Refurbish or Replace? The Life Cycle Carbon Footprint and Life Cycle Cost of Refurbished and New Residential Archetype Buildings in London

Abstract

The environmental performance of existing buildings can have a major role in achieving significant reductions in CO_2 emissions: In the UK, around 75% 2050's housing stock has already been built. While building performance improvement efforts mostly focus on operational performance, buildings environmental impact is the result of processes that occur throughout their life cycle.

To achieve significant emission reductions in an economically viable way, this study uses Life Cycle Performance approaches to carry a cross-comparison between the refurbishment and replacement of two housing archetypes in London: mid-terrace-house and a bungalow. Specifically, the study integrates Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) protocols (EN 15978:2011 and BS ISO 15686-5), thermal simulations (EnergyPlus), building generative design framework (PLOOTO - Parametric Lay-Out Organisation generator) and mathematical optimisation algorithms (NSGA-II).

Results show that the optimal refurbishment archetypes generally performed better than replacements (Refurbishments LCCF ranges between 1,100-1,500 $kgCO_{2e}/m^2$ and LCC 440-680 £/m^2 , compared to that of the replacements scenarios, ranging 1,220-1,850 $kgCO_{2e}/m^2$ and 550-890 £/m^2). The study also highlights benefit of incentivising re-use to achieve quicker emissions reductions. The study lastly discusses a range of embodied and operational performance issues.

Keywords: Life Cycle Analysis, Refurbishment, Replacement, Embodied Carbon, Whole Life Carbon, Life Cycle Carbon Footprint, Life Cycle Cost, Environmental Impact,

1. Introduction

The built environment is responsible for 40% of the global energy consumption [1]. The global construction industry is also responsible for approximately 40% of raw aggregates consumption and for 25% of the world`s wood consumption [2]–[4]. The UK is one of the world`s highest CO_2-emitting countries [5]. Following the Kyoto protocol of 1992 and the Paris 2015 UN Climate Change Conference, the UK government has committed to reducing at least 80% of its CO_2 emissions, compared to its 1990 baseline figures, by 2050 [1]. The buildings industry, therefore, can play an important role to the success of this commitment.

While much of the effort for improving building energy efficiency has been focused on new buildings, the environmental performance of existing buildings can have a significant environmental impact. In the UK, new buildings account for around 1% of the total building stock every year [6], and around 75% of the housing stock that will still remain in 2050 has already been built [7]. To achieve the UK government`s CO_2 reduction targets in an economically viable way, a detailed investigation is required, aiming to identify the most efficient reduction mechanism: the refurbishment of existing buildings or their demolition and replacement by new ones.

The debate regarding the refurbishment or replacement of existing buildings is highly complex as it involves an examination of a wide range of aspects, both qualitative (social, cultural and aesthetical) and quantitative (environmental or economic) [6], [8], [9]. Furthermore, while the environmental impact of buildings is the result of processes that occur throughout their life-cycle (e.g., construction, use and demolition), current building performance improvement efforts focus mainly on the performance of buildings once they are built and occupied [10]. There is therefore a need for a more holistic and comprehensive approach for clearly defining and evaluating building performance, in the context of their life cycle, to better inform decision makers and stake holders when they are faced with the two design alternatives: refurbishment or replacement.

This study aims to estimate and compare both the environmental and the economic benefits of residential building refurbishments and replacements scenarios. In particular, this study aims at addressing the following question: Is the optimal refurbishment of existing buildings preferable over their optimal replacement, in respect of Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC)?

2. Background

2.1. To Refurbish or to Replace – Review of Evidence

Although both the refurbishment of existing buildings and the construction of new ones have the potential to significantly improve the life cycle impact of buildings [6], [11], [12], the different alternatives have advantages at different stages of the building`s life: while refurbished buildings allow re-using some parts of the existing structures and save part of their embodied resources (carbon and costs), new buildings are likely to have better operational use, due to better potential orientation, flexibility in their spatial arrangement and the integration of advanced building technologies (e.g., highly-efficient Hating Ventilation and Air Conditioning (HVAC systems), better air-tightness, efficient glazing systems etc.).

The nature of the problem, however, makes it hard to gather evidence and reach a clear conclusion: Studies that compare refurbishment and replacements often evaluate the benefits of each alternative differently. Aspects such as energy, CO_2 and cost are often examined, but also are social, aesthetical, and cultural ones. In many cases conclusions are drawn based on very limited evidence or quantified analysis, and while most studies suggest that refurbishments could be preferable over refurbishment - evidence for the balance between the potential life cycle performance of the different design alternatives is still unestablished [6], [13].

Some studies did examine the potential benefits of refurbishment or replacements by examining case study buildings. These case studies can be categorized into three different groups, reflecting their overall conclusion (Table 1):

Study	Replacement	Refurbishment	Ambiguous
ARUP, Capital & Government (2010)			X
Alba-Rodríguez (2017)		X	
Boardman et al. (2005)			X
Ding (2013)		X	
Empty Homes Agency (2008)			X
Erlandsson & Levin (2004)		X	
Gaspar & Santos (2015)		X	
Hawkins & Mumovic (2014)	X		
Itard & Klunder (2007)		X	
Rønning et al. (2009)	X		

Table 1: To refurbish or to Replace? - Current debate

- *Evidence in support of Replacement*: Rønning et al. [21] presented a comparison between the refurbishment and replacement of an existing office building in Norway. The study concluded that a replacement was preferable in terms of LCCF over an assumed 60 years life span, with an expected CO_2 payback time of 15 years. Hawkins & Mumovic [19] analysed the 60 years LCCF of two university building case studies by comparing the performance of four refurbishment scenarios and one replacement alternative, and concluded that the new-built scenarios achieved the biggest impact reductions.

- *Evidence in Support of Refurbishment:* A study by Itard & Klunder [20] examined different life cycle aspects of two post-war residential blocks in the Netherlands. The study examined four different scenarios on each building (simple maintenance, envelope refurbishment, extensive intervention and complete replacement), and showed that replacement was the least favourable option. Other studies [17], [18] compared the refurbishment and replacement of case studies in Sweden and Portugal. Both concluded that refurbishments had better life cycle performance. Using a more complete analysis approach, Ding [11] compared refurbished, reconstructed (new-built, but with the same style as the refurbished ones) and a complete new-built design, and concluded that the refurbishments scenario had performed best. Another study [22] examined the refurbishment and replacement of an existing residential block in Spain that had been damaged during construction, and showed that even in the case of a severely damaged building, the refurbishment alternative resulted with a better environmental and economic impacts.

- *Ambiguous Results:* A report by the Empty Homes Agency [16] examined the LCCF of six residential buildings in the UK (three newly built and three refurbished), over an assumed life span of 50 years. The study showed that the difference between the LCCF of the new built and the refurbished buildings were negligible. Another study by ARUP [14] examined three scenarios (maintenance, small refurbishments and a state-of-the-art replacement) over the life time of an existing office building. Analysis showed that demolishing a well-performing building made no sense in terms of life cycle performance, whereas in the case of poor performing buildings – replacement by an efficient new design might be the better solution. Boardman et al. [15] presented a "bottom-up" UK building stock model, and concluded that while most existing buildings can be refurbished, the worst-performing buildings (14% of the entire stock) should be replaced.

It is noted, though, that even when analysing the performance of case study buildings, most studies compared the performance of a refurbished building with a small number of replacement alternatives (a single replacement design, in most cases). A large number of scenarios were not explored, and as a result there is no way to verify that the best design alternatives had been compared.

3. Methodology

3.1. Study Design

The review of literature has pointed out that even when analysing the performance of case study buildings, most studies compared the performance of a refurbished building with a small number of replacement alternatives (a single replacement design, in most cases). An analysis of a large number of refurbishment / replacement scenarios can be challenging, and as a result there was no way to verify that the best design alternatives had been compared.

