	£ 5,397.12	3340.484kg
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common cement mortar 1:3	£ 87.59	0.23	31	6.54	98.017	£ 2,715.29	3040.0312
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	31	0.62	3.29	£ 333.87	102.0644
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	55	11.77	98.017	£ 4,817.45	5393.6421
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	55	1.09	3.29	£ 592.35	181.0808
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	26	5.59	98.017	£ 2,277.34	2549.7277
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	26	0.53	3.29	£ 280.02	85.6036
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	50	10.82	98.017	£ 4,379.50	4903.3386
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	50	1.01	3.29	£ 538.50	164.6212
											Total	£ 15,934.32	16420.11kg
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Dee	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Glass	£ 92.70	0.86	1	0.01	20.86	£ 92.70	20.8686
2.6.1	External windows	B2020100	First Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Window Frame		0.71	2	0.02		£ -	0.0142
											Total	£ 794.75	265.211kg
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Panel 44mm	£ 93.59	0.71	4	0.06	23.915	£ 93.59	95.7026
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Frame/Mullion	£ -	0.71	3	0.04		£ -	0.0284
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Architrave		0.71	2	0.01		£ -	0.0071
2.6.3	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Handle			0	0		£ -	0
											Total	£ 93.59	95.738kg
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		15	1.09		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	29	0.36	29.044	£ 813.16	842.4128
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		8	0.57		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	15	0.19	29.044	£ 420.60	435.7322
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		7	0.53		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	14	0.18	29.044	£ 392.56	406.6844
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		5	0.34		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	9	0.11	29.044	£ 252.36	261.4378
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		4	0.31		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	8	0.1	29.044	£ 224.32	232.39
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		4	0.32		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	9	0.11	29.044	£ 252.36	261.4378
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		15	1.09		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	29	0.36	29.044	£ 813.16	842.4128
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		15	1.1		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	29	0.37	29.044	£ 813.16	842.4166
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		8	0.58		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	16	0.19	29.044	£ 448.64	464.7762
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Air Infiltration Barrier	£ -		6	0.49		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - St	Gypsum Wall Board	£ 28.04	0.38	13	0.16	29.044	£ 364.52	377.6328
											Total	£ 4,794.84	4967.333kg
											Grand Total	£ 32,794.94	28302.395kg

Appendix 10. Construction Costs and Embodied CO_2 (Cradle to Site) Calculation – Basic Terraced House

