Delivering Value for Money with BIM-embedded Housing Refurbishment

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Abstract

Purpose – The aim of this research is to examine if BIM is feasible as an information management platform to determine a financially and environmentally affordable housing refurbishment solution based on the LCC and LCA calculation.

Design/methodology/approach – A case study in conjunction with BIM simulation approach using BIM tools was adopted to identify the feasibility of BIM for the simultaneous formulation of LCC and LCA in housing refurbishment.

Findings – This research reveals that BIM is a suitable for the information management platform to enable construction professionals to consider trade-off relationship between LCC and LCA simultaneously, and determine the most financially and environmentally affordable refurbishment solution. The interoperability issues in data exchange among different BIM tools and unstandardized BIM object libraries with incomplete datasets of construction materials are recognized as the major shortcomings in a BIM system. Essential remedial actions to overcome the shortcomings in the current BIM tools are identified.

Research limitations/implications – Actual housing information and various refurbishment materials for the BIM simulation are limited.

Practical implications – This research contribute to supporting construction professionals to prepare practical BIM adoption for the integration of the LCC and LCA that can significantly improve early decision makings on sustainable housing refurbishment.

Originality/value – This research will contribute to providing proper remedial actions to overcome the shortcomings in the current BIM tools, and insights for construction professionals to understand the implication of BIM-embedded housing refurbishment.

Keywords: BIM, Housing Refurbishment, LCC, LCA, Sustainable Construction

Paper type: Article

Introduction

Refurbishment in the building sector is an internationally overarching issue to achieve energy efficiency improvement, and in particular, the European countries have released various sustainable refurbishment strategies and initiatives (Almas et al., 2011; European Union, 2012; Jensen and Maslesa, 2015). For example, the UK government has released the whole-house refurbishment strategy, Great British Refurbishment to refurbish 80% of the total old housing stock complying with the modern energy standard by 2020 (DECC, 2009) as the UK possesses the oldest housing stock among developed countries with 8.5 million properties over 60-years-old (EST, 2007). Since the investment in housing refurbishment will be compensated from reduced energy bill over a building life cycle, the value for money is a vital aspect to be considered from the outset of a refurbishment project. Consequently, researchers recommend the integrated use of Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) methodologies to deliver value for money for clients by offering the most affordable refurbishment solution economically and environmentally (Swarr et al. 2011; Ortiz et al., 2016). 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) and the better performance of a low carbon house can be examined in comparison with a traditional house. While the operational cost is being reduced, the amount of embodied CO_2 in a low carbon building becomes three times higher than in a conventional building (Sartori and Hestnes, 2007). Blengini and Di Carlo (2010) proved that the costs for the construction phase and operation phase are in inverse proportion to each other. Thus, the trade-off relationship, which is the balance between energy efficiency improvement and capital investment based on the LCC and LCA, needs to be fully considered and considerately planned as a house has a long lifespan. Yet, not all construction professionals can understand the trade-off relationship between the LCC and LCA in terms of the capital investment and energy efficiency improvement based on various refurbishment alternatives (Menassa, 2011).

Integration of LCC and LCA in Sustainable Refurbishment

The European Directive 2012/27 has been established as a strategy for energy efficiency improvement aiming at cost-effective refurbishment and less CO_2 emission (European Union, 2012). The strategy provides two main approaches - Energy Performance of Building Directive and Energy Efficiency Directive – focusing on the balanced cost-energy efficiency optimal approach to sustainable refurbishment alternatives. In addition, the EU established the legislative framework - Directive 2014/24/EU - to promote sustainable public procurement through LCC (Official journal of the European Union, 2014) although the consideration of LCA has been limitedly given. In alignment with the European Directives, the Italian National Energy Strategy recommended the roadmap scenario for the continuous optimisation of refurbishment processes based on the building classifications, and the Nordic SURE (SUstainable REfurbishment) guideline has been established by a consortium of researchers from the Finland and Norway. The two national energy improvement strategies emphasise the importance of assessing the current status of housing and clients' energy improvement target in order to provide the most cost-effective refurbishment solutions (Almas et al., 2011). Jensen and Maslesa (2015) proposed an advanced process tool, the RENO-EVALUE to provide a clear process that can facilitate better communication and collaboration at the early phase of refurbishment projects among stakeholders to achieve the targeted sustainability. The unique strength of this tool is capable of prioritising stakeholder's demands and establishing a clear target of renovation focusing on the value-adding decision supporting tool at the early phase of a project. The emphasis on the importance of the early phase of a refurbishment project is also supported by other researchers (Juan et al., 2009; Almas et al., 2011). Jenkins et al. (2012) proposed a step-by-step refurbishment measure adoption strategy, 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 based on the customers' requirements since there is no universal refurbishment solution. Through the literature review, it is evident that researchers commonly advocate the importance of the early collaboration and involvements of stakeholders to make a proper decision-making at the early design phase, and the necessity of using proper tools to determine the most affordable refurbishment solutions. However, the LCC and LCA information for determining proper refurbishment alternatives are currently considered at the end of the design phase, and separately formulated when flexibility of refurbishment solutions and opportunities to explore various refurbishment alternatives are significantly limited (Ma et al., 2012; Thuvander et al., 2012). Consequently, the current refurbishment practice fails to accommodate the holistic consideration of the LCC and LCA to compare various design alternatives and materials (Tsai et al., 2011). Furthermore, the trade-off relationship between the LCC and LCA depending on various combinations of refurbishment alternatives are not considered simultaneously, and it results in neglecting 50% of possible refurbishment alternatives that can render better outcomes of refurbishment (Schneider and Rode, 2010). In response to the current fragmented practice in the LCC and LCA calculation for sustainable refurbishment, the European Standards has released a holistic assessment standard, CEN TC 350 to measure the financial and environmental impacts of a building and construction (CEN, 2013). The standard recommends adopting two major sustainability assessment standards - Product level, **EN 15804 (CEN, 2012)** and Building level, **EN 15643 series (CEN, 2010)**. These standards underline the importance of detailed information requirements for the economic and environmental assessment of building performance and construction works, which echoes the emphasis of various sustainable refurbishment strategies and studies. However, the interactions between the Product and Building levels standards are not fully integrated (Paleari et al., 2012), and there is a potential issue to integrate the LCC and LCA seamlessly for assessing refurbishment alternatives due to a lack of interoperability in datasets between the two standards (BRE, 2016). Consequently, researchers have undertaken studies to examine a way to integrate LCA and LCC, and recognised the potential solution in a Building Information Modelling (BIM) system as a data integration complementary platform between LCC and LCA methods (Liu and Issa, 2014; Ortiz et al., 2016).