Finding an optimal design for a building may be a lengthy and intensive task – it aims at finding the building (or buildings) with the best possible performance. In some cases, means that a comparison between the performance of a very large number of potential designs should be carried. Specifically, when approaching the design of a new building, the number of possible designs can be very large – depending on a set of design limitations (e.g., site boundaries, building and rooms use, rooms proximities and adjacency etc.). Furthermore, while involved in the design procedure, designers' preconceptions may be involved towards a favourable design, while other design solutions might, in fact, perform better.

To enable an exploration of the full potential of the design spaces, an automated process of generating and optimising building layouts, could help in designing highly efficient buildings. To compare the life cycle performance of the optimal refurbishment and that of the optimal replacement, this study used PLOOTO (Parametric Lay-Out Organisation generaTOr) – a framework for generating and optimising building layouts in terms of life cycle performance. The principles behind the framework have been discussed extensively in [23]–[25]. The study design is described in Figure 1.

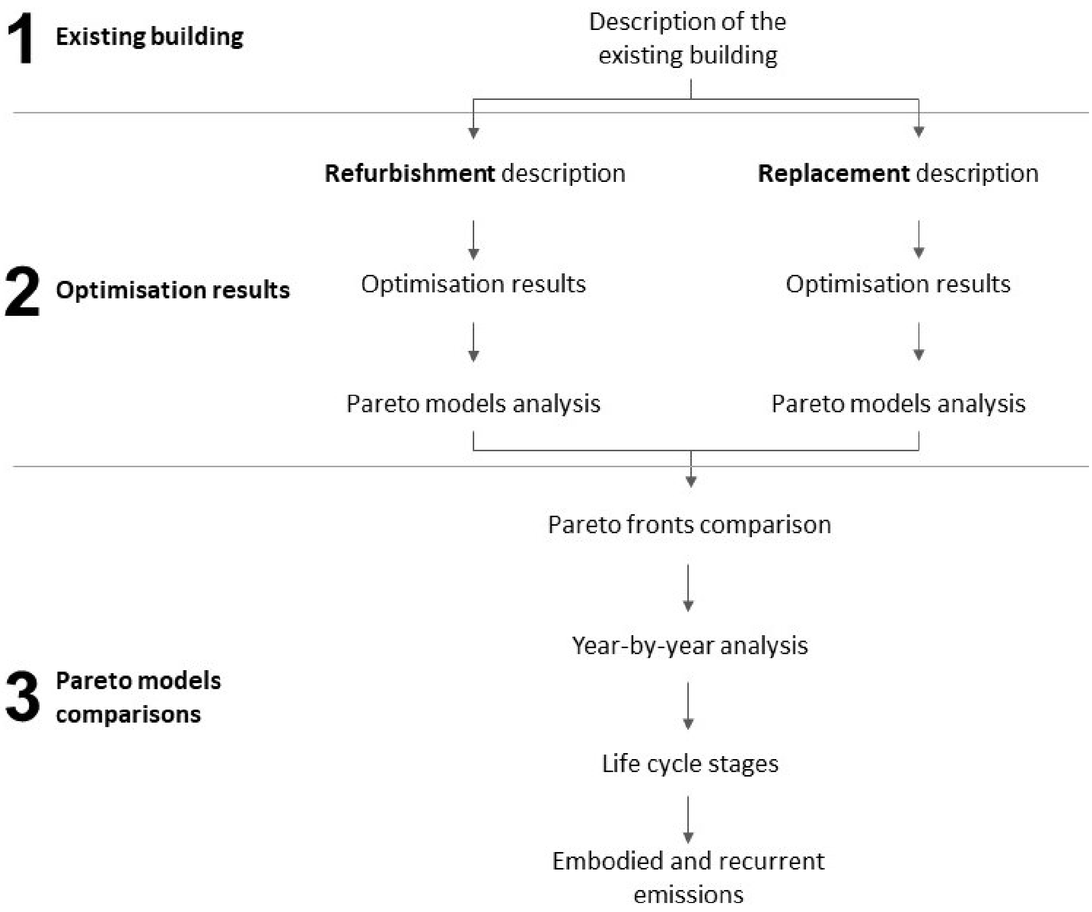

Figure1: Study design – a comparative simulation and analysis

3.2. Tools and Frameworks

To automate the process of optimising building designs by their Life Cycle Carbon Footprint and Life Cycle Cost, four themes were used in a synthesised manner in this study:

- *Life Cycle Performance*: Buildings' 'performance' in this study was evaluated in respect of their life cycle and estimated their LCCF (Life Cycle Carbon Footprint) and LCC (Life Cycle cost). EN 15978:2011 (Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method) [26] was used for estimating LCCF figures. The protocol identified five main life-stages: product, construction, usage, end-of-life, and recycling, as shown in Figure 2. CO_2 emissions figures should be calculated at each stage and finally summarised, to get an estimation of the total emissions over the life of the building. ISO 15686-5 (Building and constructed assets - Service life planning) [27] was used for LCC calculation. The protocol details the principles of life cycle costing for buildings and construction assets during construction and operation, and has been widely used by leading professional organisations across the UK [28], [29].

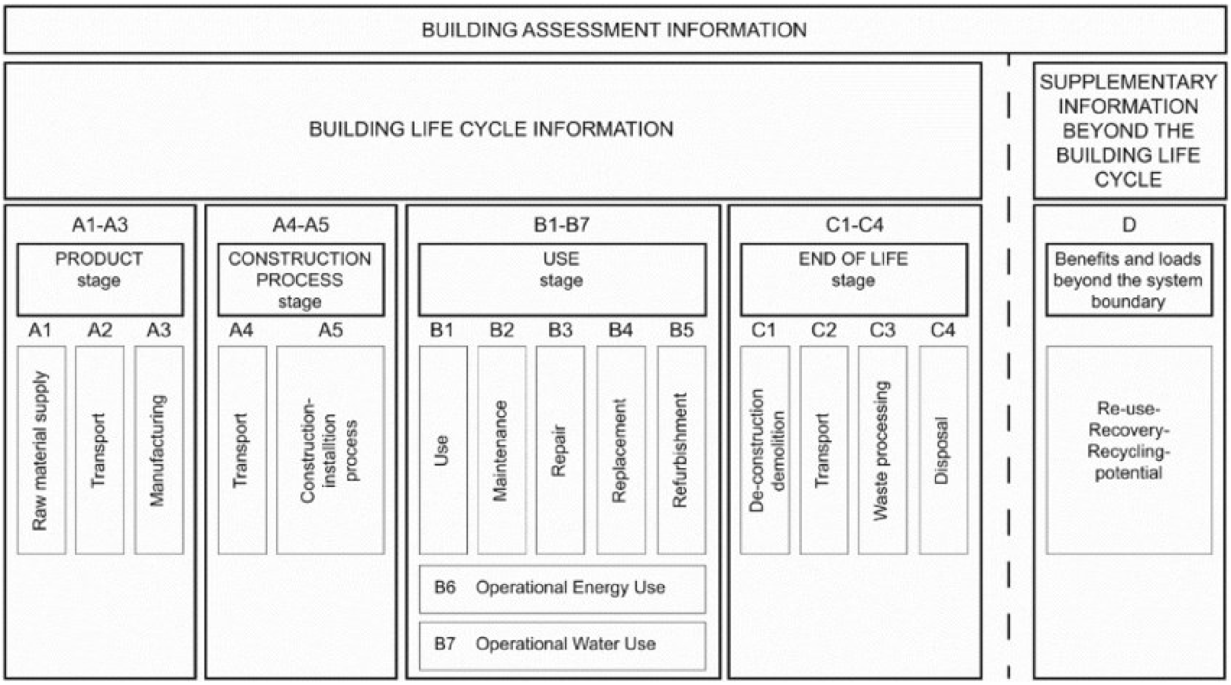

Figure 2: Building life cycle, according to EN 15978:2011 [26]

- *Thermal Simulations:* To estimate the LCCF and LCC values, operational energy use should be calculated (for space, water heating and lighting). The required the integration of a thermal simulation tool within the framework. EnergyPlus [30] – one of the most commonly used dynamic thermal simulation tools was used to estimate overall consumptions.