Terraced House Basic

NRM Code	Element	Assembly Code (Autodesk Revit)	Level	Family	Family and Type	Material: Name	SMM7 Construction Costs (Material + Labor)	Univ. of Bath Material: Embodied CO2 (Cost)	m2 Material: Area	m3 Material: Volume	Black Book Construction Embodied CO2	Total Cost	kg Total Embodied CO2
1	Substructure												
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	31	0.69	2.42	£ 761.36	75.3926
1.1.3	Lowest Floor Construction	B1010375	Ground Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer, 75x225	£ 8.78	0.71	31	7.06	3.045	£ 272.18	99.4076
											Total	£ 1,033.54	174.8kg
2	Superstructure												
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Wood Sheathing, Chipboard	£ 24.56	0.54	31	0.69	2.42	£ 761.36	75.3926
2.2.1	Upper Floor	B1010375	First Floor	Floor	Floor: Timber Suspended Floor	Structure, Timber Joist/Rafter Layer	£ 8.78	0.71	31	7.06	3.045	£ 272.18	99.4076
2.2.1	Upper Floor	B1010375	Ground Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	30	0.36	29.044	£ 841.20	871.4568
2.2.1	Upper Floor	B1010375	First Floor	Basic Ceiling	Basic Ceiling: Generic	Gypsum Wall Board	£ 28.04	0.38	30	0.36	29.044	£ 841.20	871.4568
											Total	£ 2,715.94	1917.714kg
2.3.1	Roof Structure	B1020400	Loft	Floor	Floor: Roof Ceiling Joist	Structure, Timber Joist/Rafter Layer 100x150		0.71	31	3.09	4.058	£ -	127.9919
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Wood Strutt 50x150	£ 6.61	0.71	43	1.08	2.184	£ 284.23	94.6788
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Structure, Timber Truss Joist/Rafter Layer	£ 12.49	0.71	43	6.46	4.058	£ 537.07	179.0806
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing, Tile 65mm lap 100mm gauge	£ 58.40	0.45	43	1.64	37.56	£ 2,511.20	1615.818
2.3.1	Roof Structure	B1020400		Basic Roof	Basic Roof: Cold Roof - Timber	Roofing Felt	£ 6.83	0.41	43	0	5.22	£ 293.69	224.46
											Total	£ 3,626.19	2242.029kg
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common cement mortar 1:3	£ 87.59	0.23	20	4.32	98.017	£ 1,751.80	1961.3336
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	20	0.41	3.29	£ 215.40	65.8492
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	49	10.56	98.017	£ 4,291.91	4805.2618
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	49	0.98	3.29	£ 527.73	161.3276
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	17	3.63	98.017	£ 1,489.03	1667.1239
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	17	0.34	3.29	£ 183.09	55.9708
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Brick, Common	£ 87.59	0.23	48	10.29	98.017	£ 4,204.32	4707.1827
2.5	External walls	B2010100		Basic Wall	Basic Wall: Ext - 215 - Brick	Plaster	£ 10.77	0.12	48	0.96	3.29	£ 516.96	158.0352
											Total	£ 13,180.24	13582.085kg
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	Ground Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Glass	£ 140.41	0.86	2	0.02	24.41	£ 140.41	48.8372
2.6.1	External windows	B2020100	First Floor	Dbl Plain	Dbl Plain: 1200 x 1050mm Deep	Window Frame		0.71	3	0.04		£ -	0.0284
2.6.1	External windows	B2020100	First Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Glass	£ 92.70	0.86	1	0.01	20.86	£ 92.70	20.8686
2.6.1	External windows	B2020100	First Floor	Sgl Plain	Sgl Plain: 630 x 1050mm Deep	Window Frame		0.71	2	0.02		£ -	0.0142
											Total	£ 654.34	216.345kg
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Panel 44mm	£ 93.59	0.71	4	0.06	23.915	£ 93.59	95.7026
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Frame/Mullion	£ -	0.71	3	0.04		£ -	0.0284
2.6.2	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Architrave		0.71	2	0.01		£ -	0.0071
2.6.3	External doors	B2030200	Ground Floor	IntSgl (7)	IntSgl (7): 910 x 2110mm	Door - Handle			0	0		£ -	0
											Total	£ 187.18	191.476kg
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		11	0.8		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	21	0.27	29.044	£ 588.84	610.0266
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		9	0.68		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	18	0.23	29.044	£ 504.72	522.8794
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		11	0.8		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	21	0.27	29.044	£ 588.84	610.0266
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		10	0.78		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	21	0.26	29.044	£ 588.84	610.0228
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Air Infiltration Barrier	£ -		5	0.39		£ -	0
2.7	Internal walls and partitions	C1010100		Basic Wall	Basic Wall: Partn - p 75i p - Stu	Gypsum Wall Board	£ 28.04	0.38	10	0.13	29.044	£ 280.40	290.4894
											Total	£ 2,551.64	2643.445kg
											Grand Total	£ 23,949.07	20967.894kg