Integration of LCC and LCA in BIM Environment

Basbagill et al. (2013) and Crawley et al. (2008) argue the potential use of BIM to improve current practice of refurbishments because BIM is capable of enhancing collaboration and integration of project information among stakeholders by improving the overall information flow throughout a project life cycle (Eastman et al, 2011; Wong and Fan, 2013). Rysanek and Choudhary (2013) assert that refurbishment projects should utilise a tool including BIM to support informed decision making among various refurbishment alternatives, while considering multiple criteria such as the implication of cost and the environmental impact. Indeed, BIM is currently mandated as a methodology to procure all public construction projects by many countries including UK, US, European countries, and Asian countries since BIM is capable of facilitating informed decisions regarding sustainability of a building at the early design phase where most of the level of sustainability is determined (Kim et al., 2016). In alignment with the global initiatives of BIM strategies, there have been endeavours to investigate the BIM capability of formulating LCC and LCA based on different refurbishment alternatives, and of coping with design changes internationally. Hong et al. (2012) and Kim et al. (2013) proposed an integrated model to assess the LCC and LCA based on a well-structured life cycle information datasets in the South Korean construction context. Researchers assert the importance of the availability of life cycle information of various refurbishment alternatives at the early design phase, and this research is supported by Kim and Park (2013) as researchers conducted a BIM feasibility study for housing refurbishment in the UK context whether BIM is feasible for an information management system for housing refurbishment, and consequently BIM is recognised as feasible when sufficient BIM datasets including the LCC and LCA are available. Park and Kim (2014) recognized that BIM is capable of accommodating customers' preference for housing refurbishment in terms of refurbishment materials and options at the early design stage, which has been emphasised through the literature as a key aspect of sustainable refurbishment. Ferreira et al. (2015)

and Dukanovic et al. (2016) apply the LCC and LCA to a residential building refurbishment in Italy and Serbia respectively, and researchers recognise that BIM is capable of managing the life cycle information of structural components of buildings. Overall research findings explicitly indicate that BIM is capable of enabling design and construction professionals to integrate the LCC and LCA, and facilitate stakeholders' early involvement as it has been emphasised by researchers in sustainable refurbishment. Researchers share the same perspectives that the integration of life cycle information of each refurbishment alternative are essential to generate the most affordable refurbishment solution in a BIM environment using the LCC and LCA calculations.

Although researchers recognised BIM as a possible solution, researchers also pointed out that BIM can only be an enabler when proper and reliable datasets are available. Indeed, the LCC and LCA datasets are still maintained, calculated and compared separately within a BIM system, and eventually it fails to achieve the seamless updates on LCC and LCA calculations depending on different selections of refurbishment alternatives (Shadram et al., 2016). Although the International Council for Local Environmental Initiatives developed the SMART SPP Guide to integrate LCC and LCA for the sustainable procurement (ICLEI, 2016), the tool is still calculating the LCC and LCA separately. To overcome the unintegrated practice, researchers argue that the improvement on data exchange format and interoperability of LCC and LCA datasets are essential (Shadram et al., 2016). For the data exchange improvement, Hjelseth (2010) proposed a BIM object development containing life cycle information of building components. The concept of BIM objects development is supported by Jrade and Abdulla (2012), and researchers examined the capability of Industry Foundation Classes (IFC) as the information communication medium to confirm whether IFC can facilitate a seamless data exchange between LCC and LCA datasets within a BIM system. Consequently, the researchers discovered that IFC has a limitation to establish a direct data exchange as there are data loss and distortions within a BIM system between LCC and LCA. **Bueno and Fabricio (2017)** argue that a universal data exchange protocol such as IFC is required to be developed further in order to calculate and integrate the LCC and LCA study results simultaneously. Thus, this research aims at examining BIM as an information management platform for housing refurbishment if it is feasible to formulate the LCC and LCA calculation simultaneously, and cope with different refurbishment alternatives in terms of refurbishment material specifications. More importantly, this research is expected to reveal a remedy strategy to overcome the current data interoperability issues in a BIM system.