- *Generative Design*: PLOOTO [23]–[25] was used to perform a comparison between the performance of refurbished buildings with that of new ones. This involved the development of a generative-design algorithm, that integrated the generative procedure and thermal simulation tool (EnergyPlus) using EPPY – an EnergyPlus/Python library [31].

- *Mathematical Optimisation Frameworks:* To enable a faster evaluation of the life cycle performance of a large set of models, mathematical optimisation frameworks offer an efficient and rapid search for optimal solutions [32]–[34]. The optimisation component of PLOOTO uses a Genetic Algorithm (GA) application has been developed, based on Non-Sorting Genetic Algorithms – II (NSGA-II) [23]–[25].

4. Implementation

4.1. Life Cycle Impact Assessment

To test the case studies, the buildings life cycle scopes are described in Table 2, for both LCCF and LCC. The scope description is based on the BS EN 15978:2011. Sources of CO_2 emissions and costs data for the different scenarios and the different building materials are presented Tables 3 and 4 and Tables 6-8.

Table 2: Study life cycle scope (based on BS EN 15978:2011)

	A1-A3 Product stage			**A4-A5 Construction**		**B1-B7 Use**							**C1-C4 End of Life**			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
	Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal
LCCF	✓	✓	✓	✓	✓				✓		✓	✓	✓	✓	✓	✓
LCC	✓	✓	✓						✓		✓	✓				

Table 3: Life cycle-scope assumptions

Life Cycle Stage	Data source and references: CO_{2e} *emissions*	Data source and references: Costs
A1 + A2 + A3	EPD, Bath ICE [35]. Geometries based on the .IDF model (replacement rates and waste rates applied)	Building components and materials cost. Geometries based on the .IDF model (replacement rates and waste rates applied)
A4	3% from overall Embodied CO_{2e}*	Out of the scope of this study
A5	7% from overall Embodied CO_{2e}*	Out of the scope of this study
B4	EPD and Bath ICE [35]. Assumed life expectancy [36]–[38]	EPD and Bath ICE [35]. Assumed life expectancy [36]–[38]
B6	Space heating - EnergyPlus simulation. Electricity for lighting – manual calculation	Space heating - EnergyPlus simulation. Electricity for lighting – manual calculation
B7	Based on [39]	Based on [39]
C1 +C2 + C3 + C4	2% from overall Embodied CO_{2e}*	Out of the scope of this study

* *Based on* [40]–[44]

Table 4: Modelling and simulation assumptions and data sources

Modelling assumptions	Data source and references
Assumed building life span	60 years [45]
Energy cost increase, on top of inflation	10% every 5 years [46]
Discount rate (for NPV calculation)	3% (BSRIA, 2016)
Gas emission rates	0.216 $kgCO_{2e}/kWh$ [47]
Gas cost (including assumed annual standing charge and VAT)	0.045 £/kWh [48]
Electricity emission rates	0.519 $kgCO_{2e}/kWh$ [47]
Electricity cost (including assumed annual standing charge and VAT)	0.16 £/kWh [48]
Assumed boiler life span	15 years
Boiler unadjusted cost	£2,000
Initial boiler efficiency	93%
Annual reduction in boiler efficiency	1% [49]
Weather file	London Gatwick. epw
Heating set points for the different rooms, domestic hot water consumption and internal loads	All based on the NCM (National Calculation Method) [47]

The generation of models and the evaluation of their LCCF and LCC was carried out in an automated manner by PLOOTO and its NSGA-II optimisation application. To calculate models' embodied performance, the application identified the modelled building materials and their quantities, and then sums up their associated embodied CO_2 and costs (including CO_2 incurred by replacements, waste, and transportation., as described in Tables 2 – 4). For their operational performance, models were simulated in EnergyPlus, to estimate their energy consumption. Following the Building Research Establishment's (BRE) Green Guide for Specification [45], it is assumed that the buildings' service life is 60 years. Relevant operational CO_2 and energy costs values were assigned to each model and added to those of the embodied figures. LCCF and LCC were calculated using the following formulas:

$$LCCFi = \sum(Eip + Eit + Eic + Eir + Eio + Eieol) \qquad (1)$$

Where:

LCCFi = Life Cycle Carbon Footprint –Emissions per total floor area ($kgCO_{2e}/m^2$) of the i'th model

Eip = Emissions due to overall building materials production and manufacturing

Eit = Emissions due to transport to site

Eic = Emissions due to construction works on site

Eir = Emissions due to replacements works

Eio = Emissions through the operational stage of the building (lighting, space and water heating)

Eieol = Emissions through the End of Life stage and disposal of the building

$$LCCi = \sum (Cip + Cir + Cio) \qquad (2)$$

Where:

LCCi = Life Cycle Cost - Cost per total floor area (£/m^2) of the i'th model

Cip = Cost of overall building materials

Cir = Cost related to replacements works

Cio = Overall cost of the operational stage of the building (lighting, space and water heating over 60 years)

4.2. The Existing Buildings

4.2.1. Geometry

In a study by Oikonomou et.al. [50], nine ‘geometric archetypes’ which represent around 76% of the London housing stock were identified. For this study, two of those architypes were selected to be used as case studies, for compare the life cycle performance of their refurbishment and replacement. The selection of these architypes was based on a combination of how common these buildings are within the London housing stock, how different their layouts and spatial arrangements are, and based on expected difference in their thermal performance (because of differences in their surface-to-volume ratio for example). The selected geometric architypes are:

A Mid-Terrace House: A two-storey building, in which the living space, kitchen and dining rooms are placed at the ground floor while the bedrooms are located at the first floor (Figure 3). According to Oikonomou et.al. [50], nearly 45% of the housing units in London are a variation of a mid-terraced house. This archetype shares two partitions (party-wall) with its neighbouring buildings, and has only three exposed surfaces – roof, front, and back façade (In thermal modelling, it is assumed that these walls are adiabatic – there is no heat is transferred between the houses). This means that, in terms of thermal efficiency, this is considered to be a relatively efficient housing units, as it has minimal exposed surface through which heat can escape. In terms of construction costs – since external walls tend to be typically more expensive (as they may have better finishes and sometime fenestration), this archetype is also considered to bare lower use of materials and construction costs.

A Bungalow House: A single storey building in which all rooms are placed on the ground floor. A bungalow house is a stand-alone structure. This means that all its external walls are exposed to the local external climate conditions, and heat transfer occurs throughout its entire envelope. While Bungalows are not a very common housing form in London, they are analysed here as they are considered to be an exact opposite of the terraced house, in terms of environmental and economic efficiencies. As bungalows are typically spread over a single floor, their compactness is low, and they have a high surface-to-volume ratio. The more external envelope they have – the more heat transfer would occur, and more energy would be required for maintaining occupants' thermal comfort. Larger surface area also means higher costs for building construction.