Appendix 11. NPV Calculation – Basic Detached House

	Construction Costs	Maintenance Costs						Opreation Costs		Occupancy Costs		End of life cost		
Year	Construction Costs	Major Repair Costs	Routine Maintenance Costs	Decorate Costs	Minor Repair Costs	Major Replace Costs	Reactive Repair Costs	Clean Costs	Energy Costs	Waste Treatment	Sewage	End of life cost	Total LCC	
0	£ 41,371.35												£ 41,371.35	
1			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N4
2			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N5
3			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N6
4			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N7
5			£ 1,362.40		£ 10.28		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 3,085.95	=N8
6			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N9
7			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N10
8			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N11
9			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N12
10		£ 9.36	£ 1,362.40		£ 10.28		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 3,095.31	=N13
11			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N14
12			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,772.02	=N15
13			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N16
14			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N17
15		£ 102.79	£ 1,362.40	£ 270.00	£ 10.28		£ 446.33	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 3,838.22	=N18
16			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N19
17			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N20
18			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N21
19			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N22
20		£ 9.36	£ 1,362.40	£ 2,555.76	£ 10.28		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 5,651.07	=N23
21			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N24
22			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N25
23			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N26
24			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,772.02	=N27
25			£ 1,362.40		£ 10.28		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 3,085.95	=N28
26			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N29
27			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N30
28			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N31
29			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N32
30		£ 643.42	£ 1,362.40	£ 270.00	£ 915.19	£ 1,490.40	£ 446.33	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 6,774.17	=N33
31			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N34
32			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N35
33			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N36
34			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N37
35		£ 1,175.80	£ 1,362.40		£ 220.53	£ 112.31	£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 4,584.31	=N38
36			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,772.02	=N39
37			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N40
38			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N41
39			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N42
40		£ 9.36	£ 1,362.40	£ 2,555.76	£ 389.76		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 6,030.55	=N43
41			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N44
42			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N45
43			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N46
44			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N47
45		£ 102.79	£ 1,362.40	£ 270.00	£ 10.28		£ 446.33	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 3,838.22	=N48
46			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N49
47			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N50
48			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,772.02	=N51
49			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N52
50		£ 4,533.92	£ 1,362.40		£ 10.28		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 7,619.87	=N53
51			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N54
52			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N55
53			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N56
54			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N57
55			£ 1,362.40		£ 10.28		£ 66.85	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 3,085.95	=N58
56			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 5,502.02	=N59
57			£ 1,362.40	£ 270.00				£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 3,216.26	=N60
58			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N61
59			£ 1,362.40					£ 180.36	£ 1,150.00	£ 156.00	£ 97.50		£ 2,946.26	=N62
60		£ 643.42	£ 1,362.40	£ 2,825.76	£ 915.19	£31,235.81	£ 446.33	£ 242.92	£ 1,150.00	£ 156.00	£ 97.50		£ 39,075.34	=N63
NPV	£ 41,371.35	£ 6,841.78	£ 65,101.04	£38,726.31	£ 2,361.31	£32,106.54	£ 2,195.61	£ 9,206.97	£ 54,951.70	£ 7,454.32	£ 4,658.95		£ 246,730.83	
	=B65												=NPV(A66,N4:N63)+B65	