Research methodology

As this research focuses on the current contemporary event, a case study is chosen as the most suitable research strategy (Yin, 2003). A case study with BIM simulation is carried out to examine how BIM can serve as a life cycle information integration platform to support proper decision makings for housing refurbishment, and why BIM tools - Autodesk Revit and IES VE/IMPACT - can suggest an optimised refurbishment solution based on the simultaneous LCC and LCA information. For a case study with BIM simulation, a typical UK detached solid wall house is selected because this is the most energy inefficient housing type requiring immediate attention and in needs of refurbishment (National Refurbishment Centre, 2012), and the least affected housing type by the operating conditions such as indoor temperature of an adjacent house like terraced or semi-detached house. The average housing condition data for a solid wall house published by the UK government was used to build up a case housing model hypothetically because the condition of housing indicates a wide range of variation in its characteristic such as year built, construction types, physical dimensions, and construction materials, which cannot be generalized (Jenkins et al., 2012). Nevertheless, the hypothetical BIM model simulation is able to establish a base for design and construction professionals to compare potential alternatives before actual refurbishment is carried out. Therefore, it is worth emphasising that the outcome of this research should be used as a supporting tool for decision making, not as definitive decision making criteria. A hypothetical basic BIM model is created by BIM tools - Autodesk Revit for 3D modelling and IES Virtual Environment/Integrated Material Profile And Costing Tool (IES VE/IMPACT) for the LCA and LCC calculation including trade-offs relationships. Autodesk Revit is currently the most prevalent tool in the construction industry (NBS, 2016), and the IES VE/IMPACT has been adopted for various energy simulations including commercial (Jankovic, 2016) and residential buildings (Murray et al., 2012; Crawley et al., 2008), because it is the most advanced BIM tool that can conduct various energy simulations in refurbishment considering all possible building conditions and without additional data and model processing steps. More importantly, IES VE/IMPACT is specifically developed to calculate a whole building energy assessment based on LCC and LCA simultaneously. It has a full capability to conduct a complete energy and carbon performance analysis based on the EN 15804 (CEN, 2012) environmental profiles methodology for the LCC and LCA calculations in conjunction with two international building services standards - CIBSE and ASHRAE (Kurnitski, 2008; Sousa, 2012). IES VE is also qualified software for calculating energy savings recommended by Department of Energy in the US (DOE, 2016). Thus, IES VE/IMPACT is an internationally recognised tool, and highly relevant to this research to conduct a BIM simulation for the simultaneous LCC and LCA calculations based on the international standard.

Basic information for a house model

Detailed information of a basic house model regarding rooms and construction materials is provided in Appendix 1. The gross internal floor area was used for the calculation of LCC and LCA and energy performance simulation, and the total usable floor area is 130 m^2. The information regarding air permeability, weather data and thermal bridging have been inherited from IES VE/IMPACT.

Refurbishment Practices and Insulation Materials

The current refurbishment best practices inducing insulation of external wall, loft, and underfloor insulation between joists, and triple glazing were applied to compare the LCC and LCA outcomes between a basic and refurbished house model. The fibre glass and Expanded Polystyrene (EPS) were selected for the insulation materials based on the previous research findings of home occupants' consideration over insulation material selection (Park and Kim, 2014), which is the initial cost as the first priority. The selected materials belong to the relatively low cost range compared to other high initial material costs such as Vacuum Insulated Panel. In addition, the two insulation materials are only commonly available in both Autodesk Revit and IES VE/IMPACT material database, and they have been chosen for examining the seamless information exchange.

Energy Performance Standards and Material Specifications

Building Regulation (BR) Part L 2010, BR Part L 2013 and the Fabric Energy Efficiency Standard (FEES) were adopted for energy simulations to calculate the LCC and LCA based on each energy standards. The BR Part L 2010 and 2013 mandates the minimum energy efficiency standard for a new build house in the UK, and the FEES has been recently introduced to the BR Part L 2013 aimed at achieving zero carbon homes by 2016, which is the most energy efficient standard available at present. These energy efficiency standards have been adopted because these are the most reliable standards at present. As each country has its own unique building regulation depending on its geographic location and temperature, it is challenging to examine all energy efficiency standards for domestic buildings. However, the UK energy efficiency standards adopted in this research have similar U-values to other energy efficiency standards for domestic buildings in European countries such as Denmark and Finland (Scottish Building Standards Agency, 2007). For example, the basic U-values for an external wall are 0.3, 0.2 and 0.24 in the UK, Denmark, and Finland respectively, and the differences can be considered negligible. The detailed information of U-values and material specifications of wall, roof, floor, door and window based on different energy standards have been provided in Appendix 2.

