The Life Cycle Impact of Refurbishment Packages on Residential Buildings with Different Initial Thermal Conditions.

ABSTRACT

Existing buildings constitute a large portion of the UK's housing stock. Refurbishment of existing buildings can, therefore, have an important role in achieving the UK government's CO_2 reduction targets. While building regulations and rating frameworks mainly focus on the improvements of the operational performance of buildings, Life Cycle Analysis (LCA) is considered to be a more appropriate framework to account for long-term CO_2 savings. This study evaluates a range of retrofit approaches (simple, medium, and deep), in terms of Life Cycle Carbon Footprint (LCCF) applied on a terraced house - one of the most common housing archetypes in London. The initial state of the original building has also been examined assuming three initial states (never refurbished, refurbished in compliance with the 1976 and with the 2000 building regulations). Results showed that for all initial state scenarios, deep retrofit achieved the lowest life cycle carbon emissions, in absolute figures, compared to the simple and medium retrofits. Simple retrofit packages, on the other hand, achieved quick and significant improvements, especially in buildings with poor initial thermal conditions. The study also indicated that retrofit packages applied on highly efficient building fabrics result in longer carbon payback time periods. The study recommends establishing a 'staggered' retrofitting approach, which pushes for 'older building first' and 'simple retrofit packages first', as these gain quick CO_2 savings. Deep retrofit packages and treatment of relatively new buildings should be implemented at a later stage, to push buildings further to Zero-Carbon target.

KEYWORDS
Life Cycle Analysis (LCA), Embodied Carbon, Operational Carbon, Retrofit, Housing, Life
Cycle Carbon Footprint

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Authors' contributions

Authors A, B and C conceived of the presented idea and developed the theoretical framework. Author A, took the lead in writing the manuscript, performed the thermal simulations and analysed the data. Authors A and B contributed to the interpretation of the results. Authors B and C supervised the findings of this work. All authors provided critical feedback and helped shape the research, analysis and manuscript.

1. INTRODUCTION

The improvement of the environmental performance of buildings is an increasingly important area of research, especially in light of the global commitment, spanning from the Kyoto Protocol of 1992 to the Paris Agreement of 2015, to significantly reduce carbon emissions.

In the UK, the government has committed to target net-zero emissions of greenhouse gases by 2050. According to the new work plan, emissions will need to fall by 15 $MtCO_{2e}$ each year. For that to happen, new buildings must ensure that all residential buildings built after 2025 are thermally efficient, use low-carbon heat technologies and are designed for a changing climate (Committee on Climate Change 2019).

One main challenge for the UK housing is the aging stock. Existing buildings constitute a large portion of the UK housing stock: By 2050, houses built before 2000 will represent around 75% of the UK's building stock (Lstiburek 2007). Consequently, many existing buildings will have poor thermal performance as they have been built before 1990's – when energy saving measures and EU policies were first introduced (Semprini et al. 2017). Since existing buildings will make a major contribution to the success of the UK government in achieving its CO_2 reduction targets, their retrofit has become increasingly important.

In 2011, the European Committee for Standardisation (CEN) published a calculation method for the assessment of the environmental performance of a building using Life Cycle Assessment (LCA). This methodology is prescribed in EN 15978, Sustainability of construction works- Assessment of environmental performance of buildings – Calculation method. The EN 15978:2011 has been adopted by the British Standards Institution Group (BS EN 15978:2011) and has been prepared to be aligned with the relevant ISO standards for environmental management using LCA, ISO 14040:2006 and 14044:2006 (BRE 2018).

However, though buildings consume energy and emit greenhouse gasses during all lifecycle stages, (i.e., construction, use, maintenance and demolition) (BS EN 15978:2011; Ibn- Mohammed et al. 2013), much of the focus has been given on the reduction of buildings operational emissions - those resulted by space heating and cooling, supply of hot water, ventilation and lighting - while neglecting the calculation of embodied carbon or ones that require a full life-cycle performance evaluation of retrofit projects. The relative contribution of other life-cycle stages has increased; therefore, integrated, and holistic methods are essential to avoid the issue of shifting problems (Soares et al. 2017).

Where retrofit studies do examine the life cycle performance of buildings, they often analyse the retrofit of a single building using a single retrofit scenario (Zavadskas et al. 2008; Less et al. 2012; Hall et al. 2013; Moncaster and Symons 2013; Leinartas and Stephens 2015; Jermyn and Richman 2016; Rodrigues and Freire 2017; Uidhir et al. 2020). Some studies explored the impact of several refurbishment scenarios (Tokede et al. 2018) however, improvement in building performance due to refurbishments is highly dependent on the initial state of the examined building (Murray et al. 2019); buildings with good initial thermal conditions (low U-values, efficient systems etc.) will often have good initial thermal performance. A retrofit of such buildings will therefore typically show little performance improvements. Buildings with poor initial thermal conditions (high U-values, high infiltration, and non-efficient systems) will tend to have poor thermal performance. A retrofit of such buildings will, therefore, show bigger performance improvements (Evrard et al. 2016).

In practice, different buildings may require different retrofit measures, depending on their initial state and the scale of the required retrofit. Therefore, it is not clear if deep retrofit is always the best approach in terms of embodied and operational carbon for buildings with different initial conditions, thermal fabric (U-values) and system efficiencies. The current approach towards the examination of retrofitting measures may result in limited set of outputs and a series of recommendations that may fit to a limited number of buildings in practice.

This study examines the life-cycle impact of a set of realistic retrofitting scenarios, adopting concepts from the BS EN 15978:2011 protocol regarding the scope of the system boundary that applies to a building level and the calculation methods. The Life Cycle Stages included within the scope of this study are carbon emissions caused by extraction and manufacture (Stages A1-A3), construction (Stage A5), replacement (Stage B4) and operational energy use (Stage B6). It examines a case study building in three different initial states:

A. a ‘Never refurbished’ building
B. Refurbished following the 1976 building regulations, and
C. Refurbished following the 2000 building regulations.

Three retrofit scenarios are examined for each of the initial states:

A. Simple refurbishment
B. Medium retrofit, and
C. Deep retrofit

The study aims to evaluate which retrofit package is most beneficial to each initial state, by comparing the Life-Cycle Performance results of each refurbishment package – initial scenario combination. All retrofit scenarios are linked to the current UK regulations and best practice approaches. Furthermore, this study takes into consideration not only the embodied carbon of the materials required for the buildings' retrofit but also for building services and systems.

2. LITERATURE REVIEW

2.1 Retrofit Measures

2.1.1 Reduction targets and retrofit measures

Many studies around refurbishments use a 'reduction-targets-oriented' approach: they often have an energy or CO_2 reduction targets to achieve, and therefore they aim to explore what kind of refurbishment measures are required to achieve those reduction targets (Less et al. 2012; Moran et al. 2012; Cluett and Amann 2014; Leinartas and Stephens 2015; Jermyn and Richman 2016). A number of studies have examined the required measures that could achieve a reduction target of more than 50% in housing energy use: Leinartas and Stephens (2015) investigated the cost-optimal deep energy retrofit packages of the Chicago housing stock and found that 50% energy savings could be achieved by deep retrofit solutions, including thermal envelope, lighting and Heating Ventilation and Air Conditioning (HVAC) system upgrades. Less et al. (2012) have monitored 11 Deep Energy Retrofit (DER) case studies, where the energy reduction target (70% or more energy savings) was achieved by similar approach – efficient envelope improvements (wall, roof and foundation insulation, window improvement and air leakage prevention), efficient mechanical systems, lighting, appliances, and miscellaneous electrical loads.

Though these studies have identified measures that could help refurbishment projects in improving their thermal efficiencies, the practicality of a "one-fit-all" retrofit strategy for all buildings is not realistic, as a single building retrofit design may not necessarily apply to other buildings (Jermyn and Richman 2016). The main obstacles are the differences in the initial condition of the building, including thermal performance, geographical location (climate) and uses (Capeluto 2019). To achieve drastic reductions in emissions or energy use, retrofit measures and design strategies should be tailored to specific buildings on a "case-by-case" approach, and consider not only the climate but also the initial state of the building. For this reason, two main refurbishment approaches have been discussed in literature: simple retrofit and deep retrofit. Each approach is characterised by a set of environmental design strategies to increase the energy efficiency of existing buildings.

2.1.2 Simple & Deep retrofit measures

The definition of simple and deep retrofit is not consistent across the literature, and several different approaches are discussed. Lowe et al. (2012) found a qualitative difference between deep and simple retrofit. As the authors note, simple retrofit can be achieved by insulation improvements while deep retrofit requires the replacement of existing heating and ventilation systems with Mechanical Ventilation with Heat Recovery (MVHR) as well as the use of renewables. Cluett and Amann (2014) defined deep energy retrofitting as a refurbishment that aims to save at least 50% of the house's operational energy, compared to its pre-retrofit use. Another definition has been introduced by the European Commission (2017) who noted that a renovation is considered to be deep if its total cost is more than 25% of the building's value, or if more than 25% of the building's surface is being refurbished.

As for specific measures – there seem to be no clear agreement across the literature, where considering deep and simple retrofits: A number of studies identify boiler replacement, for example, as a simple measure that does not require major renovation (Shorrock et al. 2005; Harvey 2006; Jones et al. 2013). According to Harvey (2006), replacing an old, 60-70% efficient boiler with a new, 90% efficient, condensing one, could save 20-30% in fuel use, and Jones et al. (2013) added that apart from using a more efficient systems, there are other easily applied measures, such as loft insulation and double-glazed windows, could be considered as simple retrofit.

Leinartas and Stephens (2015) and Jermyn and Richman (2016) on the other hand, have considered similar measures under a 'deep retrofit' definition. In that respect, Lowe et al. (2012) add that the Passivhaus approach could also be considered as a deep retrofit strategy.

Renewables — specifically photovoltaics (PVs) — are often considered as the last deep retrofit measures to be implemented with the intent to offsetting energy consumption (Less et al. 2012; Lowe et al. 2012). Moran et al. (2012) state that since PVs can reduce the CO_2 emissions in such a significant way, they should not be considered as a final stage of retrofit strategies; instead, they should sit alongside fabric improvements. The long-term benefits of deep retrofits seem to outweigh the initial capital cost investments (Jermyn and Richman 2016). Nevertheless, there is the risk of the high embodied energy and carbon when implementing deep retrofit measures which take several years to fully recover and risk counteracting their installed benefit (Dowson et al. 2012).

Table 1 summarises the studies that had covered Deep and Simple retrofits.

Study by:	**Deep Retrofit measures**
Jermyn and Richman (2016)	Building envelope improvements • increasing wall, roof, foundation wall and slab insulation • upgrading windows by decreasing overall window U-factors and • increasing air tightness by sealing penetrations and air leakage paths System improvements • installing heating and cooling systems with higher efficiencies and • heat or energy recovery ventilation systems
Leinartas and Stephens (2015)	Building envelope improvements • increasing exterior wall and attic insulation System improvements • installing high efficiency Mini Split Heat Pump (MSHP) with electric baseboard heating system or • upgrades to existing HVAC system efficiency
Jones et al. (2013)	Building envelope improvements • increasing wall and roof insulation and • installing triple-glazed windows System improvements • installing Mechanical Ventilation Heat Recovery (MVHR) ventilation system and • ground-source heat pump Renewables • installing solar thermal evacuated tube collectors and • photovoltaic panels (PVs)
Lowe et al. (2012)	Building envelope improvements • high-performance windows and doors System improvements • installing Mechanical Ventilation Heat Recovery (MVHR) and • lights and appliances Renewables • installing photovoltaic panels (PVs)
Study by:	**Simple Retrofit measures**
Jones et al. (2013)	Building envelope improvements • increasing loft insulation and • installing double-glazed windows System improvements • installing high-efficiency boiler
Dowson et al. (2012)	Building envelope improvements • increasing wall and loft insulation System improvements • gas central heating
Lowe et al. (2012)	Building envelope improvements • increasing fabric insulation
Harvey (2006)	System improvements • installing high-efficiency boiler

Although a number of studies have examined retrofit measures, there is no unified definition for what is considered to be simple and deep retrofit. As seen in the literature review both simple and deep retrofits can include thermal envelope, system improvements, and integration with renewables. This study will, therefore, approach simple, medium, and deep retrofit by exploring best practice criteria for packages and policies.

2.1.3 Cost-effective measures

Due to the unique nature of each case study, the different retrofit measures applied, as well as the wide range of climate zones involved makes, it is not clear if the aforementioned simple/deep retrofit measures are cost effective. Consequently, the most efficient cost and performance solution needs to be defined for each case, as it is dependent on climate.

According to a Climate Change Committee's report (CCC 2019), no new UK homes will be connected to the gas grid from 2025 in the interests of heat decarbonisation. However, in the UK, the replacement of old boilers with new efficient ones can be expected to continue to deliver reductions in emissions (CCC 2018). Optimising boiler efficiency is still considered to be a cost-effective measure, as heat pumps are not yet a mass market solution and the initial cost investment for a boiler is offset somewhat by reduced energy bills.

Window replacement is a common retrofit measure applied in most projects. Dowson et al. (2012); Jones et al. (2013); Leinartas and Stephens (2015); Jermyn and Richman (2016) have found that high performance windows were not found to be cost-effective, as they have a long payback period and a high cost relative to the energy savings**.** On the other hand, a study by Banihashemi et al. (2015) examined the performance of double-glazed windows in four different climatic conditions in Iran and showed that in temperate and hot-arid climates, double-glazed windows were beneficial in both cold and hot months, while in cold and hot humid climates, where heating and cooling loads are dominant respectively, double-glazed windows were found to be advantageous only in those dominant months.

Additional insulation is another typical measure applied in retrofits. Less et al. (2012) study results showed that superinsulation and extreme airtightness are less cost effective in warm climates such as Northern California's**.** However, in Toronto, exterior walls and slab improvements were found to be cost-effective as they reduced the energy used for both heating and cooling (Jermyn and Richman 2016). It was reported in literature that, cost-effective measures regarding the reduction of operational carbon are related to the origin and the cost of the fuel used. While cost-effective measures concerning the building fabric vary according to the building's climate and location.