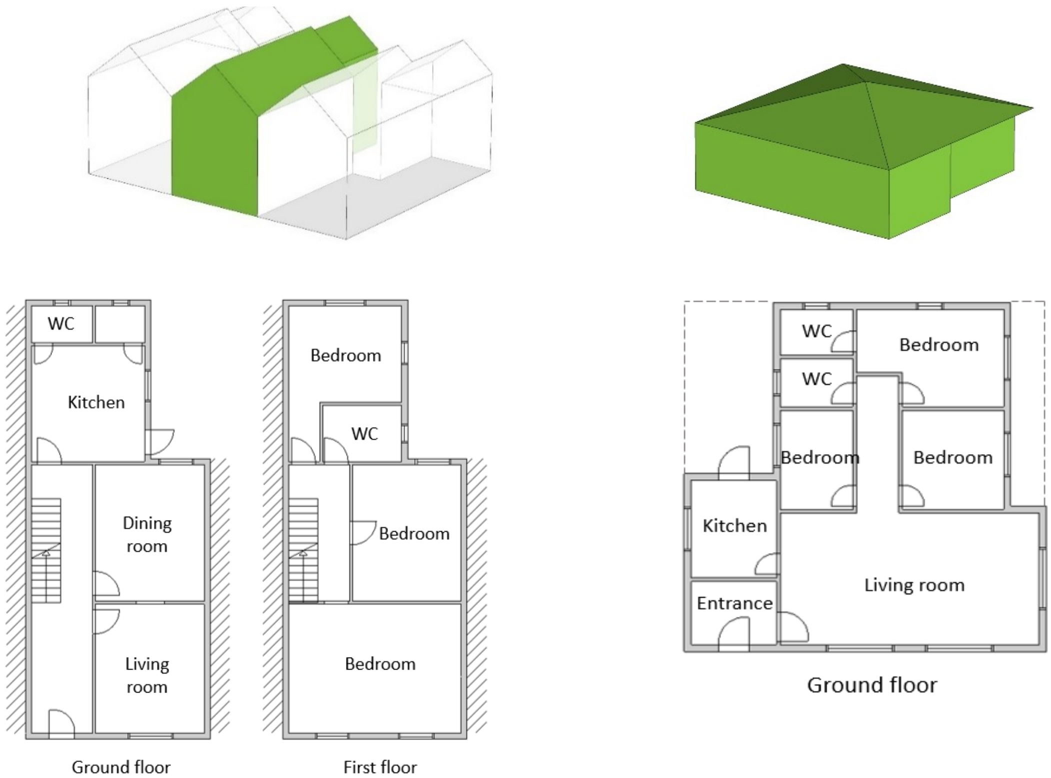

Figure 3: The existing-buildings case studies. Mid-terrace house (left) and the Bungalow house (right) [50].

4.2.2. Materials

The assumed build-ups for the original case studies are presented in Table 5. It is assumed that the structure of the buildings is a mix of bricks (for external walls), concrete (for the ground floor slabs) and timber (internal partitions, roofs, and external walls' sub-structure).

The assumed build-ups of the original buildings were used for calculating the embodied CO_2 of the existing buildings. These are taken into consideration as a preliminary "demolition" of existing building elements (in the case of a refurbishment), or of the entire building (in case of a replacement). These demolitions are inseparable from the analysis, as they allow for the refurbishment or the replacement to take place, and without them – new construction could not be carried out.

Table 5: The assumed build-ups of the existing buildings

External wall	Internal wall	Internal floors	Ground floor	Roof	Windows	Structure
Brick + structure Plasterboard Render	Render Plasterboard Mineral Wool Sub-structure Plasterboard Render	Render Plasterboard MDF + structure Hardwood	Ground Screed Sub-structure Hardwood	Roof Slate Sub-structure Plasterboard Render	Single glazed timber frame	Reinforced Concrete, Timber joists at 40 cm intervals

4.3. The Refurbishment & Replacement Scenarios

In developing the refurbishment and replacement scenarios, it is important to note that each build-up alternative was made to meet at least the minimal relevant standards: The standards for improving retained thermal elements, as described in approved document L1B: Conservation of fuel and power in existing buildings [51] for the refurbishment scenario, and the notional building parameters, as stated in approved document L1A: Conservation of fuel and power in new dwellings [10] and the Standard Assessment Procedure (SAP) [52] for new ones.

4.3.1. Refurbishment

The refurbishment scenario in each case study is based on the same layout as that of the existing building. As part of the optimisation process, a variety of build-ups is suggested, each with different embodied CO_2 and cost values. The alternative build-ups for the refurbishment scenarios are described in Table 6. It is assumed that structural external brick walls, ground floor screed and all timber constructions (highlighted elements in Table 6) are kept untouched, and all other materials are replaced. This means that the embodied CO_2 of these material was not taken into account when carrying the LCCF analysis.

Table 6: Refurbishment building components & build-ups. (materials that were kept in the refurbishment scenario are highlighted)

Building element	Construction 1	Construction 2	Construction 3	Construction 4	Construction 5
Roof	Plasterboard + render	Mineral wool / XPS / EPS	Ceramic tiles / Slate / Fibre cement		
Ext. wall (a)	Plasterboard + render	Mineral wool / XPS / EPS	Brick structure		
Ext. wall (b,c)	Plasterboard + render	Brick structure	Mineral wool / XPS / EPS	Aluminium cladding / Plasterboard + render	
Party wall	Plasterboard + render	Mineral wool / XPS / EPS	Brick structure		
Ground floor	Wood flooring / Carpet	MDF	Mineral wool / XPS / EPS	Screed	Ground
	Concrete	Mineral wool / XPS / EPS	Screed	Ground	
Internal partitions	Plasterboard + render	Timber structure	Sound insulation	Plasterboard + render	
Internal floor/ceiling	Wood flooring / Carpet / Laminated flooring	MDF	MDF + Timber structure	Mineral wool / XPS / EPS	Plasterboard + render
Window	Timber / uPVC / Aluminium frame	Double-glazed pan			

4.3.2. Replacement

For the replacement scenario, it is assumed that the entire existing building is removed and replaced. This means that the embodied CO_2 of the entire building is added to the LCCF analysis, as otherwise the new building cannot be built. For the optimisation procedure, a number of build-ups are defined, as described in Table 7.

Table 7: Replacement building components & build-ups

Building element	Construction 1	Construction 2	Construction 3	Construction 4	Construction 5
Roof	Plasterboard + render	Mineral wool / XPS / EPS	Ceramic tiles / Slate / Fibre cement		
Ext. wall	Plasterboard + render	Mineral wool / XPS / EPS	Brick/Aluminium cladding / Plasterboard + render		
Party wall	Plasterboard + render	Mineral wool / XPS / EPS	Brick		
Ground floor	Wood flooring / Carpet	MDF	Mineral wool / XPS / EPS	Screed	Ground

	Concrete	Screed	Mineral wool / XPS / EPS	Ground
Internal partitions	Plasterboard + render	Sound insulation	Plasterboard + render	
Internal floor/ceiling	Wood flooring / Carpet / Laminated flooring	MDF	Mineral wool / XPS / EPS	Plasterboard + render
Window	Timber / uPVC / Aluminium frame	Double-glazed pan		

4.4. Modelling & Simulation Assumptions

Other modelling and simulation assumptions, particularly thermal properties, embodied carbon values, assumed life span, occupancy schedules and internal gains are shown in Tables 8 and 9.

Embodied Carbon: Figures for embodied carbon were based on Bath ICE [35] – one of the UK's most well-established data base for embodied carbon of construction materials. When data for specific construction elements were not available, Environmental Product declarations (EPD) were used (Appendix A).

Life Span: The life span of construction materials may have an important impact on buildings' life cycle performance and on design decision making. Frequent replacement of construction elements may increase the building's life cycle carbon and costs. On the other hand, elements with long life span may have higher embodied carbon and initial costs, as they are design to be more robust and last longer. In this study, the life spans of each construction element were identified [53]-[55]. Once a material reached its lifespan, it is assumed that it is replaced, so that the rate of replacement will be reflected in the life cycle carbon and cost calculations (e.g., if an element's life span is a third of that of the building's – it is assumed that this element is replaced twice throughout the building's life. The replacements' embodied carbon and cost are therefore added to the life cycle analysis).