Research Results

LCC and LCA study outcomes

The LCC and LCA study outcomes of refurbished houses with different energy standards have been identified lower than a basic house model as shown in Table 1. The sum of installed materials does not exceed the life cycle cost and environmental impact of new build house, and in terms of the energy consumption, approximately 80% of energy cost can be saved when the maximum energy standard (FEES) is adopted, and 74% energy cost saving is achievable for the minimum energy standard (BR 2010/2013) adoption. Thus, housing refurbishment is confirmed as an economically beneficial and environmentally responsible option for energy efficiency improvement to a client and a community. It has been examined that an average of 50% CO_2 emission reduction can be achieved as 49% and 51% reduction were achieved when the minimum and maximum energy standards were applied respectively. The research outcome in terms of CO_2 emission reduction is supported by the previous research result that the maximum of 50% to 60% CO_2 reduction can be achieved through whole-house fabric refurbishment (Boardman, 2007), which indicates this research outcome can be considered reliable.

Table 1. Life Cycle study Result with Fibre Glass (FG) and EPS

The LCC continues to increase as higher energy standards are adopted, and the LCC is much smaller when fibre glass is used compared to the EPS. 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 within a BIM tool (See Appendix 3 and 4). Construction costs for both material options continue to increase as higher energy standards are adopted. 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 Appendix 2). Based on the LCC and LCA outcomes, the fibre glass is the most affordable construction materials for refurbishment compared to the EPS. Thus, it is recommended selecting a material with a low material cost and a low embodied CO_2 as it renders less life cycle costs and environmental footprints. It is confirmed that a BIM system can facilitate the simultaneous LCC and LCA calculation by reflecting changes in material specifications and energy standards.

If only the construction costs are considered, the minimum energy standard should be adopted as both material options continue to increase. However, construction professionals and clients need to investigate the operating costs simultaneously as it presents a different increasing pattern from the construction costs. Operating costs of the EPS indicate the same pattern as the construction cost, while the operating costs of the fibre glass does not continuously increase (See Table 1). For example, the operating costs of the fibre glass with the BR 2013 (Notional) and the FEES (Maximum) are less than the operating costs with the BR 2010 (Notional). The fluctuation of operating costs is caused by the inverse proportion relationship as 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 (Blengini and Di Carlo, 2010). 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. Hence, this research confirms that the trade-off relationship between cost and energy efficiency improvement can be formulated and considered for the refurbishment plan within a BIM system in conjunction with the LCC and LCA studies.

Furthermore, the trade-off relationship, which is a certain level of inevitable compromise between LCC and LCA, needs to be considered at the early design stage to identify the optimum point where the total cost of construction cost and energy cost result is at the minimum level. It can be advised that the LCC information needs to be understood and utilised individually and collectively for better decision making since the LCC is comprised of the construction cost and operational costs. Based on the findings, construction professionals can advise customers to adopt a higher energy standard such as FEES (Maximum), when they wish to achieve high energy efficiency, since it is more financially and environmentally beneficial.

Data Interoperability in a BIM environment

Once the LCC and LCA outcomes are calculated, construction professionals can modify selected refurbishment solution by applying different construction materials and/or thickness. As BIM is supposed to facilitate a seamless information exchange between BIM tools, the modified refurbishment information within the life cycle information calculation tool (IES VE/IMPACT) should be transferred back into the initial house model to authorise the final decision on refurbishment solution. However, the feedback loop currently cannot be accommodated due to the different material datasets and interoperability problems between BIM tools as shown in Figure 1. When the updated information is transmitted back to the original BIM tool (Revit), the imported model is either presented as a simple picture with no material data (DFX), or presented in an uncoordinated manner with no material data (gbXML).