Literature also indicates that smart building technologies — and specifically Smart Readiness Indicators (SRIs) — will be considered as a cost-effective measure to maintain healthy and comfortable homes with reduced energy consumption and carbon impact, and to promote the integration of renewable energy sources (European Commission DG Energy 2018).

2.2 Life Cycle Analysis (LCA)

Life Cycle Analysis is an environmental assessment & management framework that aims to inform decision makers on the environmental impact of production processes. Life cycle studies are best used in a comparative manner, where the environmental impact of several alternatives are assessed and compared: stakeholders can identify the best alternative out of a set of given options by comparing the performance of different 'System Units' (a product or a service, or a building, in the case of the built environment) (ISO 14040 2006). Life cycle assessments are carried in what is referred to as a 'cradle to grave' approach (Duda and Shaw 1997), which often use the *"ISO 14040 - Environmental management — Life cycle assessment — Principles and framework"* - one of the most widely accepted LCA frameworks (ISO 14040 2006).

In adapting ISO 14040 to the built environment – *"EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings – Calculation method"* brings general LCA concepts into the built environment. The Global Warming Potential (GWP) has been selected and used as an environmental indicator to measure CO_2 equivalent emissions (BS EN 15978:2011), defining the following stages in the life cycle of buildings (Figure 1):

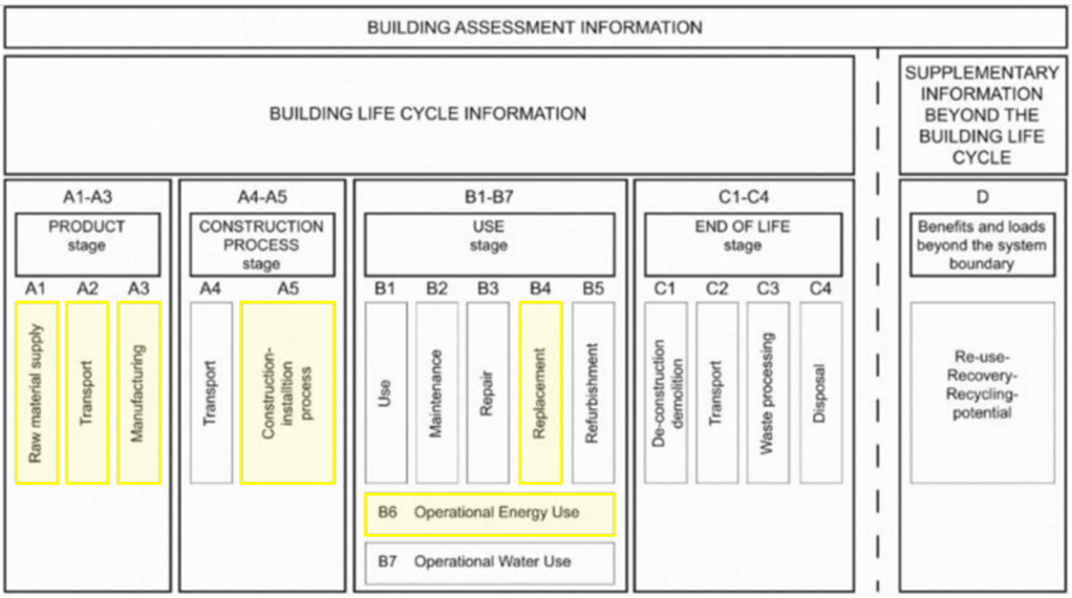

Figure 1: Display of modular information for the different stages of building assessment. The Life Cycle Stages included in the carbon calculations highlighted in yellow.
Source: BS EN 15978:2011

A1 – A5: Product and Construction Processes (also called 'Embodied Carbon') – describing the CO_2 emissions involved in the production of building materials and during the construction stage.

B1-B7: Use (also called 'Operational Use') **–** The CO_2 emissions due to operational use of the buildings – energy consumption for heating, cooling & lighting, but also refurbishment and maintenance processes.

C1-C4: End of Life – The End-of-Life stage includes all demolition-related processes, such as the deconstruction of the building, transport to landfills and other associated demolition actions.

D: Loads Beyond the system boundary – This section refers to the potential of recycling of building materials or the use of renewable energy systems.

A study by Schwartz et al. (2018), reviewing the life cycle performance of more than 250 buildings, had shown that the Embodied and Operational emissions are the major contributors to overall life cycle carbon footprint of buildings. Other studies have shown that demolition related CO_2 can vary between 0.5 to 6% of the building`s embodied CO_2 (Chen el al. 2005; Gustavsson et al. 2010; Tae et al. 2011; Dodoo et al. 2014). Based on these observations, the contribution of the Operational phase and that of the Embodied carbon are of a major importance.

2.2.1 Life Cycle Stages Operational Phase

While literature that examines life cycle energy performance in buildings often concludes that the largest energy demand during a life of a building is attributed to operational consumption, the proportion of embodied carbon in 'environmentally efficient buildings' is increasing, as much focus is given to building fabric and systems improvements (Sartori and Hestnes 2007). Still, the operational phase holds the larger portion of the environmental impacts, compared to the other phases of the LCA (Blengini 2009; Cuéllar-Franca and Azapagic 2012; Rossi et al. 2012).

Analysis showed a difference in life cycle energy and particularly in operational energy between cold and non-cold/developing countries (Ramesh et al. 2010; Rossi et al. 2012). In their research, Rossi et al. (2012) compared the operational energy of three European countries: Belgium, Portugal, and Sweden, and found buildings in Sweden to have the largest operational energy, due mainly to its cold climate. Interestingly, however, when examining the relative contribution of operational-related CO_2, this trend was completely reversed, as it depends on the supply energy mix. In the case of Sweden, for example, around 50% of the energy is produced through renewable sources having low CO_2 emissions of electricity production, having a major impact on the life cycle carbon footprint of a building (Rossi et al. 2012). The use of different primary fuels, as well as the use of different building materials and construction techniques, leads to differences in the total life cycle energy of buildings (Ramesh et al. 2010).

A more recent study by Rodrigues and Freire (2017) found that the Life Cycle of a building is also affected by occupancy trends and the way buildings are used. Analysis showed that high residential occupancy has greater environmental impacts than low residential occupancy or office use mainly due to higher heating and cooling needs. Specifically, highly insulated retrofit was found to be more beneficial for high occupancy levels with higher thermal comfort conditions.

2.2.2 Embodied Carbon

Following the operational phase, the second contributor to the life cycle energy demand is the non-operational phase, which has a contribution of around -10-20%- to the life cycle of buildings (Ramesh et al. 2010). According to Moncaster and Symons (2013), most research emphasises on the calculation of operational energy, not considering the design-construction stage, refurbishment and end of life which are equally important stages for energy and carbon optimisation and reduction.

When it comes to life cycle performance, the design stage proves to be very important (Cuéllar-Franca and Azapagic 2012). Embodied impacts are not negligible and carbon emissions should be calculated at all life cycle stages rather than at a single stage (Stephan et al. 2012; Moncaster and Symons 2013). Moncaster and Symons (2013) outline the difficulty in calculating the whole life embodied energy and carbon of buildings in the UK mainly due to lack of data. Manufacturers do not provide data for cradle-to-gate product impacts, CO_2 emissions during construction phase or end of life. Aside from the missing data, another issue in getting complete life cycle figures is that CO_2 calculations often consider only the embodied CO_2 of the initial design, and do not take into account later phases (Moncaster and Symons 2013).

Hammond and Jones (2008) note that there is a difference between embodied energy and embodied carbon values mainly due to differences in production processes, calculation methods, boundary conditions and general assumptions. Technological differences and different fuel mixes are also considered major causes for inconsistencies (Hammond and Jones 2008). To minimise these, the European Commission (European Commission DG Environment 2002) has come up with a framework to standardise embodied CO_2 calculations across the industry. Environmental Product Declaration (EPD) is a standardized protocol, by which manufacturers can carry an analysis of the environmental impact of their products' production line and allow results comparisons with similar products by different manufactures.

2.2.3 The Potential Impact of Operational Performance Improvements on Embodied and Life Cycle Performance

Ramesh et al. (2010) and Ibn-Mohammed et al. (2013) show that attempts to minimize building operational energy often lead to an increase in its energy, and Pelsmakers (2015) show that embodied energy could increase by approximately 30-40% upon improvement of the building’s fabric, as achieving lower operational energy demand tends to require more materials and technologies. Thormark (2002) notes similar conclusions, stating that the embodied energy in low-energy houses accounts for 40% of the total energy use of the building, and the UK Green Building Council (2019) notes that the embodied emissions from construction can account for up to half of the carbon impacts associated with the building over its life cycle.

A review by Ibn-Mohammed et al. (2013) summarises that in the near future, the embodied emissions in buildings will increase, mainly due to legislation and technologies that will focus on operational reduction as well as refurbishment of existing building stock. This has led to debate about whether retrofit is a better solution than demolition. According to Schwartz et al. (2018) there is no clear-cut answer to the question of whether to refurbish or to replace. The finding of their literature review showed that refurbishment had a lower Life Cycle Carbon Footprint (LCCF) than newer buildings, but some new buildings can perform better than refurbished ones.

2.3 The Knowledge Gap

The UK’s Green Building Council report (2019) states that apart from the significance of operational carbon, of equal importance is the embodied carbon of buildings. While the UK government regulation focus primarily on the operational performance (Building Regulations, Part L), embodied carbon can have an important contribution to emissions from the built environment. A whole life carbon assessment is considered to be a more appropriate performance evaluation approach, as the contribution of embodied carbon is not negligible, on a life-cycle perspective (UK Green Building Council 2019)**.**

While life cycle analysis has become an increasingly important research domain, this literature review has found that studies often focus on the analysis of a single, or limited number of design scenarios. More specifically, there is a lack of research on the refurbishment of existing buildings, and particularly on the impact of the initial thermal state of the existing building on its life cycle carbon performance.

This issue is of an increasing importance, especially in practical terms: new buildings in the UK (annually) account for only around 1% of the total stock (Power 2008), and around 75% of the 2050 housing stock has already been built (Sustainable Development Commission 2007). The refurbishment of existing buildings can, therefore, have a significant contribution to the reduction of carbon emissions from the built environment. As the condition of buildings in stock varies, it is important to explore the impact the thermal state of the existing building has on potential CO_2 savings.

This study examines the life cycle carbon footprint of the refurbishment of an existing residential building. Specifically, the study explores how three different initial states of the existing building (never refurbished, refurbished to medium thermal standard, and refurbished to high thermal standard) perform, when one of three refurbishment packages are applied on each (simple, medium, and deep refurbishments).

3. METHODOLOGY

This study evaluates three different retrofit packages (simple, medium, deep) aiming to find the best approach in terms of embodied and operational carbon by using a case study building. The initial condition of the building is not unique; three different initial scenarios regarding the building's initial state are explored: 1900-1918 Never Refurbished, 1976 Refurbishment and 2000 Refurbishment. Overall, nine retrofitted case studies are explored for the same house archetype (Figure 2).

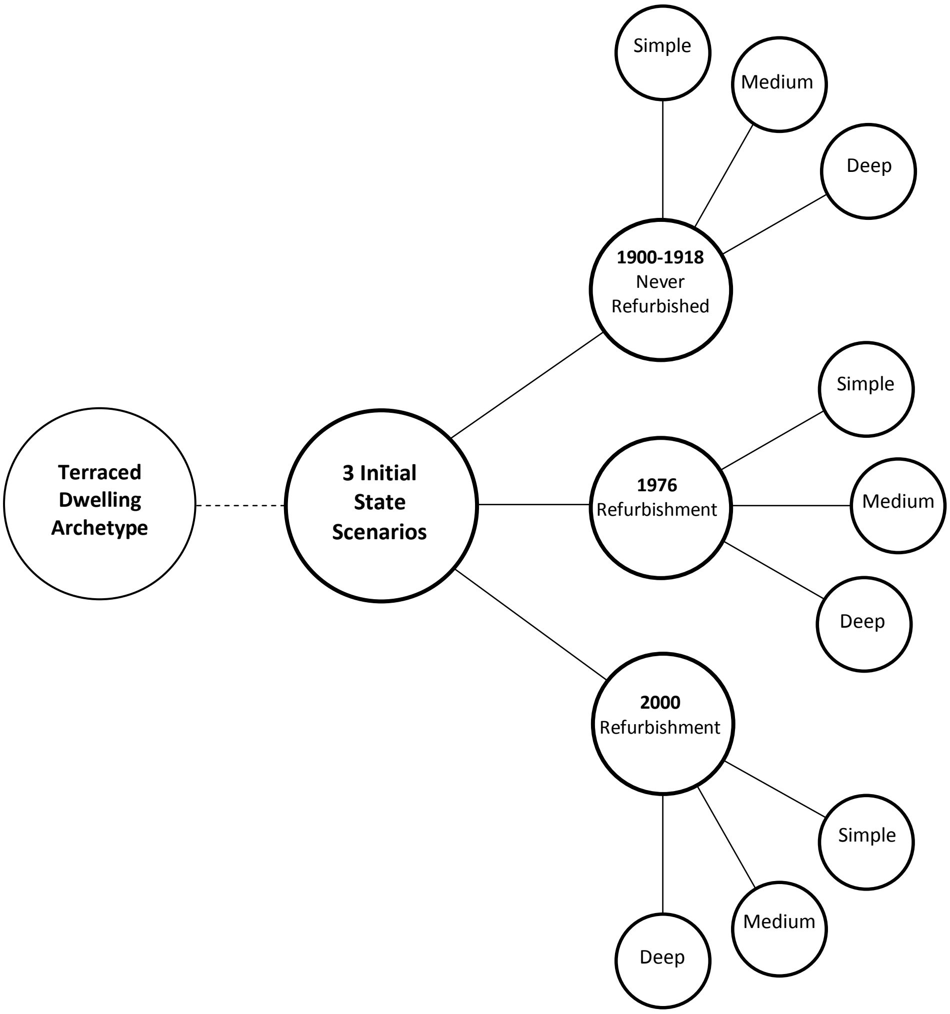

Figure 2: Scenarios Workflow

3.1 The Case Study

This study examines the life cycle performance of a case study building. Based on a study by Oikonomou et al. (2012), who classified housing archetypes in London for thermal analysis purposes, this study uses a ‘Terrace House with a large T’ (Figure 3) – which has the highest percentage of occurrences in London (15.4%) – as a case study.