0.78% =A66, Discount Rate

r 3.50% =B67

i 2.70% =B68

0.78% =(1+B67)/(1+B68)-1

Appendix 12. NPV Calculation – Basic Semi-Detached/End Terraced House

	Construction Costs	Maintenance Costs						Opreation Costs		Occupancy Costs		End of life cost		
Year	Construction Costs	Major Repair Costs	Routine Maintenance Costs	Decorate Costs	Minor Repair Costs	Replace Costs	Reactive Repair Costs	Clean Costs	Energy Costs	Waste Treatment	Sewage	End of life cost	Total LCC	
0	£ 32,794.94												£ 32,794.94	
1			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N4
2			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N5
3			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N6
4			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N7
5			£ 1,362.40		£ 7.95		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 3,001.57	=N8
6			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N9
7			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N10
8			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N11
9			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N12
10		£ 9.36	£ 1,362.40		£ 7.95		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 3,010.93	=N13
11			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N14
12			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,700.72	=N15
13			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N16
14			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N17
15		£ 79.48	£ 1,362.40	£ 270.00	£ 7.95		£ 325.96	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 3,620.90	=N18
16			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N19
17			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N20
18			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N21
19			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N22
20		£ 9.36	£ 1,362.40	£ 2,555.76	£ 7.95		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 5,566.69	=N23
21			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N24
22			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N25
23			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N26
24			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,700.72	=N27
25			£ 1,362.40		£ 7.95		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 3,001.57	=N28
26			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N29
27			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N30
28			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N31
29			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N32
30		£ 466.63	£ 1,362.40	£ 270.00	£ 804.66	£ 1,152.39	£ 325.96	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 5,957.16	=N33
31			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N34
32			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N35
33			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N36
34			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N37
35		£ 836.00	£ 1,362.40		£ 193.06	£ 112.31	£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 4,134.99	=N38
36			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,700.72	=N39
37			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N40
38			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N41
39			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N42
40		£ 9.36	£ 1,362.40	£ 2,555.76	£ 277.80		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 5,836.54	=N43
41			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N44
42			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N45
43			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N46
44			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N47
45		£ 79.48	£ 1,362.40	£ 270.00	£ 7.95		£ 325.96	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 3,620.90	=N48
46			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N49
47			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N50
48			£ 1,362.40	£ 2,825.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,700.72	=N51
49			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N52
50		£ 3,992.94	£ 1,362.40		£ 7.95		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 6,994.51	=N53
51			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N54
52			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N55
53			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N56
54			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N57
55			£ 1,362.40		£ 7.95		£ 56.10	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 3,001.57	=N58
56			£ 1,362.40	£ 2,555.76				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 5,430.72	=N59
57			£ 1,362.40	£ 270.00				£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 3,144.96	=N60
58			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N61
59			£ 1,362.40					£ 180.36	£ 1,078.70	£ 156.00	£ 97.50		£ 2,874.96	=N62
60		£ 466.63	£ 1,362.40	£ 2,825.76	£ 804.66	£ 26,441.70	£ 325.96	£ 242.92	£ 1,078.70	£ 156.00	£ 97.50		£ 33,802.24	=N63
NPV	£ 32,794.94	£ 5,625.21	£ 65,101.04	£ 38,726.31	£ 2,006.01	£ 27,087.35	£ 1,659.07	£ 9,206.97	£ 51,544.69	£ 7,454.32	£ 4,658.95		£ 229,848.88	
	=B64												=NPV(A67,N4:N63)+B64	