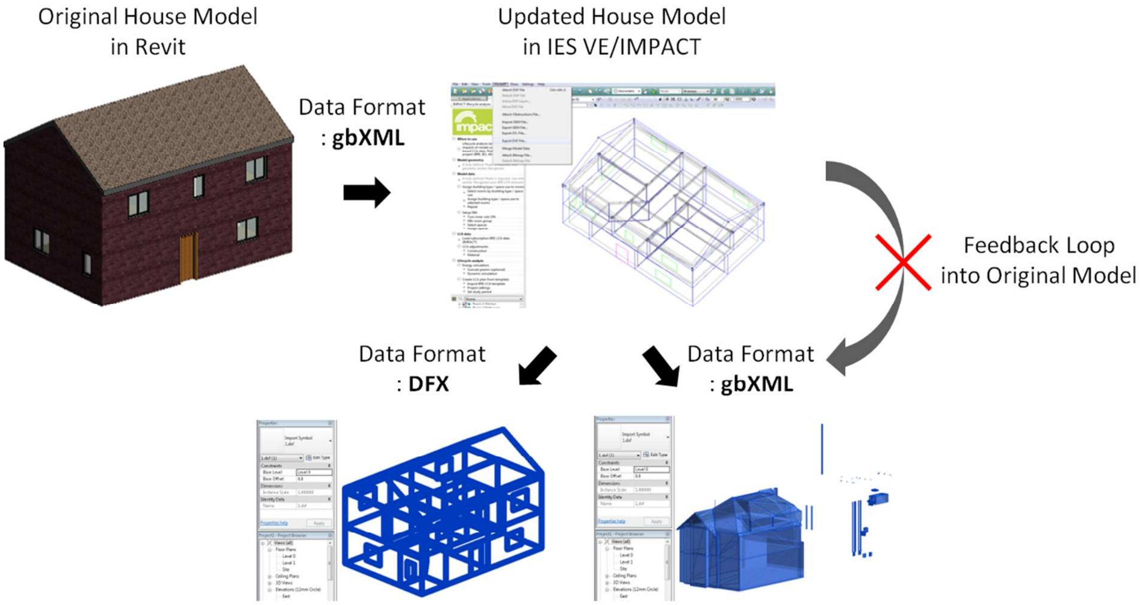

Figure 1. Broken Feedback Loop in a BIM System

Discussions

Data Interoperability between BIM tools

This research identifies that interoperability among various BIM tools is still a critical technical barrier. Although the concept of IFC and Green Building XML (gbXML) data formats is recognised by researchers as a universal medium for seamless data exchange regardless of proprietary BIM tools.

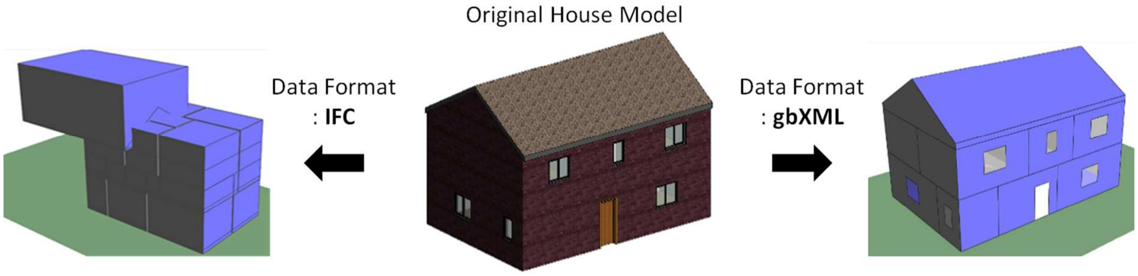

Figure 2. Data Exchange Result in IFC (left) and gbXML (right) Data Format

As shown in Figure 2, the geometric arrangement is broken when IFC data retrieved from Revit is transferred to IES VE/IMPACT, while gbXML format transfers a geometrically congruent model. 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 tools. In addition, essential refurbishment information including specification of insulation materials is not transferred, although the gbXML format transfers geometric information without distortion of a model. The missing information about the insulation materials and thickness need to be manually entered and reviewed. More importantly, essential data loss while transmitting a model must be thoroughly reviewed and amended before conducting the LCC and LCA calculation to avoid a situation known colloquially as 'garbage in, garbage out'.

Unstandardised Datasets of LCC and LCA

As aforementioned, researchers emphasise that BIM objects should be equipped with standardised datasets including specification of materials and thermal performance for the reliable LCC and LCA calculation. However, it is revealed that the current BIM objects are built on a database provided by specific proprietary BIM tools. Consequently, Revit has its own generic material codes, and IES VE/IMPACT also has its own LCC and LCA datasets. For example, a fibre glass is specified as 'B1020400' in Revit, while IES VE/IMPACT recognises it as 'Fibre Glass'. In the LCC dataset, a fibre glass is specified as '3015103A', while embodied CO_2 is not specified in the LCA dataset.

Essential remedy actions for broken feedback loop

Housing refurbishment solution development based on LCC and LCA using BIM tools is confirmed possible, but this research realised that there is a limitation in a BIM system and no definitive solution to resolve the broken feedback loop and unstandardised datasets. To challenge this, this research reveals essential remedy actions to fully utilize BIM tools and filling the gap in the seamless data communications as shown in Table 2. Furthermore, establishing standardised common BIM objects library with proper LCC and LCA datasets are highly recommended to utilize BIM tools for housing refurbishment because the application of BIM concept cannot add more value to the customers and the construction industry without reliable datasets regarding construction materials.