Waste Rate: Construction waste is an important issue in life cycle analysis, as some construction materials are prone to have higher waste than others. In this study, waste rates were obtained from [56]-[58]. To account for the waste rate, the percentage of waste (ratio) was added to the overall embodied carbon and costs of each element that was used in the building, both in the construction and in the replacements phases (if an element’s life span was shorter than the building’s). This gives a more accurate description of the real embodied carbon and costs of construction decision making.

Costs: Costs were assigned for each construction element based on Spon`s Architects` and Builders` Price Book’ [59] – a costing guide which is frequently used in practice.

Table 8: Materials data

Material name	**Thickness (m)**	**Embodied Carbon ($kgCO_2e/kg$)***	**Density (kg/m^3)**	**Life Span (years)****	**Waste rate (%)*****	**Cost (GBP/m^2)******
Plasterboard	0.0125	0.302	668	75	22.5	8
Mineral Wool 100mm	0.1	1.37	19.5	100	15	6
XPS 50mm	0.05	2.82	35	100	5	11
EPS 100mm	0.1	3.17	25	100	5	7
Concrete 100	0.1	0.107	2400	75	5	25
Ground (London Clay)	1	0	0	100	0	0
Brick	0.102	0.158	1550	100	20	45
Aerated Block	0.1	0.28	600	100	20	20
Screed	0.2	0.25	2300	75	5	150
Clad Cement Board	0.008	0.724	1700	45	8	45
Clad Aluminium	0.0009	11	2700	43	8	35
Roof Ceramic Tiles	0.013	0.48	1600	45	8	35
Roof Slate	0.008	0.04	2850	74	8	75
Roof Fibre Cement	0.008	2.8	1700	45	8	50
Flooring Hardwood	0.02	1.09	750	39	10	70
Flooring Laminated wood	0.005	3.3	600	20	10	25
Flooring Carpet (nylon)	0.01	4.5	400	10	5	38
MDF	0.01	1.2	700	39	10	6
Mineral Wool 75mm	0.075	1.37	19.5	100	15	5
EPS 75mm	0.075	3.17	25	100	5	6
Plaster (render)	0.02	0.13	668	39	5	15
Sub structure timber (@ 0.6 length, 1m height)	0.05	1.09	750	100	15	8

* Embodied Carbon is based on : [35] and EPDs (Appendix A).
** Life span based on: [53]–[55]
*** Waste rates based on: [56]–[58]
**** Costing data based on: [59]

Table 9: Occupancy and Lighting schedules, Internal loads and thermostats. Values range between 0 – 1, when 0 means 0% (or 'off') and 1 means 100% (or 'fully on'). 'Temp' = temperature [47], [60].

Schedule name	Kitchen		Bedroom		Circulation/Toilet		Livingroom	
	Time	Entry	Time	Entry	Time	Entry	Time	Entry
Occupancy schedules								
Occupancy hours	00:00 – 07:00 07:00 – 10:00 10:00 – 20:00 20:00 – 23:00 23:00 – 24:00	0 1 0 0.2 0	00:00 – 07:00 07:00 – 08:00 08:00 – 09:00 09:00 – 22:00 22:00 – 23:00 23:00 – 24:00	1 0.5 0.25 0.0 0.25 0.75	00:00 – 07:00 07:00 – 10:00 10:00 – 20:00 20:00 – 23:00 23:00 – 24:00	0 1 0 0.2 0	00:00 – 16:00 16:00 – 19:00 19:00 – 22:00 22:00 – 24:00	0 0.5 1 0
Lighting	00:00 – 07:00 07:00 – 10:00 10:00 – 20:00 20:00 – 23:00 23:00 – 24:00	0 1 0 1 0	00:00 – 07:00 07:00 – 09:00 09:00 – 19:00 19:00 – 23:00 23:00 – 24:00	0 1 0 0.2 0	00:00 – 07:00 07:00 – 10:00 10:00 – 19:00 19:00 – 24:00	0 1 0 1	00:00 – 16:00 16:00 –23:00 23:00 – 24:00	0 1 0
Equipment	00:00 – 07:00 07:00 – 10:00 10:00 – 19:00 19:00 – 23:00 23:00 – 24:00	0.07 1 0.07 0.25 0	00:00 – 07:00 07:00 – 09:00 09:00 – 17:00 17:00 – 20:00 20:00 –22:00 22:00 - 24:00	0.07 1 0.07 0.5 1 0.5	00:00 – 07:00 07:00 – 09:00 09:00 – 17:00 17:00 – 20:00 20:00 –22:00 22:00 - 24:00	0.07 1 0.07 0.5 1 0.5	00:00 – 16:00 16:00 – 18:00 18:00 – 22:00 22:00 – 23:00 23:00 – 24:00	0.07 0.5 1 0.7 0
	Time	Temp	Time	Temp	Time	Temp	Time	Temp
Thermostat	00:00 – 05:00 05:00 – 10:00 10:00 – 17:00 17:00 – 23:00 23:00 – 24:00	12°C 18°C 12°C 18°C 12°C	00:00 – 09:00 09:00 – 20:00 20:00 – 24:00	18°C 12°C 18°C	00:00 – 05:00 05:00 – 10:00 10:00 – 17:00 17:00 – 23:00 23:00 – 24:00	12°C 18°C 12°C 18°C 12°C	00:00 – 14:00 14:00 – 23:00 23:00 – 24:00	12°C 21°C 12°C
Internal loads								
Electric Equipment [W/m^2]	30.28		3.58		2.16		3.9	
People [W/zone]	120		220		110		220	
Lighting [W/m^2]	8		2.8		2.8		4.1	

5. Results

The comparison between the life cycle performance of the refurbishments and the replacements of the case studies is presented below. It is important to note that each scenario (refurbishment or replacement) was simulated three times, to ensure that the optimisation procedure did not get stuck in a 'local optimum', and to increase the likelihood that a global optimal design has been found. In all case studies, all three runs got the same results. For convenience, only one set of results is presented here.

5.1. Case Study 1: Mid-Terrace House

5.1.1. The Case Study Models

- *The Refurbishment Model:* For the thermal simulations and optimisation process, the case study building was divided into separated thermal zones. The model generation and optimisation assumed that each thermal zone would have one window, and that these windows could only be installed on external walls which are also non-partition wall.

- *The Replacement Model:* For the life cycle impact assessment of the replacement buildings, new building designs had to be generated and their performance had to be evaluated. Any new design had to be of a similar program, size, and volume as those of the original existing building. Therefore, possible room dimensions were identified based on the original case-study building, and a proximity matrix was set to describe desired room adjacencies, as shown in Table 10. These inputs were then inserted to PLOOTO for the generation of different floor layouts and spatial arrangements. PLOOTO had generated 32 building layouts, as seen in Figure 4. It is noted that the layout of the original building was also found by PLOOTO. This means that a scenario in which the existing building is demolished and replaced by a new building of the same layout was also examined.