0.78% =A67

Appendix 13. NPV Calculation – Basic Terraced House

	Construction Costs	Maintenance Costs						Opreation Costs		Occupancy Costs		End of life cost		
Year	Construction Costs	Major Repair Costs	Routine Maintenance Costs	Decorate Costs	Minor Repair Costs	Replace Costs	Reactive Repair Costs	Clean Costs	Energy Costs	Waste Treatment	Sewage	End of life cost	Total LCC	
0	£ 23,949.07												£ 23,949.07	
1			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N4
2			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N5
3			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N6
4			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N7
5			£ 1,362.40		£ 6.54		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 2,701.28	=N8
6			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N9
7			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N10
8			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N11
9			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N12
10		£ 18.72	£ 1,362.40		£ 6.54		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 2,720.00	=N13
11			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N14
12			£ 1,362.40	£ 2,825.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,411.61	=N15
13			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N16
14			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N17
15		£ 65.43	£ 1,362.40	£ 270.00	£ 6.54		£ 227.64	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 3,218.03	=N18
16			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N19
17			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N20
18			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N21
19			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N22
20		£ 18.72	£ 1,362.40	£ 2,555.76	£ 6.54		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 5,275.76	=N23
21			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N24
22			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N25
23			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N26
24			£ 1,362.40	£ 2,825.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,411.61	=N27
25			£ 1,362.40		£ 6.54		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 2,701.28	=N28
26			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N29
27			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N30
28			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N31
29			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N32
30		£ 337.99	£ 1,362.40	£ 270.00	£ 665.56	£ 948.79	£ 227.64	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 5,098.38	=N33
31			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N34
32			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N35
33			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N36
34			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N37
35		£ 543.19	£ 1,362.40		£ 159.66	£ 224.62	£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 3,622.21	=N38
36			£ 1,362.40	£ 2,825.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,411.61	=N39
37			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N40
38			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N41
39			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N42
40		£ 18.72	£ 1,362.40	£ 2,555.76	£ 187.85		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 5,457.07	=N43
41			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N44
42			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N45
43			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N46
44			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N47
45		£ 65.43	£ 1,362.40	£ 270.00	£ 6.54		£ 227.64	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 3,218.03	=N48
46			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N49
47			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N50
48			£ 1,362.40	£ 2,825.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,411.61	=N51
49			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N52
50		£ 3,313.78	£ 1,362.40		£ 6.54		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 6,015.06	=N53
51			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N54
52			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N55
53			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N56
54			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N57
55			£ 1,362.40		£ 6.54		£ 46.33	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 2,701.28	=N58
56			£ 1,362.40	£ 2,555.76				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 5,141.61	=N59
57			£ 1,362.40	£ 270.00				£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,855.85	=N60
58			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N61
59			£ 1,362.40					£ 180.36	£ 789.59	£ 156.00	£ 97.50		£ 2,585.85	=N62
60		£ 337.99	£ 1,362.40	£ 2,825.76	£ 665.56	£ 21,280.45	£ 227.64	£ 242.92	£ 789.59	£ 156.00	£ 97.50		£ 27,985.80	=N63
NPV	£ 23,949.07	£ 4,460.82	£ 65,101.04	£ 38,726.31	£ 1,619.56	£ 21,953.41	£ 1,213.25	£ 9,206.97	£ 37,729.84	£ 7,454.32	£ 4,658.95		£ 202,349.80	
	=B64												=NPV(A67,N4:N63)+B64	

0.78% =A67

Appendix 14. BIM Framework Validation Survey Results

Expert 1.

Q1. What is your background and years of experience in your work? Please describe.

I am an architect with over thirty years' experience as an energy and sustainability consultant, mostly in the domestic sector, and I have specialised in retrofit for the last six years. I am a Director of the Centre of Refurbishment Excellence (CoRE), a member of the Board of Trustees of the National Energy Foundation and a member of the RIBA's Sustainable Futures Group.

Q2. Does the proposed framework suit for the housing refurbishment projects using BIM?

Yes [X]	No []
If Yes, how this framework can be improved further? Please specify. I think your process is nearly correct, but there needs to be option evaluation based on energy modelling at stage R1. By the time you get to stage R2 you may be committed to a sub-optimal retrofit strategy. I would put more emphasis on energy modelling to support option evaluation and less emphasis on energy modelling to establish the performance of the design (although you will have to do that as well, to establish your LCC and LCA values).	If No, what is the reason(s)? Please specify.

Q3. Is the proposed framework practical?

Yes [X]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify. See my answer to Q2, above	If No, what is the reason(s)? Please specify.

Q4. Are the outcomes of life cycle cost and life cycle assessment useful as a decision making criteria to determine affordable refurbishment solution regarding material(s) and energy standard(s)?

Yes [X]	No [ ]
If Yes, how the practicality of this framework	If No, what is the reason(s)? Please specify.

can be improved further? Please specify. I think the LCC and LCA values are useful, but they probably need to be converted into more immediate indicators. For example, you could calculate the net present value (NPV) of each measure or improvement package, or its carbon cost effectivess (CCE – as described in the Construction Products Association / RIBA publication *An Introduction to Low Carbon Domestic Refurbishment*).	

Q5. Please provide any additional comments and opinions.