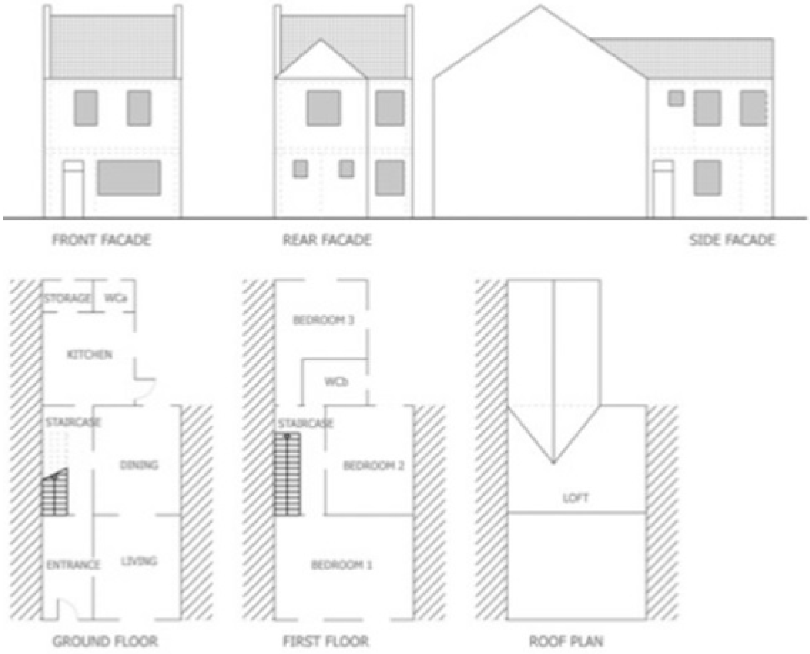

Figure 3: Terraced House with Large T archetype
Source: Oikonomou et al. (2012)

To enable a more realistic and detailed description of the case study, an existing building with similar geometric features was found (Figures 4, 5 and 6). The selected house is located in Hawthorn Road (Figure 4), within the London Borough of Haringey. The property comprises two floors, each approximately 62 m^2, with a total area of 123.20 m^2.

Figure 4: London Borough of Haringey & location of the property
(Latitude:51o35’23’’N, Longitude:0o07’34’’W)
Sources: London Borough of Haringey 2016, Bing Maps

Figure 5: Front View of Hawthorn road house
Source: Prestia (2010)

Figure 6: Floor plans of Hawthorn road house adjusted to Oikonomou et al. (2012) archetype
Source: Prestia (2010)

3.2 Study approach

Based on the BS EN 15978:2011 standard, this study is structured as follows:

The building's life cycle is broken down into four sections as shown in Figure 1. In a systematic literature review, covering the life cycle performance analysis of more than 200 buildings, Schwartz et.al (2018) found that the highest percentage of carbon emissions is attributed to Operational phase (approximately 75% of carbon footprint); the second contributor is embodied carbon (approximately 24%) and the last one was the End-of-Life stage (EoL), with an around 1% of the buildings' overall life cycle carbon footprint.

The life cycle stages examined in this study concerning the embodied carbon calculations include the product stages (A1-A3), the construction process stage (A5) and the use stage (B4). The operational carbon impacts are included in the use stage (B6). The end-of-life stages (C1-C4) and stage (D) are important for future design and to support the buildings’ circular economy potential, however, this study focused on stages A1-A3, A5 and B4, and the EoL stages are therefore excluded from the LCCF calculations.

3.2.1 IESVE Model Assumptions

The Integrated Environmental Solutions Virtual Environment (IESVE) energy simulation tool is used for this study to assess the environmental performance of the retrofitted scenarios through estimating the energy demand of the case studies. The calculations are based on first principles models of heat transfer process and are driven by real weather data. Two types of Chartered Institution of Building Services Engineers (CIBSE 2006) weather files were used for the simulations, Design Summer Year and Test Reference Year for London Heathrow.

The house is modelled on IESVE and comprises two floors: a ground and first floor. For this study, the orientation examined is the one with the front façade-living room to 0^{o} deviation from North – similar to the actual building’s orientation. Each floor is divided into five thermal zones (Figure 7) based on achieving criteria of optimal use and conditions of each space.

Figure 7: Case study dwelling plans divided in thermal zones

The case study model uses the project profiles of the National Calculation Methodology (NCM) template for dwellings for schedules and use profiles. Each room or thermal zone of the house is assigned to an NCM template for this specific room. As a result, each space has different daily profiles, thermal conditions, and internal gains (people, lighting, and equipment). Analytical inputs regarding thermal zones and schedules are presented in Appendix D.

3.3 Initial State Scenarios

Three scenarios for the house's initial state have been identified. These are summarised in Table 2. For the first scenario the house has never been refurbished and is characterised by absence of insulation and presence of single-glazed windows. Furthermore, for the second scenario the roof, external walls and floor are insulated; windows are still single-glazed, and the gas boiler is 75% efficient. As for the third scenario it is assumed that the external fabric is well-insulated, windows are double-glazed, and the gas boiler is 80% efficient. Analytical assumptions concerning the U-values and systems of initial state scenarios are presented in Appendix A.

Table 2: Summary of Initial State Scenarios

1) 1900-1918 * - Initial State Scenario						
Technical Characteristics	Wall	Roof	Floor	Windows U-value (W/m^{2}K)	Non-condensing Gas Boiler Efficiency (%)	Air perm. m^3/(m^{2}h)
Insulation Thickness (mm)	0	0	0	Single-Glazed 4.80	75	20
Element U-value (W/m^{2}K)	2.1	2.30	1.06			
2) 1976 ** - Initial State Scenario						
Technical Characteristics	Wall	Roof	Floor	Windows U-value (W/m^{2}K)	Non-condensing Gas Boiler Efficiency (%)	Air perm. m^3/(m^{2}h)
Insulation Thickness (mm)	20	50	6	Single-Glazed 4.80	75	15
Element U-value (W/m^{2}K)	1.00	0.60	1.00			
3) 2000 * - Initial State Scenario**						
Technical Characteristics	Wall	Roof	Floor	Windows U-value (W/m^{2}K)	Non-condensing Gas Boiler Efficiency (%)	Air perm. m^3/(m^{2}h)
Insulation Thickness (mm)	100	180	130	Double-Glazed 2.00	80	10
Element U-value (W/m^{2}K)	0.35	0.20	0.25			

Insulation: Mineral Fibre board

**Data retrieved from CIBSE Guide A - Environmental Design (7th Edition), CIBSE & BRE, 2014. SAP 2012: The Government's Standard Assessment Procedure for Energy Rating of Dwellings*

***Data retrieved from The Building Regulations 1976 - Statutory Instruments, vol. 1676.*

****Data retrieved from The Building Regulations 2000 - London: Stationery Office.*

3.4 Retrofit Scenarios

Whereas some literature has taken the approach finding required refurbishment measures to reach certain reduction targets (Less et al. 2012; Leinartas and Stephens 2015; Jermyn and Richman 2016; Semprini et al. 2017), this study takes a more realistic approach – one that tries to assess the process of refurbishments as they are in practice. Rather than setting a reduction target in mind, the study has tried to reflect the priorities of homeowners by identifying three sets of refurbishment packages – simple, medium and deep – based on the level of likelihood of implementation, complicity and cost of each component of the refurbishment.

All retrofit measures are defined based on best practice methods embodied in current regulatory framework (Building Regulations 2018) and are summarised in Table 3. The simple retrofit scenario includes a more efficient gas boiler, additional roof insulation and LEDs lights. The medium scenario includes double-glazed windows and floor insulation and the deep involves installation of MVHR system, solar thermal panels, and PVs (Table 3). As shown in Figure 2, three retrofit scenarios will be applied to each initial state scenario. Analytical assumptions about U-values and systems of the retrofitted scenarios will be presented in Appendix B.

Table 3: Summarised assumptions for Retrofit Scenarios

Retrofit Scenario	Gas Boiler Effic.	Roof Insul.	LEDs	Double-glazed windows	Wall Insul.	Floor Insul.	MVHR	Solar Thermal Panels	PVs
Simple	✓	✓	✓	-	-	-	-	-	-
Medium	✓	✓	✓	✓	✓	-	-	-	-
Deep	✓	✓	✓	✓	✓	✓	✓	✓	✓

3.5 Life Cycle Analysis

In this study, the principles of the LCA are used to evaluate the embodied and operational carbon of the house, considering the building’s life span to be 60 years according to Building Research Establishment (BRE) Green Guide to Specification (Anderson et al. 2009; Pelsmakers 2015). The evaluation is based on the British adoption of the European Standard BS EN 15978:2011, for the assessment of environmental performance of buildings, as shown in Figure 1.

3.5.1 Embodied Carbon

There are currently no standardised measures to address embodied CO_2 calculation methods; various methodologies for calculating embodied CO_2 emissions exist. The embodied carbon coefficient ($kgCO_{2e}/kg$) data for all building materials used for this analysis have been collected using the Bath

Inventory of Carbon and Energy Database (Hammond and Jones 2011) (Table 4). The database uses 'cradle-to-gate' boundary conditions (Dixit et al. 2010), which were adopted for this study. The main limitation of using databases to calculate the embodied carbon is that they use generic embodied CO_2 and thus do not reflect the differences in CO_2 emissions occurring in different production processes used by manufacturers. Carbon data regarding building components and systems have been retrieved using various sources as mentioned in Table 5.

The embodied emissions calculated are divided into two parts: initial (Stages A1-A3 & A5) and recurring (Stage B4) embodied emissions for both materials and systems used. Waste rates (Stage A5) are retrieved, for both initial and recurring carbon emissions, from WRAP Net Waste Tool (2008). Waste rates represent the percentage of a component that ends up as waste during the installation/construction process (WRAP 2008).

Embodied Carbon Emissions:

i) Initial Embodied Emissions include:
Stages A1-A3: EC Coefficient ($kgCO_{2e}/kg$) x Material mass (kg)
& Stage A5: EC Coefficient ($kgCO_{2e}/kg$) x Material mass (kg) x Waste Rates (%)

Tables 4 and 5 show the initial embodied carbon for materials, components and systems used in this study.

Table 4: Embodied Carbon Coefficients of Building Materials

Building Materials	*$kgCO_{2e}/kg$	** Waste Rate (%)
Expanded Polystyrene (EPS)	3.29	5
Plaster (render)	0.13	5
Timber Studding (Hardwood)	0.24	5
Plasterboard	0.39	22.5
Chipboard	0.39	5
Timber Flooring	0.39	10

$kgCO_{2e}$ values were retrieved from Bath ICE Database (Hammond and Jones 2011)
*** Waste rates are based on data from WRAP (2008)*

Table 5: Estimated Embodied Carbon of Building Components and Systems

Building Components & Systems	Description	Embodied Carbon per m^2 of surface area ($kgCO_{2e}/m^2$)	Embodied Carbon per system ($kgCO_{2e}$)	Reference	*Waste Rate (%)
Windows	Double-glazed windows with wooden frames	130	-	Kutnar and Sinha (2012), pp. 551	5
External Doors	-	152	-	Victoria and Perera (2018), pp. 509	5
PVs	Monocrystalline Silicon	242	-	Bath ICE Database (2011) Pelsmakers (2015), pp. 406	-
Solar Thermal Panels	Flat plate collectors	120	-	Pelsmakers (2015), pp. 411	-
Gas Boiler	Condensing gas boiler, heating power <50 kWh	-	164.4	Koubogiannis and Nouhou (2016), pp. 8	3
MVHR	-	-	600	Finnegan et al. (2018), pp. 55	3
LEDs	Average residential building contains 40 LED lights	-	134	Finnegan et al. (2018), pp. 55	-

**Waste rates are based on data from WRAP (2008)*

ii) Recurring Embodied Emissions include:

Stage B4: Initial Embodied emissions ($kgCO_{2e}$) x Number of replacements

Taking into consideration the 60-year life span of the building, as well as the life span of building materials and systems (Table 6), it is assumed that components and systems of the house would need replacement at least once in 60 years to rehabilitate the house. More specifically, for this study, windows, external doors, and wooden floors are replaced once; the gas boiler, MVHR system, solar thermal panels and PVs are replaced twice and LED bulbs are replaced four times over a 60-year period, as summarised in Table 6. No replacement for building structures such as walls, roofs, and floors as they share the same life expectancy with the building. A breakdown analysis of the initial and recurring embodied carbon of materials, components and systems can be found in Appendix C.

Table 6: Estimated Service Life and Number of Replacements for Building Materials & Systems

Materials Components Systems	Service Life (years)	References	Number of Replacements (60 years lifespan)
Expanded polystyrene (EPS)	100	Bull et al. (2014), pp. 7	-
Timber studding (wall construction)	Life of building	InterNACHI (2017) Estimated Life Expectancy Chart	-
Timber joists (floor construction)	Life of building	InterNACHI (2017) Estimated Life Expectancy Chart	1
Plasterboard	39	Bull et al. (2014), pp. 7	1
Plaster (render)	39	Bull et al. (2014), pp. 7	1
Flooring hardwood	39	Schwartz (2018), pp. 236	1
Windows	37 30 50	Bull et al. (2014), pp. 7 Ashworth (1996), pp. 6 Schwartz (2018), pp. 236	1
Doors	30	Ashworth (1996), pp. 6	1
Windows/Doors	20	Iddon and Firth (2013), pp. 482	1
Gas Boiler	15 10 to 25	Bull et al. (2014), pp. 7 Pelsmakers (2015), pp. 355	2
LEDs	11.4 years for 12 hours use per day	Lighting.Philips.com (2019)	4
MVHR	15 20	Gustafsson et al. (2016), pp. 112 Spanos et al. (2007), pp. 1579	2
Solar Thermal Panels	20 to 25	Pelsmakers (2015), pp. 410 Spanos et al. (2007), pp.	2
PVs	20 to 25	Pelsmakers (2015), pp. 405 Spanos et al. (2007), pp.1579	2

3.5.2 Operational Carbon

IESVE is used as software modelling to estimate the building’s energy demand. For this study, regulated energy is calculated including energy for space heating and cooling, domestic hot water, and lighting. Unregulated energy use is difficult to estimate as it depends on user behaviour (Pelsmakers 2015) and therefore is excluded from this study.