Table 2. Essential Remedy Actions for LCC and LCA calculation in IES VE/IMPACT

More importantly, it has been recognised that reliable complementary input datasets published by highly-rated construction organizations should be secured and utilises to formulate reliable LCC and LCA information. To avoid biased LCC and LCA information calculated by automated BIM calculation functions, the data published by well-known construction organizations are recommended in conjunction with the consideration of country-specific project environments and standards. For example, Australian SMM6 (Standard Method of Measurement) should be applied in the Australian context instead of the UK SMM7. Furthermore, manual manipulations and updates on construction materials and design of BIM objects are fundamentally required as the BIM maturity level is not advanced enough to accommodate a single source data repository BIM system. The current construction industry still heavily uses the 2D paper-based drawings in conjunction with BIM tools. Thus, experience and insights of construction professionals are vital to manipulate a BIM dataset and to interpret BIM models properly instead of blindly accepting the information derived from a BIM tool.

Limitations of the research

This research was able to examine only limited types of refurbishment materials including fibre glass and EPS due to the current limited availability of standardised material datasets in BIM tools. In order to conduct a more in-depth comparative analysis of LCC and LCA with different types of refurbishment materials, more BIM objects or library with reliable LCC and LCA datasets are required. This research confines the scope of a case study to a detached solid wall house based on the UK government data, and more international perspectives on housing type and energy standards are required to expand knowledge in the implication of BIM adoption in the housing refurbishment.

Conclusion

This research examines the feasibility of BIM as the first step if it could be a suitable tool to determine affordable housing refurbishment solution based on the simultaneous LCC and LCA calculation. Consequently, BIM is identified capable of providing simultaneous LCC and LCA information on refurbishment alternatives and feasible information management platform for housing refurbishment. It is also confirmed that the most financially and environmentally affordable refurbishment solution can be determined based on the trade-offs relationships between the LCC and LCA by examining different refurbishment alternatives and energy efficiency levels. Thus, this research is expected to contribute to construction professionals to enhance understanding of the BIM-embeded environment and implication of utilising proper BIM tools to deliver value for money to clients in a housing refurbishment project. Although this research utilised UK housing type as a case study, the LCC and LCA methodology and energy standards are equivalent to European and international standards respectively. Hence, the research findings should be capable of providing a base for design and construction professionals to compare potential refurbishment alternatives before actual refurbishment is carried out. Finally, this research contributes to identifying and sharing the lessons learned by providing essential remedy actions to overcome challenges and fully utilize BIM tools, although a certain amount inefficient manual processes such as reviewing transferred model and re-entering construction information are inevitable. The revealed limitations and suggested remedial actions will enable design and construction professionals to challenge for a successful utilisation of BIM for housing refurbishment. Future research should focus on exploring further in the BIM dataset for practical implementation of a BIM system on housing refurbishment with a realistic case study.

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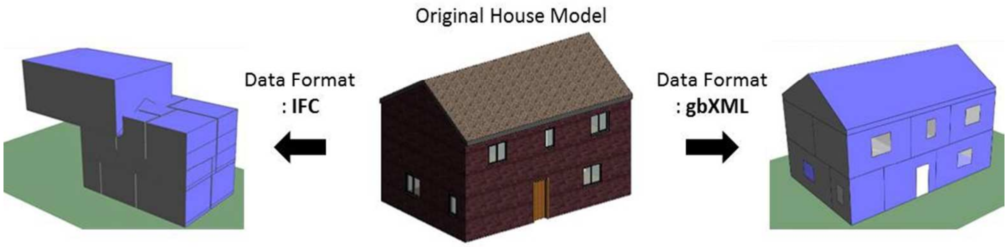

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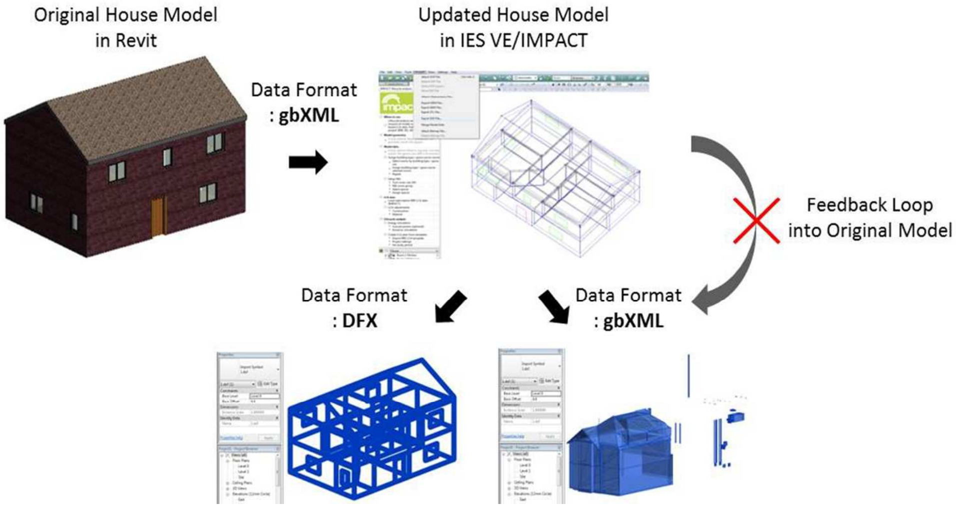

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Table 1. Life Cycle study Result with Fibre Glass (FG) and EPS