Thermal Zone			**Width**		**Length**		**Adjacent to room**
			Minimum	**Maximum**	**Minimum**	**Maximum**	
Ground floor	1	Living	600	600	360	440	4
	2	Dining	360	440	360	440	3, 4
	3	Kitchen	360	440	360	440	2, 4
	4	Core (stairs)	160	240	360	440	1, 2, 3,
1st floor	5	Bedroom 1	600	600	360	440	8
	6	Bedroom 2	360	440	360	440	8
	7	Bedroom 3	360	440	360	440	8
	8	Core (stairs)	160	240	360	440	5, 6, 7

Table 10: Case study 1 - PLOOTO inputs – possible room dimensions and proximity matrix

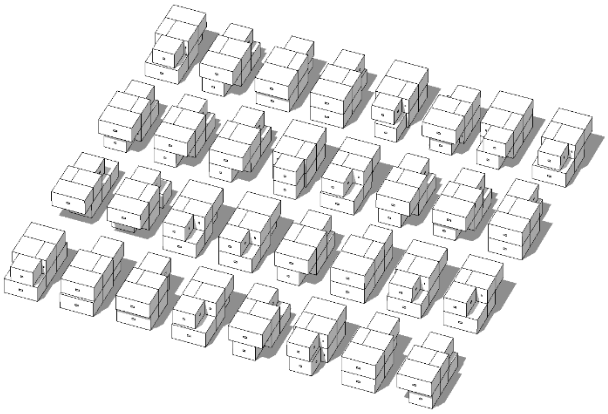

Figure 4: PLOOTO outputs – the 32 new-build terrace house designs

5.1.2. Optimisation Results and Pareto Fronts

A. Refurbishment

The optimisation results are presented in Figure 5. Results indicate that the optimisation resulted a pareto front of 5 pareto-optimal models. The LCCF range of the pareto-optimal models is between around 1,100 – 1,170 $kgCO_{2e}/m^2$, and the range of LCC is between 440 – 510 £/m^2.

An examination of the refurbishment pareto-optimal models shows that all models had the same partition wall and internal floor/ceiling (mineral-wool insulation, laminated flooring finish), and the same ground floor build-ups (mineral wool insulation and a concrete finish). Furthermore, all zones had the same window orientations (south and east) and minimal window-to-wall ration (25%) throughout the building. The optimal model differed with their external wall and roof build-ups, as well as with their window frame materials.

B. Replacement

Figure 5 also shows that the replacement optimisation runs have reached 12 optimal models. Replacements pareto-optimal models LCCF and LCC range between around 1,220 – 1,270 $kgCO_{2e}/m^2$ and 550 – 620 £/m^2. All the replacements pareto-optimal models shared some properties: All had the same external and party walls (rendered finish with mineral wool insulation), floor/ceiling build-ups (laminated finish), and window orientations (south-facing windows, whenever possible).

Interestingly, all pareto-optimal models had the same building geometry (as shown in Figure 6)– which was proven to result with the best performance among all examined layouts. The pareto-front models differed however, in their roof, ground floor slab build-ups and windows constructions, and in the kitchen`s south-facing window-to-wall ratio. It is acknowledged that the geometry that had been selected as the optimal one in terms of LCCF and LCC might have a range of other shortcomings (e.g., architectural appearance, daylight distribution etc.). It is, however, pointed out that while other objectives can potentially be integrated into the optimisation process – the current study is focused on LCCF and LCC solely.

C. Pareto-Fronts Comparison

A comparison between the pareto fronts of the refurbishment and replacement scenarios (Figure 5) shows that under the analysis scope and the constrains of this study, the optimal refurbishments is found to be favourable: The average optimal refurbishment reaches around 10% lower carbon footprint values and achieved around 20% lower life cycle costs, compared to those of the optimal replacements, with average LCCF figures of 1,134 and 1,244 $kgCO_{2e}/m^2$ for the refurbishment and replacement respectively, and average LCC values: 473 and 586 £/m^2.

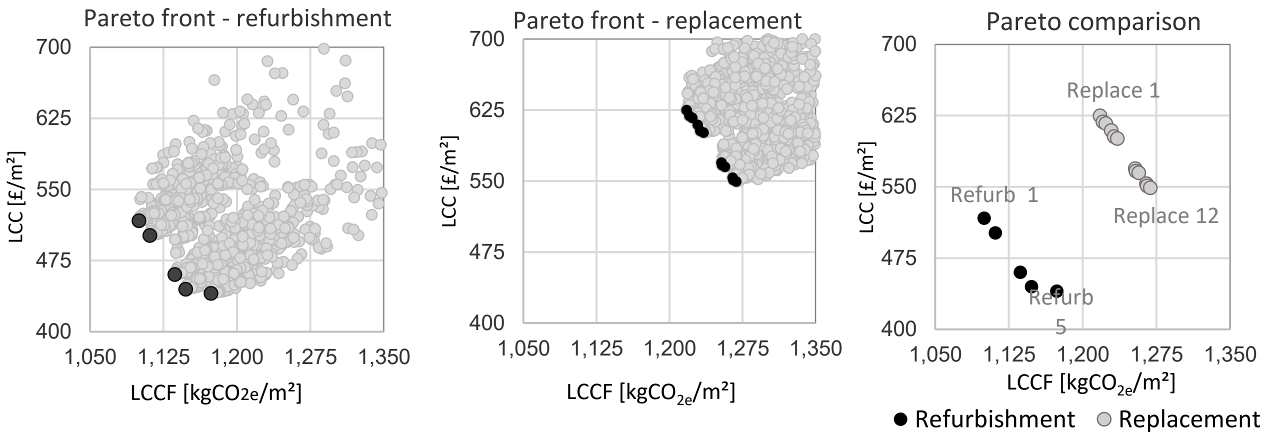

Figure 5: Terrace house refurbishment (left), replacement (middle)optimisation – LCCF/LCC over 60 years.

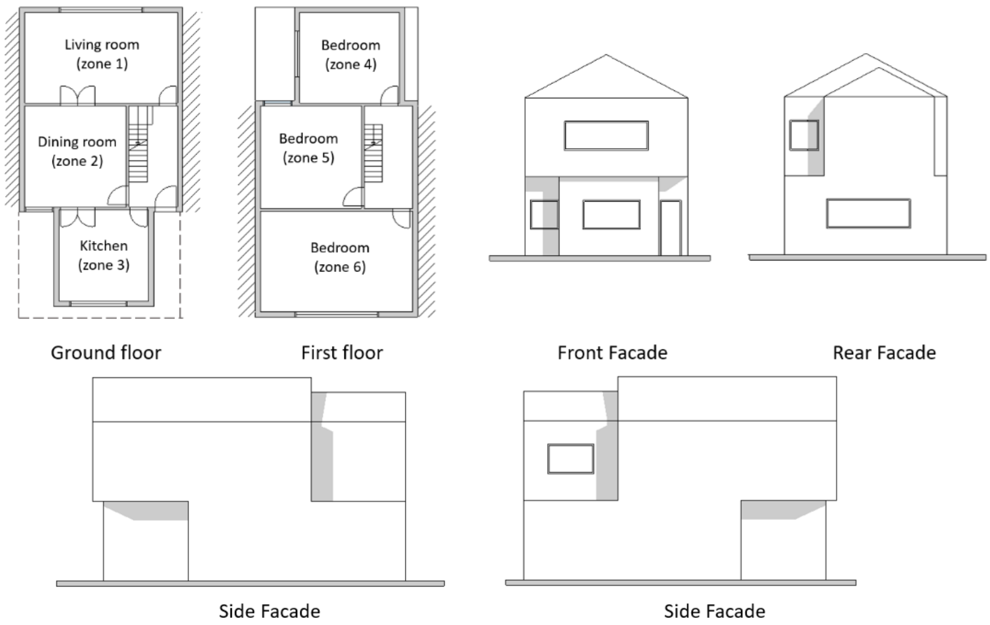

Figure 6: The optimal mid-terrace replacement layout, elevation, and thermal zones

5.1.3. Life Cycle Stages Comparison

A. Life Cycle Carbon Footprint

A comparison between the LCCF of the refurbishment and replacement best pareto-optimal models was carried. Findings (Figure 7) indicate that the refurbishment scenario retained around two thirds of the original building`s embodied CO_2 - around 50 $kgCO_{2e}/m^2$ out of the original building's 160 $kgCO_{2e}/m^2$ were replaced in the refurbishment process). Also, results show that while the replacement alternative performs 20% better in terms of space heating emissions (B6) - its overall performance (embodied carbon included) is still worse than that of the refurbishment.