The building's operational carbon is calculated by multiplying the estimated energy demand found by IESVE simulations and the CO_2 fuel intensity of the fuel used. The fuel factors used for this study are based on the Standard Assessment Procedure (SAP) fuel intensities for 2012 (Table 7). Gas grid is assumed for space heating requirements and domestic hot water and electricity grid for space cooling and lighting (Table 7).

Table 7: UK CO_{2e} conversion factors (SAP 2012) attributed to regulated emissions

Regulated Emissions	Energy Source/Fuel	CO_{2e} Conversion Factors ($kgCO_{2e}$/kWh)
Space Heating	Gas (grid)	0.216
Space Cooling	Electricity (grid)	0.519
Domestic Hot Water	Gas (grid)	0.216
Lighting	Electricity (grid)	0.519

4. RESULTS AND DISCUSSION

4.1 Life Cycle Carbon Footprint Analysis

Results show that a recently-refurbished building – one with a relatively good operational performance – may require a minimal further refurbishment (one that involves only low Embodied Carbon), while a building that had never been refurbished may require a more extensive refurbishment (which will involve higher rates of embodied carbon).

Particularly, findings indicate that in all three initial state scenarios explored, (1900-1918, 1976 and 2000), the deep retrofit scenario had achieved the lowest life cycle performance, with values ranging from 1,052 $kgCO_{2e}/m^2$ to 1,071 $kgCO_{2e}/m^2$. Medium and simple retrofits follow with 1,318-1,592 $kgCO_{2e}/m^2$ and 1,281-2,556 $kgCO_{2e}/m^2$ respectively.

It is observed from Figure 8 that, as expected, for all initial states, the deep retrofit had achieved the lowest operational carbon emissions, but at the same time, has significantly higher embodied carbon in comparison to the other two retrofit approaches. The operational related carbon emissions have higher impact than the embodied carbon on the overall carbon emissions, most probably because this is a refurbishment project, where embodied carbon values are relatively low, compared to those of new buildings. This echoes findings by Blengini (2009), Cuellar-Franca and Azapagic (2012), Rossi et al. (2012) and Schwartz et al. (2018). The contribution of the operational phase in the overall carbon ranges from 83.5% to 99%. Nevertheless, it should be noted that the contribution of the embodied carbon (Figure 8) becomes more significant in the deep retrofit scenario (Thormark 2002; Sartori and Hestnes 2007; Ramesh et al. 2010; Pelsmakers 2015). Specifically, embodied carbon of the simple retrofit (Figure 8) accounts for less than 1% of the building's LCCF compared to the deep retrofit, where values are considerably higher, at around 14.8-16.5%.

Results show that the initial state of the house both affects and determines the CO_2 reduction rates: Findings indicate that retrofitting the 'Never Refurbished' house has the biggest impact in terms of life cycle CO_2. According to Figure 8, deep retrofit reduces the non-refurbishment building's LCCF by 77%, medium by 66% and simple retrofit by 45%. The high reduction rates can be explained by the low-insulated 1900-1918 Never Refurbished building. The reduction rates of the other two initial state scenarios analysed, range from 35- 68% for the 1976 Refurbishment and 32-44% for the 2000 Refurbishment case (Figure 8).

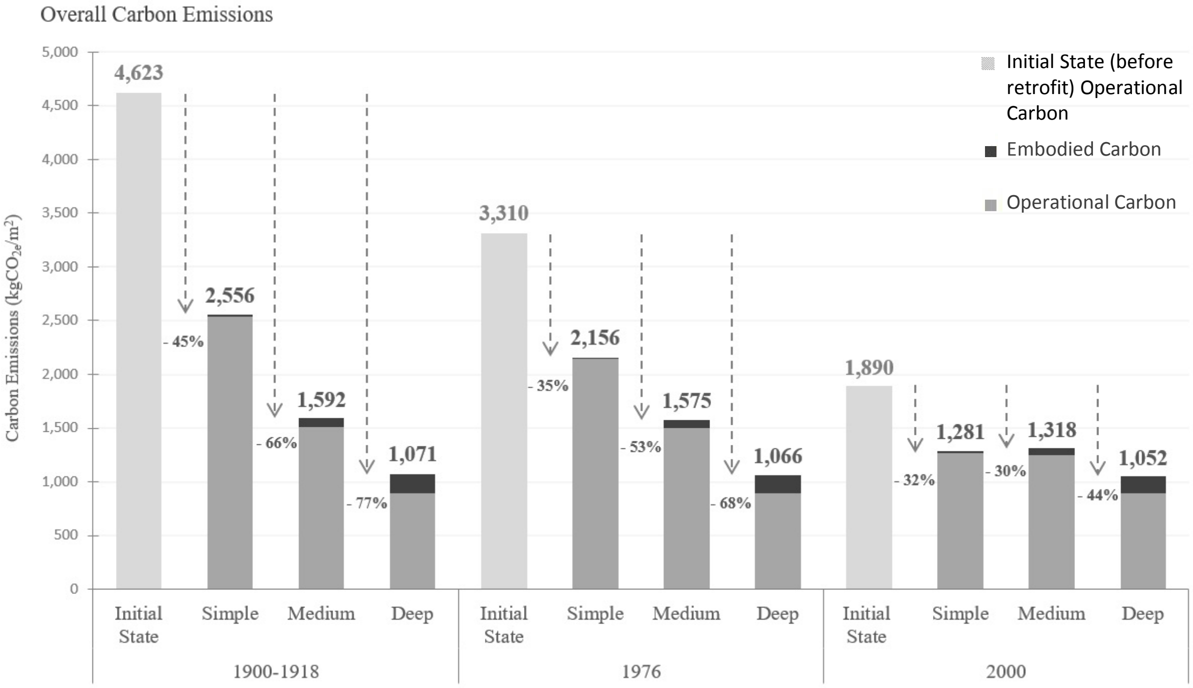

Figure 8: Reduction Rates, 1900-1918 Never Refurbished, 1976 and 2000 Refurbishments (60 years life span)

Specifically, in the 1990-1918 Never Refurbished scenario (Figure 8), simple retrofit cuts the building's initial carbon emissions by almost half (45%), while in the 2000 Refurbishment scenario (Figure 8), to achieve the same reduction rate, deep retrofit is necessary. It worth pointing out that for the 2000 refurbishment scenario, it seems that medium retrofit performs worse than a simple one. This is due to the additional embodied carbon that is involved in the refurbishment. This is an interesting finding, as it means that a simple retrofit – one that includes replacing boilers – is more beneficial, both in terms of performance and in terms of complexity of implementation and construction, than a medium retrofit.

In determining which retrofit package is most effective, results indicate that there is no clear solution, and that this is affected by the proxy by which effectiveness is measured: When looking at saving rates, ‘simple refurbishment’ shows satisfactory levels of savings in all initial-states (between 32 – 45%). In absolute figures, however, a simple retrofit of a ‘never refurbished’ building performs worse than a building that had been refurbished to comply with the 2000 regulations (2,556 and 1,281kg CO_{2e}/m^2, respectively), which may indicate that while simple retrofits can gain ‘quick savings’, deeper ones are required for long-term CO_2 reductions.

4.2 Embodied Carbon Analysis

Overall, the highest amount of embodied carbon is attributed to the 1900-1918 Never Refurbished scenario (Figure 9). This is expected as the gap between 1900-1918 and 2018 U-values is significant. In order for the 1900 house to be able to meet the 2018 U-value targets needs more insulation than the other two cases (1976 and 2000 refurbishments) resulting in higher embodied carbon results. It is assumed that the existing insulation of 1976 and 2000 initial states is preserved, and extra layers are added where necessary to comply with the current UK building regulations. In the 1976 and 2000 cases (Figure 9), the building performs better due to improved fabric and systems. Therefore, as expected, embodied carbon emissions are lower when smallest amounts of materials are used, and the building does not require major performance improvements. This echoes findings from literature.

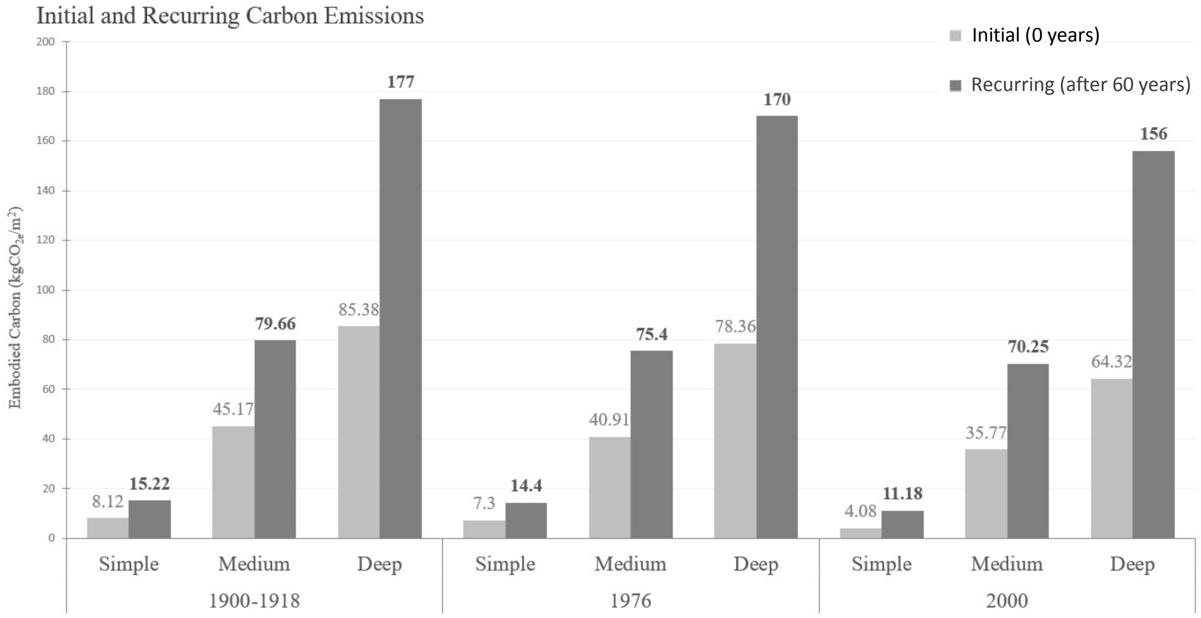

Figure 9: Embodied Carbon Emissions, initial and recurring, 1900-1918 Never Refurbished, 1976 and 2000 Refurbishments.

Results indicate the significance of recurring embodied carbon emissions in the 60-year building life span. It is clear that (Figure 9) recurring carbon in all examined cases is approximately twice as large as initial embodied carbon. The maintenance of the building envelope, components and systems over its life cycle contributes largely to the embodied carbon emitted. This reaffirms similar findings in the literature.

4.3 Operational Carbon Analysis

Figure 10 shows that in all cases, deep retrofit has the lowest operational carbon values (896 $kgCO_{2e}/m^2$) compared to the simple and medium retrofit packages. Results also show that deep retrofit's operational carbon is the same for all initial states examined. This is because all buildings, under all initial scenarios will end up having the level of refurbishments with the same fabric U-values and systems system efficiencies. The results of simple and medium refurbishment packages differ in the other two initial states, due to different starting points for each case study, resulting in different U-values and system efficiencies.

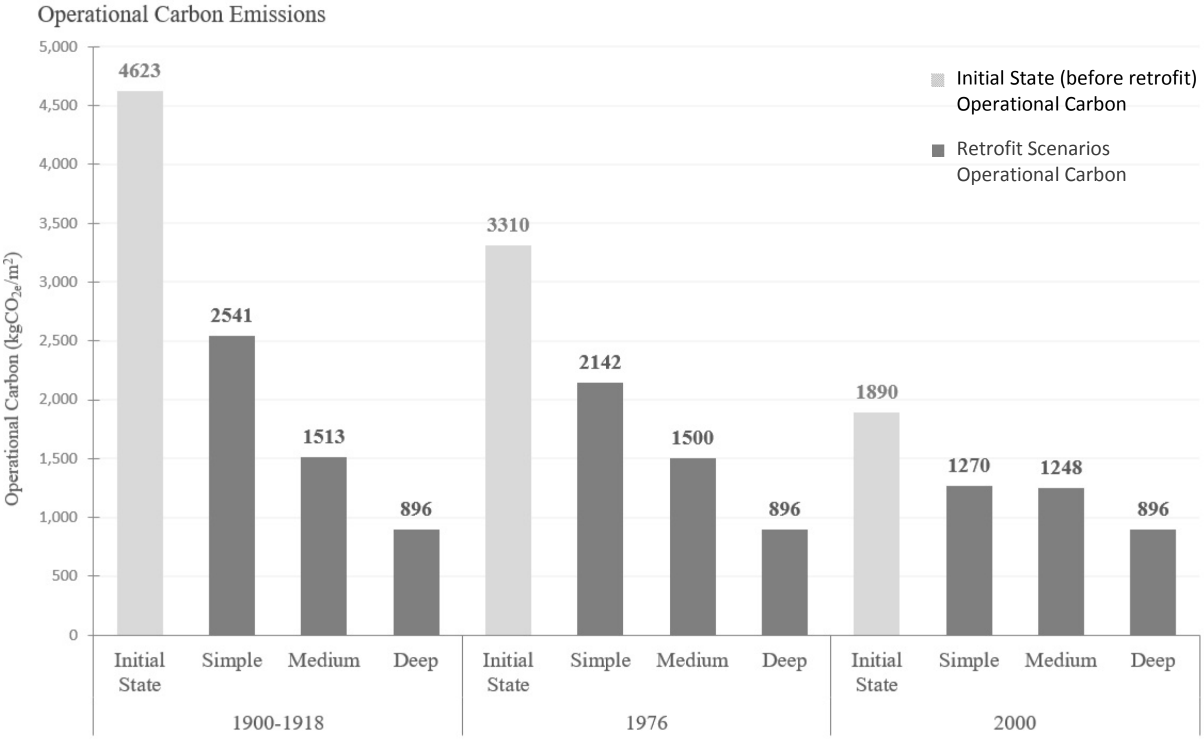

Figure 10: Operational Carbon Emissions, 1900-1918 Never Refurbished, 1976 and 2000 Refurbishments (60 years life span)

For the 1900-1918 Refurbishment (Figure 10), it is observed that medium refurbishments save around 40% more operational CO_2 than simple refurbishments, and that similar difference was noted between medium to deep retrofits. In the 2000 Refurbishment, on the other hand, when the initial state of the building was much better, medium refurbishments saved only around 2% more than simple ones, while deep refurbishments saved around 30% more emissions than medium ones. The 2000 Refurbishment before the retrofit was performing better than the 1900-1918 Never Refurbished case; thus, the operational carbon of the former has a lower reduction rate.