			Basic Model	**Adopted Energy Standard**			
				BR 2010/2013 (Min)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Max)
Energy Cost (£ /yr)			1,150	295	253	235	225
CO_2 Emission (kg/yr)			10,985	5,636	5,356	5,329	5,328
LCC (£)	Construction Cost	FG	41,371	7,066	9,055	9,899	10,425
		EPS		12,005	15,691	18,420	19,917
	O&M Cost	FG	205,359	144,414	146,070	145,829	145,939
		EPS		148,325	151,470	152,497	153,669
	Total Cost	FG	246,731	151,480	155,125	155,728	156,364
		EPS		160,330	167,160	170,917	173,586
LCA (kg)	Total CO_2	FG	45,980	17,833	21,980	26,079	28,469
		EPS		19,141.0	23,692.2	28,443	31,018

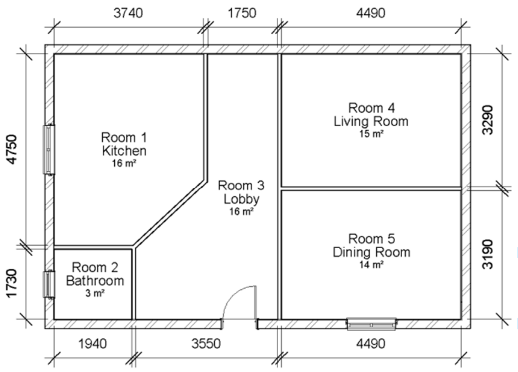
Table 2. Essential Remedy Actions for LCC and LCA calculation in IES VE/IMPACT

Capability	**Examination Result**		**Remedy Action**
Model Creation	Fully Capable		-
Weather Data	Fully Capable		-
Thermal Performance Calculation	Fully Capable		-
Material Data	Material Data Loss during BIM Model Exchange		Manual manipulation of U-value and Thickness
On-site Energy Consumption (Electricity/Gas)	Fully Capable		-
CO_2 Emission Calculation	Fully Capable		-
Renewable Energy	Fully Capable		-
LCC Calculation	Fully Capable		-
LCA Calculation	Fully Capable		-
LCC and LCA Trade-offs Calculation	Fully Capable		-
Energy Standard Application	Fully Capable		
Data Exchange (Import/Export)	Geometric Data Loss with IFC Format		Not suitable for full data exchange
	Congruent BIM Model Transfer with gbXML Format		Manual updates and modifications of BIM model and construction materials required after model import
LCC Dataset Availability	Partially Available	Construction Materials Cost	Additional Data Required: SMM7 Estimating Price Book (BCIS, 2012)
		Construction Labour Cost	
LCA Dataset Availability	Partially Available	Embodied CO_2 for Materials	Additional Data Required: a) University of Bath, (Hammond and Jones, 2011) b) BRE Green Guide Specification (BRE, 2013)
		Embodied CO_2 for Construction Works	Additional Data Required: Black Book (Franklin and Andrews, 2010)

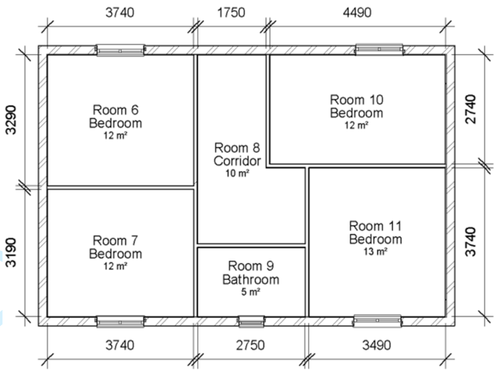
Appendix 1. Basic Information for a Hypothetical House Model

Room and Space Information

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



Ground Floor



First Floor

Detailed Construction Information

Element	Construction Type	Component	Thickness (mm)	U-value (W/m^{2}k)
Roof	Pitched Roof (Timber Joist and Rafter)	Roofing Tile	25	0.8
		Wood (Batten)	25	
		Roofing Felt	5	
		Timber Structure	140	
External Wall	Solid Brickwork Masonry Wall	Dense Gypsum Plaster Finish	13	2.1
		Solid Brickwork	220	
Floors	Suspended Timber Floor	Timber Joist Structure	225	0.7
		Chipboard	25	
		Carpet	10	
Windows	Double Glazing	Double Glazing, Timber Frame	6mm Glazing	2.0
Exterior Door	Wooden Door	Wooden Door	44	3.0

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Appendix 2. Current Energy Efficiency Standards (U-value) and Material Specifications

Current Energy Efficiency Standards (U-value)

Housing Element	**Energy Standards (W/m^{2}K)**			
	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: The standards stand for the U-value (W/m^{2}K) of each housing element

BR = Building Regulation (HM Government, 2016),

FEES = Fabric Energy Efficiency Standard (Zero Carbon Hub, 2016)

Insulation Material Specifications for Energy Standards (mm)

Housing Element	**Insulation Material**	**Energy Performance Standard**			
		BR 2010/2013 (Minimum)	BR 2010 (Notional)	BR 2013 (Notional)	FEES (Maximum)
Wall	Fibre Glass	120	170	210	260
	EPS	100	140	175	215
Floor	Fibre Glass	145	170	260	260
	EPS	120	140	215	215
Roof	Fibre Glass	190	260	300	300
	EPS	155	215	250	250
Door	Wooden Door	45	90	90	105
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)

Reference

HM Government (2016), Building Regulation 2013 Approved Document L1A, London, UK.
Zero Carbon Hub (2016), Fabric Energy Efficiency Standard, London, UK.