B. Life Cycle Cost

A comparison between the refurbishment and replacements LCC (Figure 8) shows that for both scenarios, the initial investment (product and construction) has the highest costs throughout the optimal buildings' lives. While there is a significant difference between the initial investments (stage A in figure 7) across the two scenarios, their operational performance is similar: the annual spending for heating and lighting (B6+B7) in the replacement building is lower than those of the refurbishments, but the savings are as little as around £11/m^2/60 years (or, around £1,500 over the lifetime of the building). This is associated with the good thermal performance of the refurbishment scenario – which is very similar to that of a new construction - as designed to comply with the UK building regulations for refurbishments.

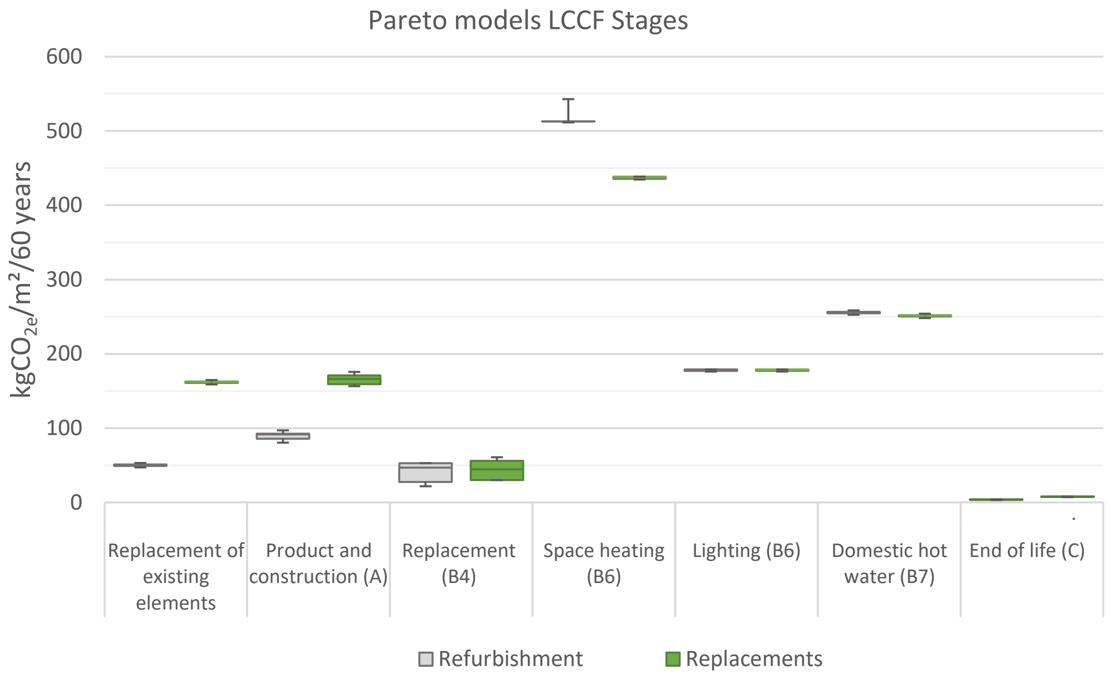

Figure 7: Terrace house refurbishment and replacements life cycle CO_2 stages breakdown

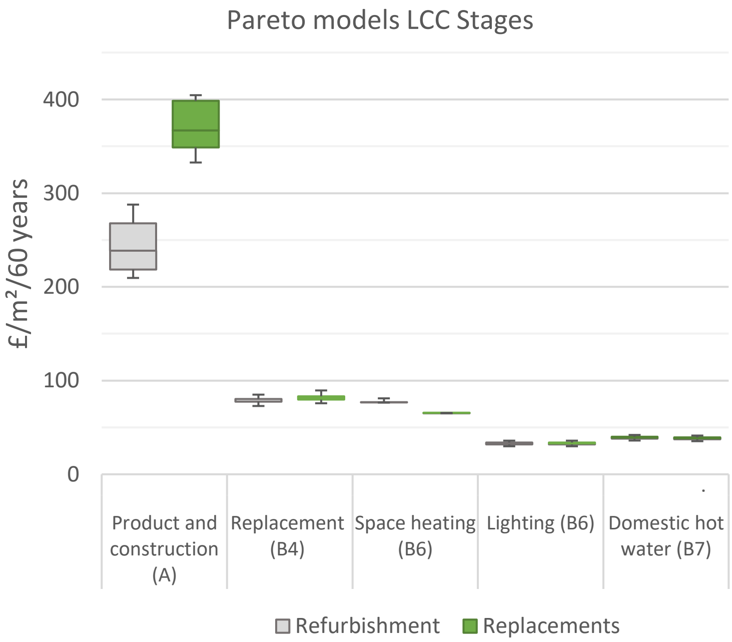

Figure 8: Terrace house refurbishment and replacements life cycle cost stages breakdown

C. Embodied and Operational Performance

When comparing the ratio of the embodied and operational CO_2 and cost outputs for the different scenarios, Figure 9 shows that the operational stage of the optimal buildings is responsible for most to their life cycle performance impact (84% for refurbishments and 70% for replacements on average). This is well aligned with the results of existing literature [61]. In contrast, the initial capital investment is the component that has the largest part of the buildings` LCC (69% for refurbishments and 77% for replacements). It is suggested that the different trend, when comparing the ratio of LCCF and LCC components, is due to the relatively low cost of a unit of energy (gas / electricity), whereas their emission rates are relatively high.

It is also noted that the environmental contribution of the 'replacement of existing elements' (i.e., the buildings elements that had been removed to allow the refurbishment or the replacement), account for only 4% in the case of refurbishment and 13% in the replacement.

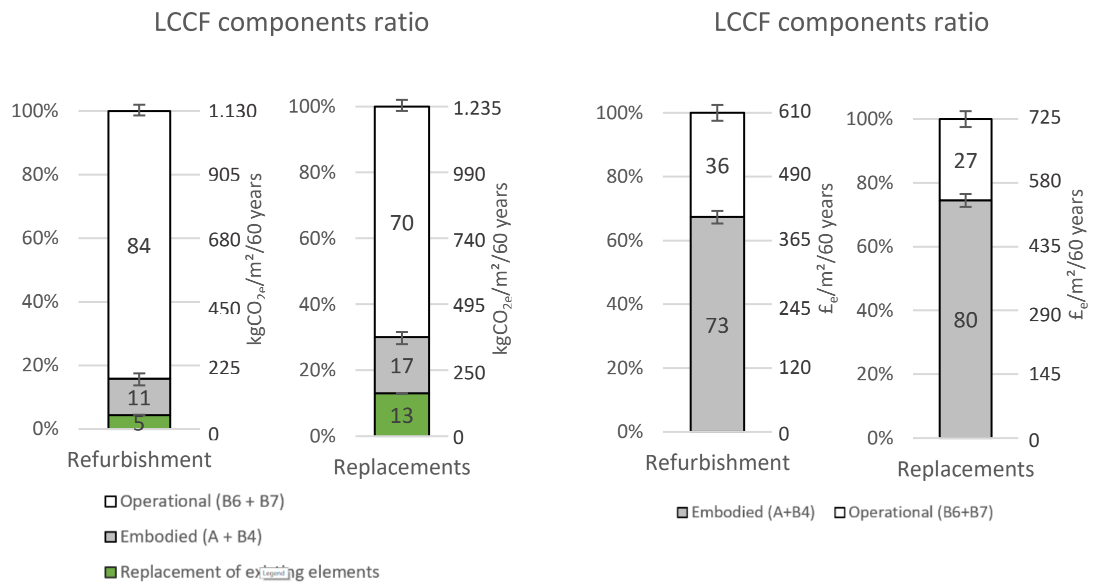

Figure 9: Refurbishment vs Replacement: life cycle performance breakdown

5.2. Case Study 2 – Bungalow

5.2.1. The Case Study Building

- *The Refurbishment Model:* To allow a modelling and simulation of the life cycle performance of the building, the bungalow case study was divided into separated thermal zones. It is assumed that each zone could only have a single window.