4.4 Operational Performance Comparative Analysis

It is quite challenging, especially in refurbishment projects, to find which refurbishment measure achieves the biggest savings. As refurbishment measures interact with each other, they quite often affect the performance of each other. To better understand the contribution and impact of refurbishment measures independently, a comparative analysis was carried.

For this analysis, the 1976 Refurbishment scenario is chosen for further analysis as it represents a more realistic approach, in terms of the initial state of buildings and their U-values and systems efficiencies, compared to the other two cases. The study focused on the impact of retrofit measures on space heating, as it has the largest share of a typical UK house energy use (CCC 2019). In the scope of this study, the retrofit measures influencing space heating are the gas boiler efficiency, and the building envelope's thermal transmittance (i.e., external walls, floors, and roof, as well as windows U-value).

The results presented below are for one year of building operation.

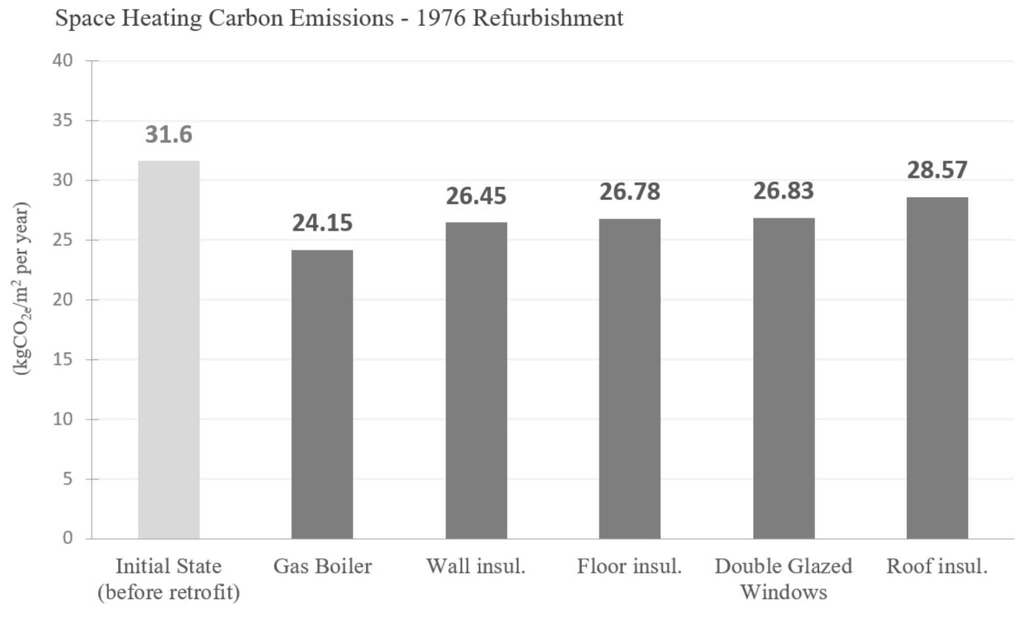

Figure 11: Retrofit measures impact on Space Heating, 1976 Refurbishment

Figure 11 shows that for the initial state of the 1976 Refurbishment scenario (for assumptions see Tables A3 & A4, Appendix A) the space heating carbon emissions were estimated at 31.6 $kgCO_{2e}/m^2$ annually. Each retrofit measure Gas Boiler, Wall insulation, Floor insulation, Double glazed windows and Roof insulation has been applied individually on the Initial state of 1976 Refurbishment scenario (for assumptions see Tables B2, B4 & B5, Appendix B). Thus, it is clear which of the aforementioned retrofit measures has the greatest impact regarding carbon reduction related to space heating.

Retrofit measures are presented on the graph from the highest to the lowest carbon impact. Efficient gas boiler has the biggest impact on heating demand for the examined case study. By replacing the old boiler, the space heating carbon emissions reached 24.15 $kgCO_{2e}/m^2$ resulting in 24% decrease from the initial state scenario. Wall and floor insulation, as well as window upgrades in compliance with the current UK building regulations, reduce CO_2 emissions by approximately 16%. Roof insulation was found to be the least effective option, saving only 10% of the initial state's emissions. Though roof insulation seems to show relatively low saving rates, it is a relatively easy to implement and more affordable measure, compared to the other fabric-related ones (wall/floor insulations or window replacements).

4.5 Carbon Payback Time

Payback time is estimated for all initial stages and retrofit scenarios, combining the results of the construction period and operation period (Huang et al. 2011). Payback time is determined by dividing the initial embodied carbon emissions by the operational savings (Valančius et al. 2018). More specifically, the CO_2 emissions payback period can be calculated as follows:

$\mathbf{Tco_2 = M_l / M_o}$ (1) (Huang et al. 2011), where:

Tco_2: payback time of CO_2 emissions
M_l ($kg\text{-}CO_2$): CO_2 emissions due to construction of the system
M_o ($kg\text{-}CO_2$): annual reduction of CO_2 emission due to system operation

Simple carbon payback time could be used as an indicator as it rapidly compares the environmental impact of different strategies over time. One of the major limitations of Simple Carbon Payback Period estimation is that it focuses on initial carbon, thus failing to consider future embodied carbon beyond the payback period; recurring carbon in later years is not estimated. However, it could be used as a decision-making tool when combined with other analysis (embodied, operational, comparative analysis).

Table 8: Estimated Carbon Payback time for all initial states and scenarios.

Initial State	Retrofit Scenarios	M_l initial embodied carbon ($kgCO_{2e}$)	M_o annual reduction in operational carbon ($kgCO_{2e}$)	Tco_{2e} Payback Time M_l / M_o (years)
1900-1918 Refurbishment	Simple	1,000	4,275	0.23
	Medium	5,566	6,390	0.90
	Deep	10,520	7,650	1.40
1976 Refurbishment	Simple	900	2,400	0.37
	Medium	5,040	3,720	1.35
	Deep	9,655	4,960	1.94
2000 Refurbishment	Simple	504	1,275	0.40
	Medium	4,407	1,320	3.35
	Deep	7,925	2,041	3.90

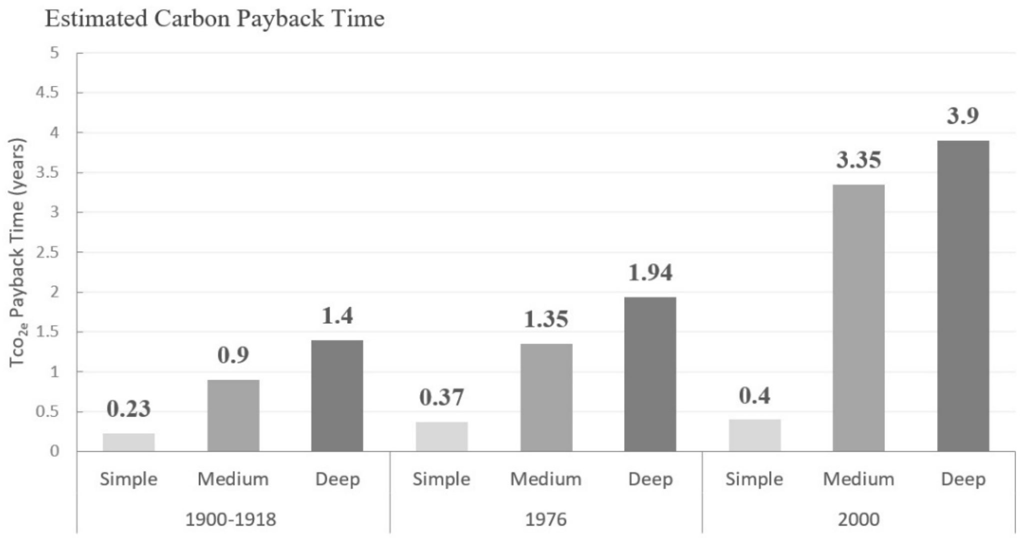

Figure 12: Carbon Payback time, 1900-1918 Never Refurbished, 1976 and 2000 Refurbishments

Table 8 and Figure 12 show the carbon payback time for all three initial states examined and their retrofit packages. The estimated carbon payback time for the simple refurbishment package is around three months, four and a half months and around five months for the 1900-1918, 1976 and 2000 Refurbishments, respectively. For the medium scenario around 11 months for the 1900-1918 Refurbishment, one year and four months for the 1976 Refurbishment and three years and four months for the 2000 Refurbishment. The deep scenario for the 2000 Refurbishment is around four years while for the 1900-1918 is only one year and five months.

According to Table 8 and Figure 12, the ‘2000 Refurbishment initial state’ building has overall the longer carbon payback time for all retrofit packages compared to the other two initial states. Due to the efficient existing fabric, the improvements in operational carbon are not significant, compared to the refurbishment’s embodied carbon. Retrofit packages applied on highly efficient building envelopes result in longer carbon payback time periods.

Comparing the retrofit packages of all three examined initial states, the shortest carbon payback period is attributed to the simple retrofit and the longest to the deep retrofit. This echoes findings from literature - the deeper the retrofit, the longer the carbon payback time (Dowson et al. 2012).

From the above estimation (Table 8), it is suggested that simple retrofit breaks even on refurbishment embodied carbon invested in a few months period for all three initial states. Deep retrofit, on the other hand, needs from around eighteen months (1900-1918 Refurbishment) to four years (2000 Refurbishment) to fully pay back the refurbishment’s embodied carbon, but the results are still considered satisfying for such a major refurbishment. All three initial states have relatively short CO_2 emission payback periods.

5. CONCLUSIONS

This study aimed at examining the most effective refurbishment package, in terms of LCCF, on a typical house in London, examining several assumed initial states for the original building.

Findings indicate that, overall, deep retrofit had achieved the largest Life Cycle Carbon Footprint savings, in absolute figures, compared to medium and simple retrofits. This was the case for all initial state scenarios – buildings that had never been refurbished (uninsulated), those that had been refurbished with compliance to the 1976 building regulations (some thermal efficiencies applied) and, surprisingly, even those that had been refurbished to comply with the 2000 building regulations.

Still, simple retrofit packages had shown high levels of saving rates (45, 35 and 32%), for the never refurbished, compliant with 1976 regulations and compliant with the 2000 regulations, respectively), while requiring significantly less complex refurbishment interventions.

Results indicate that reduction rates are highly affected by the initial state of the refurbished building. For example, a deep retrofit of a building that had never been refurbished achieved 77% savings in LCCF, while achieving 68% and 44% on a building compliant with the 1976 building regulations and one that is compliant with the 2000 regulations, respectively.

5.1 Recommendations

The present findings regarding the embodied carbon indicate that in all examined cases recurring carbon appears to be highly influential in the overall embodied carbon emissions as it was found approximately twice as large as the initial embodied carbon.

Carbon payback time analysis showed that retrofit packages applied on highly efficient building fabrics result in longer carbon payback time periods. Also, it was found that all buildings' payback time was relatively short: from 3 to 5 months for simple retrofit, 11 months to 1.4 years for the medium one and from 1.4 to 4 years for the deep retrofit. This is an encouraging finding, especially in light of demands for quick and significant CO_2 savings.

On this basis, it can be concluded that there is no unique retrofit approach that can be generalised for all initial states examined. When evaluating a preferable scheme, it is important to determine which measure is the most important: reduction rates (%) or absolute figures ($kgCO_{2e}$), as this study shows. While 'simple retrofits' can be effective in gaining 'quick savings', specially to buildings that had never been refurbished, deeper retrofits are required for long-term CO_2 reductions.

In the scope of net-zero dwellings, deep housing retrofit is a necessity. However, it should be noted again that one size does not fit all; each building requires a different retrofit approach designed to meet its particular needs. Comparing all three initial states based on a single percentage reduction target around 45-50%, results indicate that Simple retrofit is most beneficial option for the 1900-1918 Refurbishment, Medium retrofit for the 1976 Refurbishment and Deep retrofit for the 2000 Refurbishment.

Newly constructed buildings or recently refurbished ones require deeper retrofits to reflect changes in their carbon emissions. At the same time, deeper retrofits involve high embodied carbon. Based on the above, it is therefore recommended to establish a 'staggered' retrofitting approach, based on two main principles:

1. *Older buildings first*: This study has shown that the older the building the easier it is to get 'quick carbon savings': Older buildings typically perform worse, in terms of operational performance. This study shows that any intervention will therefore have a relatively high impact on performance of old buildings, compared to newer ones.

2. *Simple retrofit first*: This study has shown that simple retrofits – which are faster and easier to implement – gain quicker CO_2 reductions. It is recommended, therefore that simple retrofits are applied first – to give a rapid response to the climate emergency, while deep retrofit is applied at a later stage, to push buildings further and closer to Zero-Carbon target.

Understanding the thermal balance and the initial state of a building could help design teams to choose the most suitable retrofit package for the specific case study examined. In the context of the UK's zero carbon target, deep retrofit of existing housing stock is considered to be a powerful tool — especially when combined with an LCA holistic approach.

5.2 Limitations

The findings of this study have to be seen in light of some limitations. Uncertainties in design-based modelling inputs and unpredictable variables (e.g., changing climate, building systems malfunction, condensation, mould growth, occupant behaviour) often lead to discrepancies between the modelled and the actual performance of the building. It is difficult to realistically estimate a building's energy demand since unregulated energy use is based on individual user behaviour.

Also, it is worth mentioning that there is no framework or unified protocol to calculate the embodied carbon emissions of materials. While EPDs are increasingly used across the building sector, they are not yet widely available for the large number of materials used in typical buildings. Due to the limited information about materials, building components and systems data was retrieved from different sources, databases, online documents, and relevant previous research studies. The plethora of available methodologies for embodied carbon calculations combined with the lack of data regarding building services and materials reduces the comparability between studies and makes building environmental assessment a challenging task.