Appendix 3. LCC 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

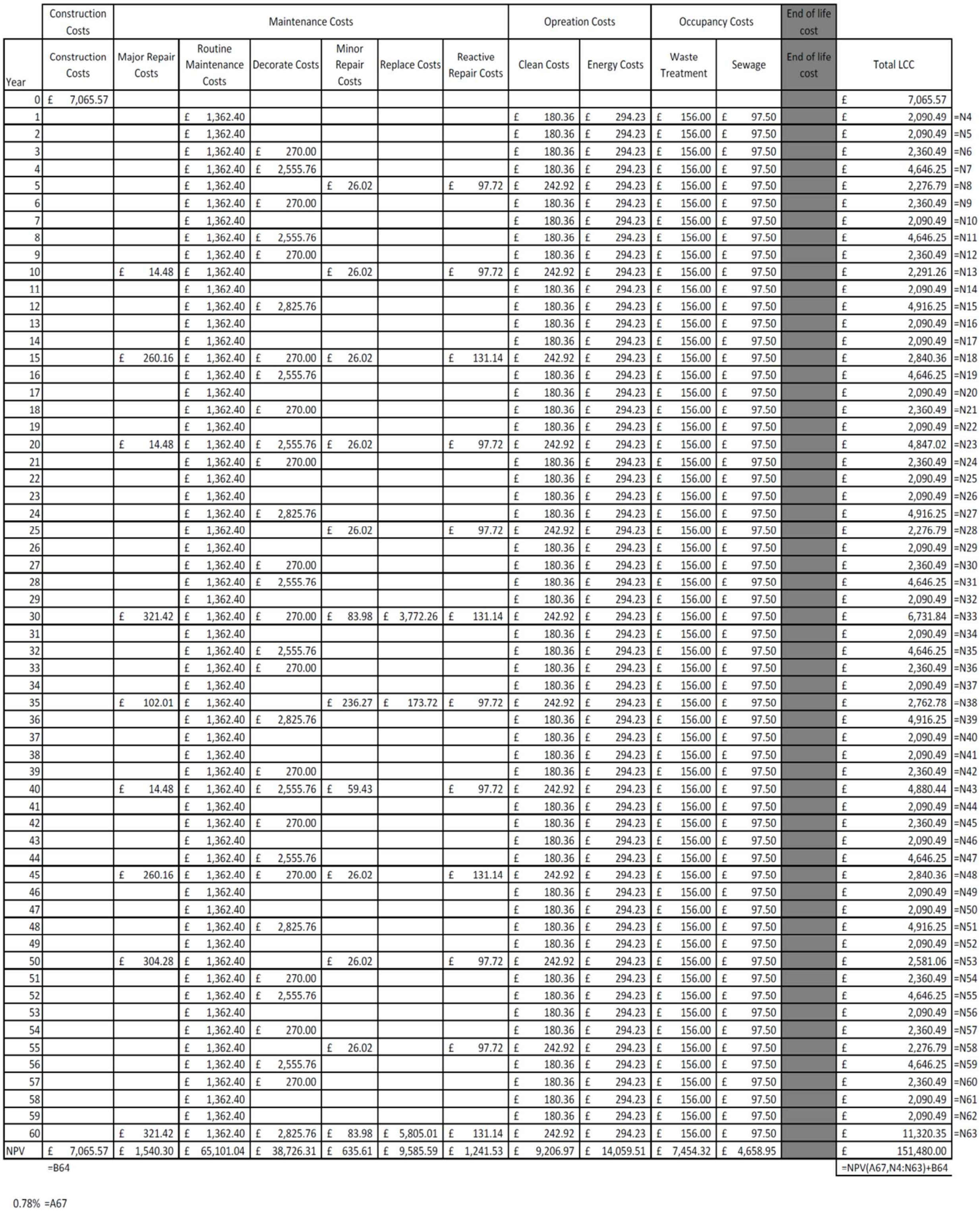
For the LCC and LCA study a 60-year life cycle is applied with a net present value method (NPV) based on a discount rate (d) of 0.78%. Equation A (Flanagan and Jewell, 2005) shows the calculation of this discount rate with the interest rate (r) of 3.5% (HM Treasury, 2011) and the inflation rate (i) of 2.7% (Office for National Statistics, 2015).

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

Reference

HM Treasury (2011), Green Book, London, UK.
Office for National Statistics (2015), Consumer Price Inflation September, 2015, London, UK

Appendix 4. LCC Calculation Table in Excel Format



	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