Your work is interesting – what happens when you generalise it beyond one improvement measure to packages of measures? How easy is it to run and compare several specification options, and to add or remove measures from proposals to see the overall effect? Where do you get your capital costs from? We have a large library of installed improvement costs for domestic improvement measures, and there is a lot of variation. WE could probably share some costs with you if that helps, especially if you could build them into your BIM Object Library somehow.

Expert 2

Q1. What is your background and years of experience in your work? Please describe.

15 years

Q2. Does the proposed framework suit for the housing refurbishment projects using BIM?

Yes [×]	No [ ]
If Yes, how this framework can be improved further? Please specify. The framework looks very nice and well thought out. It should be useful for decision making, in particular the refurbishment, throughout the life cycle of a house. You may indicate the (potential) sources for the framework, e.g. BIM objective libraries, how to derive the as-built model, and what is the level of development (LOD) for refurbishment work.	If No, what is the reason(s)? Please specify.

You may also specify the players of each strategic step, e.g. who will conduct the simulation, design review, and buildability check, etc.	

Q3. Is the proposed framework practical?

Yes [×]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify. It might be impractical to implement it now as some of the information in BIM is not ready, but it is good to think about it now.	If No, what is the reason(s)? Please specify.

Q4. Are the outcomes of life cycle cost and life cycle assessment useful as a decision making criteria to determine affordable refurbishment solution regarding material(s) and energy standard(s)?

Yes [×]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify. The LCC data and analyses are very solid! But, I had some difficulties to follow the logic. You talked a BIM framework first, and then the LCC using a wall as a hypothetical case. Please think how to combine the two together if I understand correctly that is your research aim.	If No, what is the reason(s)? Please specify.

Q5. Please provide any additional comments and opinions.

This is a very interesting piece of work! I encourage you to pursue more alongside this direction.

Expert 3

Q1. What is your background and years of experience in your work? Please describe.

6 years.

Q2. Does the proposed framework suit for the housing refurbishment projects using BIM?

Yes [V]	No [ ]
If Yes, how this framework can be improved further? Please specify. It is useful to determine optimized refurbishment solution which is low impacts on	If No, what is the reason(s)? Please specify.

environments and less cost.	

Q3. Is the proposed framework practical?

Yes [V]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify. I think this is practical. but, it is essential to develop more specific and particular BIM library for housing refurbishment. BIM library needs to provide proper BIM objects with life cycle information.	If No, what is the reason(s)? Please specify.

Q4. Are the outcomes of life cycle cost and life cycle assessment useful as a decision making criteria to determine affordable refurbishment solution regarding material(s) and energy standard(s)?

Yes [V]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify. More specific data for construction material that can calculate life cycle cost need to be defined further.	If No, what is the reason(s)? Please specify.

Q5. Please provide any additional comments and opinions.
Level of details in BIM library should be defined, and BIM object needs to be developed based on the protocol.

Expert 4

Q1. What is your background and years of experience in your work? Please describe.
Construction Company 12years and 6 months, Academic 8years and 9months

Q2. Does the proposed framework suit for the housing refurbishment projects using BIM?

Yes [O]	No [ ]
If Yes, how this framework can be improved further? Please specify. The assessment of housing condition is very	If No, what is the reason(s)? Please specify.

important for refurbishment. Also, energy system and services should be considered to develop more affordable refurbishment solution. Overall, the process captures information flow well.	

Q3. Is the proposed framework practical?

Yes [O]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify. It should be practical as it is, but it needs to be further defined in its process.	If No, what is the reason(s)? Please specify.

Q4. Are the outcomes of life cycle cost and life cycle assessment useful as a decision making criteria to determine affordable refurbishment solution regarding material(s) and energy standard(s)?

Yes [O]	No [ ]
If Yes, how the practicality of this framework can be improved further? Please specify.	If No, what is the reason(s)? Please specify.

Q5. Please provide any additional comments and opinions.

Maybe specific tools and techniques for each phase to use BIM effectively?