6. REFERENCES

Book Anderson, J., Shiers, D. & Steele, K. (2009). *The Green Guide to Specification: an environmental profiling system for building materials and component, 4th Edition*. Watford: HIS BRE Press.

Journal article Ashworth, A. (1996). Estimating the life expectancies of building components in life-cycle costing calculations. *Journal Structural Survey*, 14(2), pp.6, https://doi.org/10.1108/02630809610122730

Journal article Banihashemi, S., Golizadeh, H., Reza, H. & Shakouri, M. (2015). Climatic, parametric and non-parametric analysis of energy performance of double-glazed windows in different climates. *International Journal of Sustainable Built Environment*, 4(2), pp.307–322, http://dx.doi.org/10.1016/j.ijsbe.2015.09.002

Journal article Blengini, G.A. (2009). Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment*, 44(2), pp.319–330, https://doi.org/10.1016/j.buildenv.2008.03.007

Online report Shorrock, L.D., Henderson, J., & Utley, J. I. (2005). Reducing carbon emissions from the UK housing stock. *Housing Centre BRE Environment*, BRE Report BR480. Retrieved February 13, 2021, from http://projects.bre.co.uk/pdf_files/br480reducingcarbonemissionsfromukhousing.pdf

Online document BRE (2014). *SAP 2012:* The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Retrieved February 13, 2021, from https://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf

Online document BRE (2018). Methodology for LCA of Building using EN 15978:2011. Retrieved May 03, 2021, from https://www.greenbooklive.com/filelibrary/EN_15804/PN326-BRE-EN-15978-Methodology.pdf

British Standards Institution (2011). BS EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. *British Standards Institution Group.*

Journal article Bull, J., Gupta, A., Mumovic, D. & Kimpian, J. (2014). Life cycle cost and carbon footprint of energy efficient refurbishments to 20th century UK school buildings. *International*

Journal of Sustainable Built Environment, 3(1), pp.1–17, http://dx.doi.org/10.1016/j.ijsbe.2014.07.002

Journal article Capeluto, G. (2019). Adaptability in envelope energy retrofits through addition of intelligence features. *Architectural Science Review*, 62(3), pp.1–14, https://doi.org/10.1080/00038628.2019.1574707

Book CIBSE Guide A - Environmental Design (7th Edition), *The Chartered Institution of Building Services Engineers*, CIBSE.

Journal article Chen, Z., Lippke, B. & Stevens, N. (2005). Energy Consumption and Greenhouse Gas Emissions Related to the Use, Maintenance, and Disposal of a Residential Structure. *Journal of the Society of Wood Science and Technology,* pp. 128–139. Retrieved February 13, 2021, from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.554.5572&rep=rep1&type=pdf

Report by Cluett, R, & Amann. J. (2014). Residential Deep Energy Retrofits. American Council for an Energy-Efficient Economy (ACEEE). Retrieved February 13, 2021, from https://c2e2.unepdtu.org/wp-content/uploads/sites/3/2016/03/a1401.pdf

Online document Committee on Climate Change (CCC) (2018). *Reducing UK emissions: 2018 Progress Report to Parliament*. Retrieved February 13, 2021, from https://www.theccc.org.uk/wp-content/uploads/2018/06/CCC-2018-Progress-Report-to-Parliament.pdf

Online document Committee on Climate Change (CCC) (2019). Reducing UK emissions - 2019 Progress Report to Parliament. Retrieved February 13, 2021, from https://www.theccc.org.uk/wp-content/uploads/2019/07/CCC-2019-Progress-in-reducing-UK-emissions.pdf

Journal article Cuéllar-Franca, R.M. & Azapagic, A. (2012). Environmental impacts of the UK residential sector: Life cycle assessment of houses. *Building and Environment*, 54(C), pp.86–99, https://doi.org/10.1016/j.buildenv.2012.02.005

Journal article Dixit, M., Fernández-Solís, J., Lavy, S. & Culp, C. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy & Buildings*, 42(8), pp.1238–1247, https://doi.org/10.1016/j.enbuild.2010.02.016

Journal article Dodoo, A., Gustavsson, L. & Sathre, R. (2014). Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. *Energy and Buildings*. Elsevier B.V., 82, pp. 194–210. doi: 10.1016/j.enbuild.2014.06.034.

Journal article Dowson, M., Poole, A., Harrison, D. & Susman, G. (2012). Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. *Energy Policy*, 50(C), pp.294–305, http://dx.doi.org/10.1016/j.enpol.2012.07.019

Journal article Duda, M. & Shaw, J. S. (1997). Life Cycle Assessment. *Society*, 35, 38-43. https://doi.org/10.1007/s12115-997-1054-x

Online document European Commission (2017). Good practice in energy efficiency, for a sustainable, safer, and more competitive Europe. Retrieved February 13, 2021, from https://ec.europa.eu/energy/sites/ener/files/documents/good_practice_in_ee_-web.pdf

Online document European Commission DG Environment (2002). Evaluation of Environmental Product Declaration Schemes. Retrieved February 13, 2021, from https://ec.europa.eu/environment/ipp/pdf/epdstudy.pdf

Online document European Commission DG Energy (2018). Support for setting up a smart readiness indicator for buildings and related impact assessment - Final Report. Retrieved February 13, 2021, from https://smartreadinessindicator.eu/sites/smartreadinessindicator.eu/files/sri_1st_technical_study_-_final_report.pdf

Conference Paper Evrard, A., Trachte, S., Hermand, C., Bouillard, P. & De Herde, A. (2016). Sustainable Retrofitting of Dwellings in Brussels Capital Region: Five Scenarios of Evolution using a Multi-scale Multi-criteria and Pre-assessment Tool. In: *PLEA 2016 Los Angeles - 32nd International Conference on Passive and Low Energy Architecture*.

Journal article Finnegan, S., Jones, C. & Sharples, S. (2018). The embodied CO2e of sustainable energy technologies used in buildings: A review article. *Energy & Buildings*, 181, pp.50–61, https://doi.org/10.1016/j.enbuild.2018.09.037

Journal article Gustavsson, L., Joelsson, A. & Sathre, R. (2010). Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy and Buildings*, 42(2), pp. 230–242. doi: 10.1016/j.enbuild.2009.08.018.

Journal article Gustafsson, M., Gustafsson, M.S., Myhren, J., Bales, C. & Holmberg, S. (2016). Techno-economic analysis of energy renovation measures for a district heated multifamily house. *Applied Energy,* 177(C), pp.108–116, http://dx.doi.org/10.1016/j.apenergy.2016.05.104

Journal article Hall, M., Casey, S., Loveday, D. & Gillott, M. (2013). Analysis of UK domestic building retrofit scenarios based on the E.ON Retrofit Research House using energetic hygrothermics simulation – Energy efficiency, indoor air quality, occupant comfort, and mould growth potential. *Building and Environment*, 70, pp.48-59, https://doi.org/10.1016/j.buildenv.2013.08.015.

Journal article Hammond, G. & Jones, C. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy*, 161(2), pp.87–98, https://doi.org/10.1680/ener.2008.161.2.87

Hammond, G. & Jones, C. (2011). Bath ICE - Inventrory of Carbon & Energy V2.0, Sustainable Energy Research Team (SERT) Department of Mechanical Engineering. Bath.

Book Harvey, L.D.D. (2006). *A Handbook on Low-Energy Buildings and District-Energy Systems: Fundamentals, Techniques and Examples,* London: Routledge, pp.543-560, https://doi.org/10.4324/9781849770293

Journal article Huang, Y., Niu, J. and Chung, T. (2011). Energy and carbon emission payback analysis for energy-efficient retrofitting in buildings—Overhang shading option. *Energy & Buildings*, 44(1), pp.94–103, https://doi.org/10.1016/j.enbuild.2011.10.027

Journal article Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. & Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy & Buildings,* 66, pp.232–245, http://dx.doi.org/10.1016/j.enbuild.2013.07.026

Journal article Iddon, C. & Firth, S. (2013). Embodied and operational energy for new-build housing: A case study of construction methods in the UK. *Energy & Buildings*, 67, pp.479– 488, http://dx.doi.org/10.1016/j.enbuild.2013.08.041

Online document InterNACHI (2017). Estimated Life Expectancy Chart. Retrieved February 13, 2021, from https://trademarkhomeinspection.com/wp-content/uploads/2017/04/Life-Expectancy-Chart.pdf

Journal article Jermyn, D. & Richman, R. (2016). A process for developing deep energy retrofit strategies for single-family housing typologies: Three Toronto case studies. *Energy & Buildings*, 116, pp.522–534, http://dx.doi.org/10.1016/j.enbuild.2016.01.022

Journal article Jones, P., Lannon, S. & Patterson, J. (2013). Retrofitting existing housing: how far, how much? *Building Research & Information*, 41(5), pp.532–550, https://doi.org/10.1080/09613218.2013.807064

Article by Koubogiannis, D. & Nouhou, C. (2016). How much Energy is Embodied in your Central Heating Boiler? *IOP Conference Series: Materials Science and Engineering*, 161(1). Retrieved February 13, 2021, from https://iopscience.iop.org/article/10.1088/1757-899X/161/1/012094/pdf

Journal article Kutnar, A. & Sinha, A. (2012). Carbon Footprint versus Performance of Aluminum, Plastic, and Wood Window Frames from Cradle to Gate. *Buildings*, 2(4), pp.542– 553, https://doi.org/10.3390/buildings2040542

Journal article Leinartas, H. A. & Stephens, B. (2015). Optimizing Whole House Deep Energy Retrofit Packages: A Case Study of Existing Chicago-Area Homes. *Buildings*, 5(2), pp.323–353, https://doi.org/10.3390/buildings5020323

Report by Less, B., Fisher, J. & Walker, I. (2012). Deep Energy Retrofits: Eleven California Case Studies; Lawrence Berkeley National Laboratory: Berkeley, CA, USA. Retrieved February 13, 2021, from https://eta-publications.lbl.gov/sites/default/files/lbnl-6166e.pdf

Website article by Lighting.Philips.com (2019). What does a life of 50,000 hours mean in the case of - LEDs? Retrieved February 13, 2021, from https://www.lighting.philips.com/main/support/support/faqs/life-and-light-output/a-life-of-50000-hours

Book Lowe, R., Chiu, L.F., Raslan, R.M. & Altamirano, H. (2012). *Retrofit insights: perspectives from an emerging industry report*. Institute for Sustainability UCL.

Journal article Lstiburek, J. (2007). A Bridge Too Far. *ASHRAE Journal*, 49(10).

Journal article Moncaster, A. & Symons, K. (2013). A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy & Buildings*, 66(C), pp.514–523, http://dx.doi.org/10.1016/j.enbuild.2013.07.046

Journal article Moran, F., Natarajan, S. & Nikolopoulou, M. (2012). Developing a database of energy use for historic dwellings in Bath, UK. *Energy & Buildings*, 55, pp.218–226, http://dx.doi.org/10.1016/j.enbuild.2013.12.043

Conference paper Murray, P., Niffeler, M., Mavromatidis, G. & Orehounig, K. (2019). Optimal Retrofitting Measures for Residential Buildings At Large Scale: A Multi-Objective Approach. *Proceedings of Building Simulation 2019: 16th Conference of IBPSA*, pp.3742-3748, https://doi.org/10.26868/25222708.2019.211233

Journal article Oikonomou, E., Davies, M., Mavrogianni, A., Biddulph, P., Wilkinson, P. & Kolokotroni, M. (2012). Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London. *Building and Environment*, 57, pp.223–238, https://doi.org/10.1016/j.buildenv.2012.04.002

Book Pelsmakers, S. (2015). *The environmental design pocketbook*. 2nd ed. London: RIBA Publishing.

Journal article by Power, A. (2008). Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social, and economic viability? *Energy Policy*, 36(12), pp. 4487–4501. https://doi: 10.1016/j.enpol.2008.09.022.

Prestia, E. (2010). Low-energy refurbishments: process from design to construction, Environmental Design and Engineering, Built Environment, Thesis (MSc.). UCL (University College London).

Journal article Ramesh, T., Prakash, R. & Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, 42(10), pp.1592–1600, https://doi.org/10.1016/j.enbuild.2010.05.007

Journal article Rodrigues, C. & Freire, F. (2017). Building retrofit addressing occupancy: An integrated cost and environmental life-cycle analysis. *Energy & Buildings*, 140, pp.388–398, http://dx.doi.org/10.1016/j.enbuild.2017.01.084

Journal article Rossi, B.F., Marique, A.F. & Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, case study. *Building and Environment*, 51, pp.402–407, https://doi.org/10.1016/j.buildenv.2011.11.002

Journal article Sartori, I. & Hestnes, A. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy & Buildings*, 39(3), pp.249–257, https://doi.org/10.1016/j.enbuild.2006.07.001

Schwartz, Y. (2018). An Integrated Thermal Simulation & Generative Design Decision Support Framework for the Refurbishment or Replacement of Buildings: A Life Cycle Performance Optimisation Approach. Thesis (PhD). UCL (University College London).

Journal article Schwartz, Y., Raslan, R. & Mumovic, D. (2018). The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies. *Renewable and Sustainable Energy Reviews*, 81 (1) pp. 231-241, https://doi.org/10.1016/j.rser.2017.07.061

Journal article Semprini, G., Gulli, R., & Ferrante, A. (2017). Deep regeneration vs shallow renovation to achieve nearly Zero Energy in existing buildings: Energy saving and economic impact of design solutions in the housing stock of Bologna. *Energy & Buildings*, 156, pp.327–342, http://dx.doi.org/10.1016/j.enbuild.2017.09.044

Journal article Soares, N., Bastos, J., Pereira, L., Soares, A., Amaral, A., Asadi, E., Rodrigues, E., Lamas, F., Monteiro, H., Lopes, M. & Gaspar, A. (2017). A review on current advances in the energy and environmental performance of buildings towards a more sustainable built environment. *Renewable and Sustainable Energy Reviews*, 77, pp.845-860, https://doi.org/10.1016/j.rser.2017.04.027

Journal article Spanos, I., Duckers, L. & Holmes, K. (2007). Application of 'C.A.R.B. financial methodology' analysis for alternative energy technologies into UK housing. *Renewable and Sustainable Energy Reviews*, 11(7), pp.1571–1583, https://doi.org/10.1016/j.rser.2005.05.008

Journal article Stephan, A., Crawford, R. & De Myttenaere, K. (2012). Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy & Buildings*, 55(C), pp.592–600, http://dx.doi.org/10.1016/j.enbuild.2012.09.008

Sustainable Development Commission (2007*).* Building houses or creating communities? Retrieved February 13, 2021, from http://www.sd-commission.org.uk/data/files/publications/SDC_SCP_report_2007.pdf

Journal article Tae, S., Shin, S., Kim, H., Ha, S., Lee, J., Han, S. & Rhee, J. (2011). Life cycle environmental loads and economic efficiencies of apartment buildings built with plaster board drywall. *Renewable and Sustainable Energy Reviews*, 15(8), pp.4145-4155, doi: 10.1016/j.rser.2011.06.009

Journal article Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and Environment*, 37(4), pp.429–435, https://doi.org/10.1016/S0360-1323(01)00033-6

Journal article Tokede, O., Love, P. & Ahiaga-Dagbui, D. (2018). Life cycle option appraisal in retrofit buildings. *Energy and Buildings*, 178, pp.279-293, https://doi.org/10.1016/j.enbuild.2018.08.034

Journal article Uidhir, T., Rogan, F., Collins, M., Curtis, J. & Gallachóir, B. (2020). Improving energy savings from a residential retrofit policy: A new model to inform better retrofit decisions. *Energy and Buildings*, 209, p.109656, https://doi.org/10.1016/j.enbuild.2019.109656

UK Statutory Instruments (1976). *The Building Regulations 1976*, vol. 1676.

UK Statutory Instruments (2000). *The Building Regulations 2000*.

UK Statutory Instruments, Building Regulations (2018). *Approved Document L1B: conservation of fuel and power in existing dwellings, 2010 edition* (incorporating 2010, 2011, 2013, 2016 and 2018 amendments).

Online document UK Green Building Council (2019). Net Zero Carbon Buildings: A Framework Definition. Retrieved February 13, 2021, from https://www.ukgbc.org/wp-content/uploads/2019/04/Net-Zero-Carbon-Buildings-A-framework-definition.pdf

Journal article Valančius, K., Vilutienė, T. & Rogoža, A. (2018). Analysis of the payback of primary energy and CO_2 emissions in relation to the increase of thermal resistance of a building, *Energy & Buildings*, 179, pp.39–48, https://doi.org/10.1016/j.enbuild.2018.08.037

Journal article Victoria, M. & Perera, S. (2018). Managing embodied carbon in buildings: a Pareto approach. *Built Environment Project and Asset Management*, 8(5), pp.504–514, https://doi.org/10.1108/BEPAM-10-2017-0095

Online Document WRAP (2008). WRAP Net Waste Tool - Guide to Reference Data, Version 1.0. Retrieved February 13, 2021, from http://nwtool.wrap.org.uk/Documents/WRAP%20NW%20Tool%20Data%20Report.pdf

Journal article Zavadskas, E., Raslanas, S. & Kaklauskas, A. (2008). The selection of effective retrofit scenarios for panel houses in urban neighborhoods based on expected energy savings and increase in market value: The Vilnius case. *Energy and Buildings*, 40(4), pp.573-587, https://doi.org/10.1016/j.enbuild.2007.04.015

APPENDIX A – INITIAL STATE SCENARIOS

Table A1: Construction fabric inputs, IESVE, 1900-1918 Never Refurbished (Initial State)

Initial State	Construction	Materials	Thickness (mm)	Conductivity (W/mK)	U-values SAP (2012) CIBSE Guide A (W/m^2K)	Thermal Mass (kJ/m^2K)
1900-1918	External Wall	Brickwork (outer leaf)	220	0.84	2.1	Lightweight 135
		Plaster (dense)	18	0.50		
	Party Wall	Adiabatic	-	-	0	-
	Internal Partition	Plaster (lightweight)	10	0.16	1.92	Very lightweight 74
		Brickwork (inner leaf)	100	0.62		
		Plaster (lightweight)	10	0.16		
	Ground Floor	London clay	200	1.41	1.06	Very lightweight 69
		Cavity	200	-		
		Chipboard	25	0.15		
		Timber flooring	35	0.14		
	Internal Floor/Ceiling	Timber flooring	19	0.14	1.64	Very lightweight 4
		Cavity	100	-		
		Plasterboard	12.5	0.21		
	Roof	Clay tile	40	0.84	2.30	Very lightweight 58
		Roofing felt	5	0.19		
		Chipboard	30	0.15		
	Windows	Clear float	6	1.06	4.80	-
	External Doors	Plywood	37	0.13	2.16	Very lightweight 13.87

Table A2: System inputs, IESVE, 1900-1918 Never Refurbished (Initial State)

Systems	**Description**	**Inputs**
Heating	UK NCM system type	Central Heating using water: radiators
	Heat Source	Non-Condensing Boiler
	Heat Source Efficiency	75% efficient (Lowe 2007)
	Fuel	Natural Gas
Cooling	Natural Ventilation	Ventilation profile: CO_2>1000ppm or Internal Temp.> 25°C, Windows open
Domestic Hot Water (DHW)	Heat Source	Non-Condensing Boiler
	DHW delivery efficiency	75%
	Set Points for NCM	Mean cold water inlet temp: 10°C Hot water supply temperature: 60°C
	Consumption	Linked to occupancy
Lights	Fluorescent Lighting	Installed Power Density/100lux 5.200 W/m^2 (100 lux)
Air Exchanges	Infiltration	1 ach
MVHR	-	-
Solar Thermal Panels	-	-
PVs	-	-

Table A3: Construction fabric inputs, IESVE, 1976 Refurbishment (Initial State)

Initial State	Construction	Materials	Thickness (mm)	Conductivity (W/mK)	U-values 1976 Build. Regulations (W/m^{2}K)	Thermal Mass (kJ/m^{2}K)
1976	External Wall	Brickwork (outer leaf)	220	0.84	1.00	Very Lightweight 10.55
		Mineral Fibre Board	20	0.042		
		Plasterboard	12.5	0.21		
		Plaster (lightweight)	3	0.16		
	Party Wall	Adiabatic	-	-	0	-
	Internal Partition	Plaster (lightweight)	10	0.16	1.92	Very lightweight 74
		Brickwork (inner leaf)	100	0.62		
		Plaster (lightweight)	10	0.16		
	Ground Floor	London clay	200	1.41	1.00	Very lightweight 44
		Cavity	200	-		
		Mineral Fibre Board	6	0.042		
		Chipboard	10	0.15		
		Timber flooring	35	0.14		
	Internal Floor/Ceiling	Timber flooring	19	0.14	1.64	Very lightweight 4
		Cavity	100	-		
		Plasterboard	12.5	0.21		
	Roof	Clay tile	40	0.84	0.60	Very lightweight 10.55
		Roofing felt	5	0.19		
		Chipboard	25	0.15		
		Mineral Fibre Board	50	0.042		
		Plasterboard	12.5	0.21		
		Plaster (lightweight)	3	0.16		
	Windows	Clear float	6	1.06	4.80	-
	External Doors	Plywood	37	0.13	2.16	Very lightweight 13.87

Table A4: System inputs, IESVE ,1976 Refurbishment (Initial State)

Systems	**Description**	**Inputs**
Heating	UK NCM system type	Central Heating using water: radiators
	Heat Source	Non-Condensing Boiler
	Heat Source Efficiency	75% efficient
	Fuel	Natural Gas
Cooling	Natural Ventilation	Ventilation profile: CO_2>1000ppm or Internal Temp.> 25^{o}C Windows open
Domestic Hot Water (DHW)	Heat Source	Non-Condensing Boiler
	DHW delivery efficiency	75%
	Set Points for NCM	Mean cold water inlet temp: 10^{o}C Hot water supply temperature: 60^{o}C
	Consumption	Linked to occupancy
Lights	Fluorescent Lighting	Installed Power Density/100lux 5.200 W/m^2 (100 lux)
Air Exchanges	Infiltration	0.75 ach
MVHR	-	-
Solar Thermal Panels	-	-
PVs	-	-

Table A5: Construction fabric inputs, IESVE, 2000 Refurbishment (Initial State)

Initial State	Construction	Materials	Thickness (mm)	Conductivity (W/mK)	U-values 2000 Build. Regulations (W/m^2K)	Thermal Mass (kJ/m^2K)
2000	External Wall	Brickwork (outer leaf)	220	0.84	0.35	Very Lightweight 10.55
		Mineral Fibre Board	100	0.042		
		Plasterboard	12.5	0.21		
		Plaster (lightweight)	3	0.16		
	Party Wall	Adiabatic	-	-	0	-
	Internal Partition	Plaster (lightweight)	10	0.16	1.92	Very lightweight 74
		Brickwork (inner leaf)	100	0.62		
		Plaster (lightweight)	10	0.16		
	Ground Floor	London clay	200	1.41	0.25	Very lightweight 44
		Cavity	200	-		
		Mineral Fibre Board	130	0.042		
		Chipboard	10	0.15		
		Timber flooring	35	0.14		
	Internal Floor/Ceiling	Timber flooring	19	0.14	1.64	Very lightweight 4
		Cavity	100	-		
		Plasterboard	12.5	0.21		
	Roof	Clay tile	40	0.84	0.20	Very lightweight 10.55
		Roofing felt	5	0.19		
		Chipboard	30	0.15		
		Mineral Fibre Board	180	0.042		
		Plasterboard	12.5	0.21		
		Plaster (lightweight)	3	0.16		
	External Doors	Pine	20	-	1.80	
		insulation	6.2	-		
		Pine	20	-		
	Windows Double-Glazed Low-e	Outer Pane	6	1.06	2.00	
		Cavity	12	-		
		Inner Pane	6	1.06		

Table A6: System inputs, IESVE, 2000 Refurbishment (Initial State)

Systems	**Description**	**Inputs**
Heating	UK NCM system type	Central Heating using water: radiators
	Heat Source	Non-Condensing Boiler
	Heat Source Efficiency	80% efficient
	Fuel	Natural Gas
Cooling	Natural Ventilation	Ventilation profile: CO_2>1000ppm or Internal Temp.> 25°C Windows open
Domestic Hot Water (DHW)	Heat Source	Non-Condensing Boiler
	DHW delivery efficiency	80%
	Set Points for NCM	Mean cold water inlet temp: 10°C Hot water supply temperature: 60°C
	Consumption	Linked to occupancy
Lights	Fluorescent Lighting	Installed Power Density/100lux 5.200 W/m^2 (100 lux)
Air Exchanges	Infiltration	0.50 ach
MVHR	-	-
Solar Thermal Panels	-	-
PVs	-	-

APPENDIX B – RETROFIT SCENARIOS

Table B1: Construction fabric inputs, IESVE ,1900-1918 Never Refurbished (Retrofit)

Initial State	Retrofit Construction	Material	Thickness (mm)	Conductivity (W/mK)	U-values 2018 Build. Regulations (W/m^{2}K)	Thermal Mass (kJ/m^{2}K)
1900-1918	Roof	Clay tile	40	0.84	0.16	Very lightweight 3.00
		Roofing Felt	5	0.19		
		Chipboard	30	0.15		
		Expanded Polystyrene (EPS)	200	0.035		
		Plaster (render)	5	0.16		
	Windows Double-Glazed Argon filled	Outer Pane	6	1.06	1.60	-
		Cavity	12	Argon		
		Inner Pane	6	1.06		
	Doors	Pine	20	0.14	1.80	Very lightweight 22.79
		Insulation	6	0.035		
		Pine	20	0.14		
	Wall	Brickwork	220	0.84	0.30	Lightweight 14.37
		Timber studding	100 x 50 cavity	-		
		Expanded Polystyrene (EPS)	100	0.035		
		Plasterboard	25	0.21		
		Plaster (render)	5	0.16		
	Floor	London Clay	200	1.41	0.25	Very lightweight 89.80
		Cavity Timber joists	70 (170 x 38)	-		
		Expanded Polystyrene (EPS)	100	0.035		
		Chipboard	35	0.15		
		Timber Flooring	40	0.14		

Table B2: Construction fabric inputs, IESVE, 1976 Refurbishment (Retrofit)

Initial State	Retrofit Construction	Material	Thickness (mm)	Conductivity (W/mK)	U-values 2018 Build. Regulations (W/m^{2}K)	Thermal Mass (kJ/m^{2}K)
1976	Roof	Clay tile	40	0.84	0.16	Very lightweight 3.00
		Roofing Felt	5	0.19		
		Chipboard	30	0.15		
		Mineral Fibre Board	50	0.042		
		Expanded Polystyrene (EPS)	170 (150+20)	0.035		
		Plaster (render)	5	0.16		
	Windows Double-Glazed Argon filled	Outer Pane	6	1.06	1.60	-
		Cavity	12	Argon		
		Inner Pane	6	1.06		
	Doors	Pine	20	0.14	1.80	Very lightweight 22.79
		Insulation	6.2	0.035		
		Pine	20	0.14		
	Wall	Brickwork	220	0.84	0.30	Lightweight 10.55
		Mineral Fibre Board	20	0.042		
		Expanded Polystyrene (EPS)	80	0.035		
		Plasterboard	12.5	0.21		
		Plaster (render)	3	0.16		
	Floor	London Clay	200	1.41	0.25	Very lightweight 44.04
		Cavity Timber joists	200 (170 x 38)			
		Mineral Fibre Board	6	0.042		
		Expanded Polystyrene (EPS)	110 (90+20)	0.035		
		Chipboard	10	0.15		
		Timber Flooring	35	0.14		

Table B3: Construction fabric inputs, IESVE, 2000 Refurbishment (Retrofit)

Initial State	Retrofit Construction	Material	Thickness (mm)	Conductivity (W/mK)	U-values 2018 Build. Regulations (W/m^{2}K)	Thermal Mass (kJ/m^{2}K)
2000	Roof	Clay tile	40	0.84	0.16	Very lightweight 3.00
		Roofing Felt	5	0.19		
		Chipboard	30	0.15		
		Mineral Fibre Board	180	0.042		
		Expanded Polystyrene (EPS)	50	0.035		
		Plaster (render)	5	0.16		
	Windows Double Glazed Argon filled	Outer Pane	6	1.06	1.60	-
		Cavity	12	Argon		
		Inner Pane	6	1.06		
	Doors	Pine	20	0.14	1.80	Very lightweight 22.79
		Insulation	6.2	0.035		
		Pine	20	0.14		
	Wall	Brickwork	220	0.84	0.30	Lightweight 10.55
		Mineral Fibre Board	100	0.042		
		Expanded Polystyrene (EPS)	20	0.035		
		Plasterboard	12.5	0.21		
		Plaster (render)	3	0.16		
	Floor	London Clay	200	1.41	0.25*	Very lightweight 44.04
		Cavity Timber joists	200 (170 x 38)	-		
		Mineral Fibre Board	130	0.042		
		Chipboard	10	0.15		
		Timber Flooring	35	0.14		

** Floor U-value 2018 same with Floor U-value 2000*

Table B4: System inputs, IESVE

System	Retrofit Scenario	Description	Inputs
Heating	Simple & Medium	UK NCM system type	Central Heating using water: radiators
		Heat Source	Condensing Boiler
		Heat Source Efficiency	98% efficient
		Fuel	Natural Gas
	Deep	UK NCM system type	Dual-duct VAV
		Heat Source	Condensing Boiler
		Heat Source Efficiency	98% efficient
		Fuel	Natural Gas
Cooling	Simple & Medium	Natural Ventilation	Ventilation profile: CO_2>1000ppm or Internal Temp.> 25°C, Windows open
	Deep	Air conditioning	Centralised balanced A/C
Domestic Hot Water (DHW)	Simple Medium Deep	Heat Source	Condensing Boiler
		DHW delivery efficiency	98% (Viessmann.co.uk, ca. 2019)
		Set Points for NCM	Mean cold water inlet temp: 10°C Hot water supply temperature: 60°C
		Consumption	Linked to occupancy
Lights	Simple Medium Deep	LEDs	Installed Power Density/100lux, 2.100 W/m^2 (100 lux), Specific load per unit floor area for Led Lights 2.1W/m^2 (BRE 2016)
MVHR	Deep	Heat Recovery Thermal Wheel	95% efficient (Nuaire.co.uk, ca. 2019)
Solar Thermal Panels	Deep	Flat Plate Collectors	Area 4m^2, 0° deviation from south, Tilt 35° (Pelsmakers 2015, pp. 410)
		Storage tank	Volume: 200 litres, Storage loss at max. temperature: 0.00708 kWh/(lday), (Thickness insulation 160mm) (SAP 2012, pp. 197)
PVs	Deep	Monocrystalline type	Area 10m^2, Tilt: 35° (Pelsmakers 2015, pp. 405)

Table B5: Air permeability inputs, IESVE, 1900-1918 Never Refurbished and 1976 Refurbishment (Retrofit)

Retrofit Scenarios	Air permeability* (m^3/m^2h at 50 Pa)	Air Changes per hour (ach^{-1})
Simple	15	0.75
Medium	10	0.50
Deep	5	0.25

**Air permeability is converted to air changes per hour according to Pelsmakers, 2015, pp. 254*

Table B6: Air permeability inputs, IESVE, 2000 Refurbishment (Retrofit)

Retrofit Scenarios	**Air permeability*** **(m^3/m^2h at 50 Pa)**	**Air Changes per hour (ach^{-1})**
Simple	10	0.50
Medium	10	0.50
Deep	5	0.25

**Air permeability is converted to air changes per hour according to Pelsmakers, 2015, pp. 254*

APENDIX C – EMBODIED CARBON

Table C1: Breakdown of Initial Embodied Carbon

Initial State	Retrofit Scenario	Gas Boiler $kgCO_{2e}$	LEDs $kgCO_{2e}$	Roof insul. $kgCO_{2e}$	Double glazed windows $kgCO_{2e}$	Doors $kgCO_{2e}$	Wall insul. $kgCO_{2e}$	Floor insul. $kgCO_{2e}$	MVHR $kgCO_{2e}$	Solar Thermal Panels $kgCO_{2e}$	PVs $kgCO_{2e}$	TOTAL $kgCO_{2e}$	TOTAL $kgCO_{2e}/m^2$
1900-1918	Simple	169.33	134	698.12	-	-	-	-	-	-	-	1,001.4	8.12
	Medium	169.33	134	698.12	2,416	957.6	1,191	-	-	-	-	5,566	45.17
	Deep	169.33	134	698.12	2,416	957.6	1,191	1,436	618	480	2,420	10,520	85.38
1976	Simple	169.33	134	596.61	-	-	-	-	-	-	-	900	7.30
	Medium	169.33	134	596.61	2,416	957.6	767.75	-	-	-	-	5,040	40.91
	Deep	169.33	134	596.61	2,416	957.6	767.75	1,096	618	480	2,420	9,655	78.36
2000	Simple	169.33	134	200.27	-	-	-	-	-	-	-	503.6	4.08
	Medium	169.33	134	200.27	2,416	957.6	530	-	-	-	-	4,407	35.77
	Deep	169.33	134	200.27	2,416	957.6	530	-	618	480	2,420	7,925	64.32

Table C2: Breakdown of Recurring Embodied Carbon (60 years life span)

Initial State	Retrofit Scenario	Gas Boiler kgCO$_{2e}$	LEDs kgCO$_{2e}$	Roof insulation kgCO$_{2e}$	Double glazed windows kgCO$_{2e}$	Doors kgCO$_{2e}$	Wall insulation kgCO$_{2e}$	Floor insulation kgCO$_{2e}$	MVHR kgCO$_{2e}$	Solar Thermal Panels kgCO$_{2e}$	PVs kgCO$_{2e}$	TOTAL kgCO$_{2e}$	TOTAL kgCO$_{2e}$/m^2
1900-1918	Simple	508	670	698.12	-	-	-	-	-	-	-	1,876	15.22
	Medium	508	670	698.12	4,832	1,915	1,191	-	-	-	-	9,814	79.66
	Deep	508	670	698.12	4,832	1,915	1,191	1,436	1,854	1,440	7,260	21,804	177
1976	Simple	508	670	596.61	-	-	-	-	-	-	-	1774.6	14.40
	Medium	508	670	596.61	4,832	1,915	767.75	-	-	-	-	9,289	75.40
	Deep	508	670	596.61	4,832	1,915	767.75	1,096	1,854	1,440	7,260	20,940	170
2000	Simple	508	670	200.27	-	-	-	-	-	-	-	1,378	11.18
	Medium	508	670	200.27	4,832	1,915	530	-	-	-	-	8,655	70.25
	Deep	508	670	200.27	4,832	1,915	530	-	1,854	1,440	7,260	19,209	156

Table C3: Embodied Carbon Breakdown_Building Materials, 1900-1918 Never Refurbished (Retrofit)

Building Element	Materials	Thickness (m)	Surface Area (m^2)	Volume (m^3)	Density (kg/m^3) *	Mass (kg)	$kgCO_{2e}/kg$**	Embodied Carbon ($kgCO_{2e}$)	Waste Rate (%) ***	Embodied Carbon ($kgCO_{2e}$)	Embodied Carbon $kgCO_{2e}/m^2$
Roof	Expanded Polystyrene (EPS)	0.2	63.85	12.8	15	192	3.29	631.68	5	698.12	5.66
	Plaster (render)	0.005		0.32	800	255.4	0.13	33.2	5		
External Wall	Timber Studding (Hardwood)	0.1	8.4	0.84	500	420	0.24	100.8	5	1190.95	9.66
	Expanded Polystyrene (EPS)	0.1	76.6	7.7	15	116	3.29	381.64	5		
	Plasterboard	0.025		1.92	700	1345	0.39	524.55	22.5		
	Plaster (render)	0.005		0.383	800	306.4	0.13	39.83	5		
Floor	Expanded Polystyrene (EPS)	0.01	63.85	6.38	15	95.77	3.29	315.09	5	1436.13	11.65
	Chipboard	0.035		2.23	430	960	0.39	374.4	5		
	Timber Flooring	0.04		2.55	650	1660	0.39	647.43	10		

**Density values were retrieved from CIBSE Guide A*

Expanded Polystyrene (EPS): Table 3.47, Plaster: Table 3.38, Plasterboard: Table 3.47, Timber Flooring and Chipboard: Table 3.39, Timber studding: Table 3.47

***$kgCO_{2e}$ values were retrieved from Bath ICE Database (Hammond and Jones, 2011).*

****Waste rates are based on data from WRAP (2008).*

Table C4: Embodied Carbon Breakdown_Building Materials, 1976 Refurbishment (Retrofit)

Building Element	Materials	Thickness (m)	Surface Area (m^2)	Volume (m^3)	Density (kg/m^3) *	Mass (kg)	kgCO$_{2e}$/kg**	Embodied Carbon (kgCO$_{2e}$)	Waste Rate (%) ***	Embodied Carbon (kgCO$_{2e}$)	Embodied Carbon kgCO$_{2e}$/m^2
Roof	Expanded Polystyrene (EPS)	0.17	63.85	10.85	15	162	3.29	535	5	596.61	4.84
	Plaster (render)	0.005		0.32	800	255.4	0.13	33.2	5		
External Wall	Timber Studding (Hardwood)	0.1	8.4	0.84	500	420	0.24	100.8	5	767.75	6.23
	Expanded Polystyrene (EPS)	0.08	76.6	6.12	15	92	3.29	302	5		
	Plasterboard	0.0125		0.95	700	670	0.39	261	22.5		
	Plaster (render)	0.003		0.23	800	183.84	0.13	23.90	5		
Floor	Expanded Polystyrene (EPS)	0.11	63.85	7.02	15	105	3.29	346	5	1096.15	8.89
	Chipboard	0.01		0.63	430	271	0.39	105	5		
	Timber Flooring	0.035		2.23	650	1452	0.39	566	10		

**Density values were retrieved from CIBSE Guide A - Environmental Design*
*Expanded Polystyrene (EPS): Table 3.47, Plaster: Table 3.38, Plasterboard: Table 3.47, Timber Flooring and Chipboard: Table 3.39, Timber studding: Table 3.47, Mineral Fibre Board: Table 3.37, **kgCO$_{2e}$ values were retrieved from Bath ICE Database (Hammond and Jones, 2011)*
****Waste rates are based on data from WRAP (2008).*

Table C5: Embodied Carbon Breakdown_Building Materials, 2000 Refurbishment (Retrofit)

Building Element	Materials	Thickness (m)	Surface Area (m^2)	Volume (m^3)	Density (kg/m^3) *	Mass (kg)	$kgCO_{2e}/kg$**	Embodied Carbon ($kgCO_{2e}$)	Waste Rates (%) ***	Embodied Carbon ($kgCO_{2e}$)	Embodied Carbon $kgCO_{2e}/m^2$
Roof	Expanded Polystyrene (EPS)	0.05	63.85	3.19	15	47.88	3.29	157.54	5	200.27	1.62
	Plaster (render)	0.005		0.32	800	255.4	0.13	33.2	5		
External Wall	Timber Studding (Hardwood)	0.1	8.4	0.84	500	420	0.24	100.8	5	530.03	4.30
	Expanded Polystyrene (EPS)	0.02	76.6	1.53	15	23	3.29	75.60	5		
	Plasterboard	0.0125		0.95	700	670	0.39	261	22.5		
	Plaster (render)	0.003		0.23	800	183.84	0.13	23.90	5		
Floor	-	-	-	-	-	-	-	-		-	-

**Density values were retrieved from CIBSE Guide A - Environmental Design*

*Expanded Polystyrene (EPS): Table 3.47, Plaster: Table 3.38, Plasterboard: Table 3.47, Timber Flooring and Chipboard: Table 3.39, Timber studding: Table 3.47, Mineral Fibre Board: Table 3.37, **$kgCO_{2e}$ values were retrieved from Bath ICE Database (Hammond and Jones, 2011)*

****Waste rates are based on data from WRAP (2008).*

Table C6: Embodied Carbon Breakdown for Building Components and Systems

Building Components & Systems	Description & Area (m^2)	Embodied Carbon per surface area ($kgCO_{2e}/m^2$)	Embodied Carbon per system ($kgCO_{2e}$)	Reference	*Waste Rate (%)	Initial Embodied Carbon		Recurring Embodied Carbon	
						$kgCO_{2e}$	$kgCO_{2e}/m^2$	$kgCO_{2e}$	$kgCO_{2e}/m^2$
Windows	Double glazed windows with wooden frames (17.7 m^2)	130	-	Kutnar and Sinha (2012)	5 (115.05)	2416.05	19.61	4832.1	39.22
External Doors	(6 m^2)	152	-	Victoria and Perera (2018)	5 (45.6)	957.6	7.77	1915.2	15.54
PVs	Monocrystalline Silicon (10 m^2)	242	-	BATH, ICE Database (2011) Pelsmakers (2015)	-	2420	19.64	7260	58.92
Solar Thermal Panels	Flat plate collectors (4 m^2)	120	-	Pelsmakers(2015)	-	480	3.89	1440	11.68
Gas Boiler	Condensing gas boiler, heating power<50kWh	-	164.4	Koubogiannis and Nouhou (2016)	3 (4.93)	169.33	1.37	508	4.12
MVHR	-	-	600	Finnegan et al (2018)	3 (18)	618	5.01	1854	15.04
LEDs	Average residential building contains 40 LED lights	-	134	Finnegan et al (2018)	-	134	1.08	670	5.43

**Waste rates are based on data from WRAP (2008).*

APPENDIX D – THERMAL ZONES AND SCHEDULES

Table D1: NCM Project Profile IESVE inputs for different thermal zones

Thermal Zone	NCM Project Profiles		
	Heating Set Point (^oC)	Lighting* Loads (W/m^2)	Equipment Loads (W/m^2)
1) Bedroom	18	5.20	3.85
2) Kitchen	18	15.6	30.28
3) Dining Room	18	7.80	3.06
4) Living Room	18	7.80	3.90
5) Bathroom	18	7.80	1.67
6) Circulation Areas_Halls	18	5.20	1.67

** Fluorescent lighting*