The Replacement Model: For the life cycle impact assessment of replacement buildings, PLOOTO was used for the generating various floor layouts and spatial arrangements. Table 11 shows a detailed description of the possible room sizes ranges, as well as their possible proximities to other rooms. These were based on features of the original bungalow house, to ensure that the new layout is of similar floor area, volume and use and that the buildings of the two scenarios are comparable. PLOOTO had generated 50 different design layouts for the Bungalow, as seen in Figure 10.

Table 11: Case study 2 - PLOOTO inputs – possible room dimensions and proximity matrix

Thermal Zone			**Width**		**Length**		**Adjacent to room**
			Minimum	**Maximum**	**Minimum**	**Maximum**	
Ground floor	1	Living room	400	600	400	700	6, 5
	2	Bedroom 1	300	450	300	450	6
	3	Bedroom 2	300	450	300	450	6
	4	Bedroom 3	300	450	300	450	6
	5	Kitchen	250	400	300	400	1
	6	Hall + toilets	100	800	100	800	1, 2, 3, 4

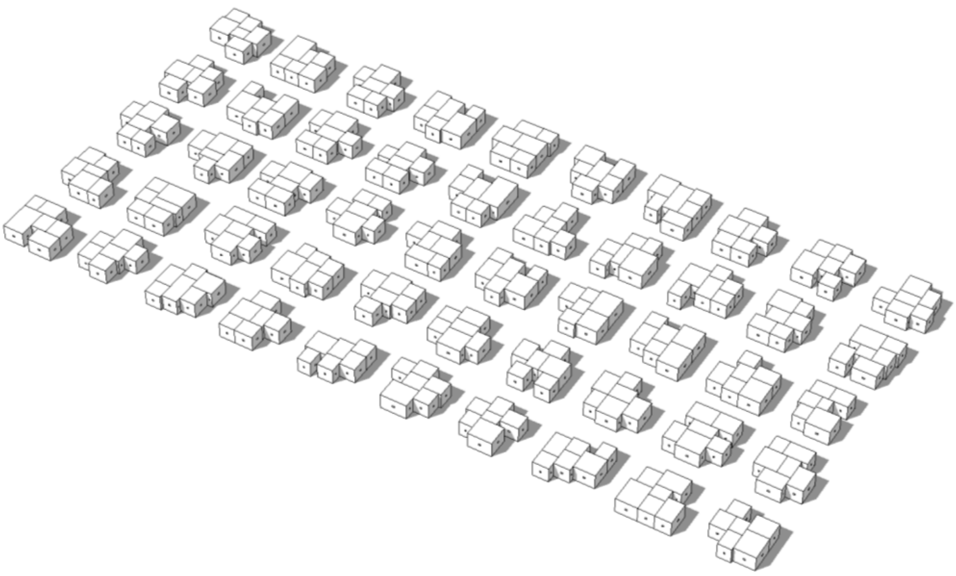

Figure 10: PLOOTO outputs – the 50 new-build bungalow designs

5.2.2. Optimisation Results and Pareto Fronts

A. Refurbishment

Figure 11 shows the output of the optimisation of a bungalow refurbishment. 14 pareto-optimal models were found, with LCCF and LCC figures ranges of between 1,340 – 1,500 $kgCO_{2e}/m^2$ and 550 – 680 £/m^2. An examination of the pareto-front models shows that all models had the same ground floor build-ups, minimal WWR (25%) and south facing window orientation whenever the building geometry made it possible. The pareto models differed in their external walls and roofs build-ups, as well as with their window frame materials and their non-south-facing window orientations.

B. Replacement

Figure 11 also shows the replacement optimisation outputs. Like the refurbishment scenario, the replacement scenario had 14 pareto-optimal models too. The LCCF range for the optimal replacements was between 1,750-1,850 $kgCO_{2e}/m^2$, and their LCC ranged between 750-890 £/m^2. All pareto-optimal models had the same external wall build-up (rendered finish with mineral wool insulation) and preferred the smallest (WWR of 25%) south-facing windows. All pareto-optimal models had the same layout (Figure 12), which, coupled with the other building properties and simulation assumptions, proved to result with the best life cycle performance compared to all other layouts.

C. Pareto-Fronts Comparison

A comparison between the pareto models of the bungalow refurbishment and replacement scenarios (Figure 11) shows that under the assumptions and scope of this case study, the refurbishment scenario is found to be favourable. An average optimal refurbishment performs around 20% better in terms of LCCF and around 30% better in terms of LCC, than an average optimal replacement for the assumed 60 years. Average LCCF values were estimated to be 1,423 and 1,792 $kgCO_{2e}/m^2$ for the refurbishment and replacement respectively, and average LCC values are 595 and 820 £/m^2).

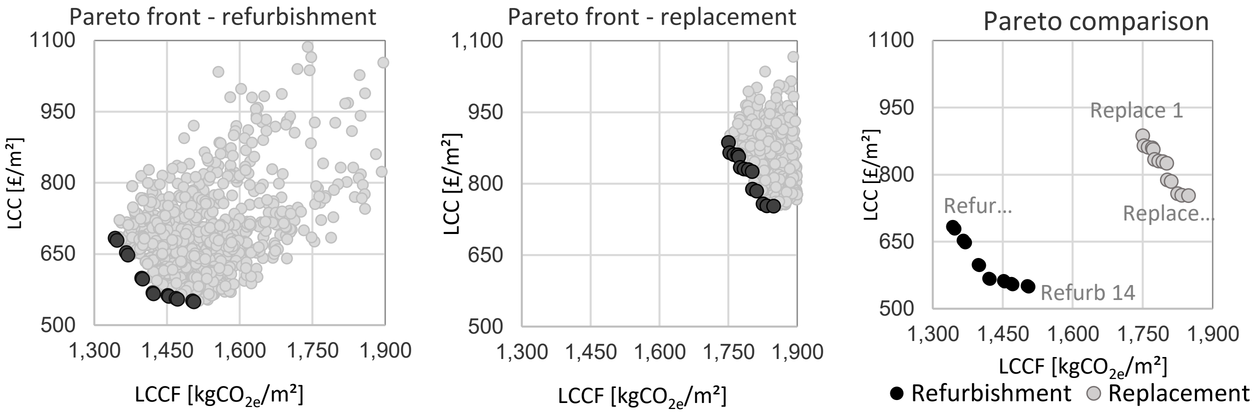

Figure 11: Bungalow refurbishment (left), replacement (middle)optimisation – LCCF/LCC over 60 years.

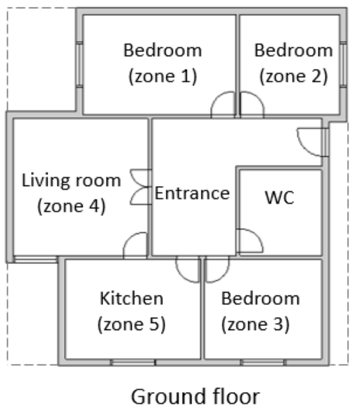

Figure 12: The optimal bungalow replacement layout, elevation, and thermal zones.

5.2.3. Life Cycle Breakdown Comparison

A. Life Cycle Carbon Footprint

A comparison between the LCCF of the bungalow's refurbishment and replacement pareto optimal models (Figure 13) shows that the refurbishment scenario could retain around 75% of the original building`s embodied $CO_2$ (only 80 out of the original building`s 270 $kgCO_{2e}/m^2$ had been replaced during the refurbishment works). Also, results show that, similarly to the terrace house analysis, the replacement buildings performed better than the refurbished ones in terms of operational CO_2 (B6 stage), while their overall life cycle performance (embodied performance included) was still worse.

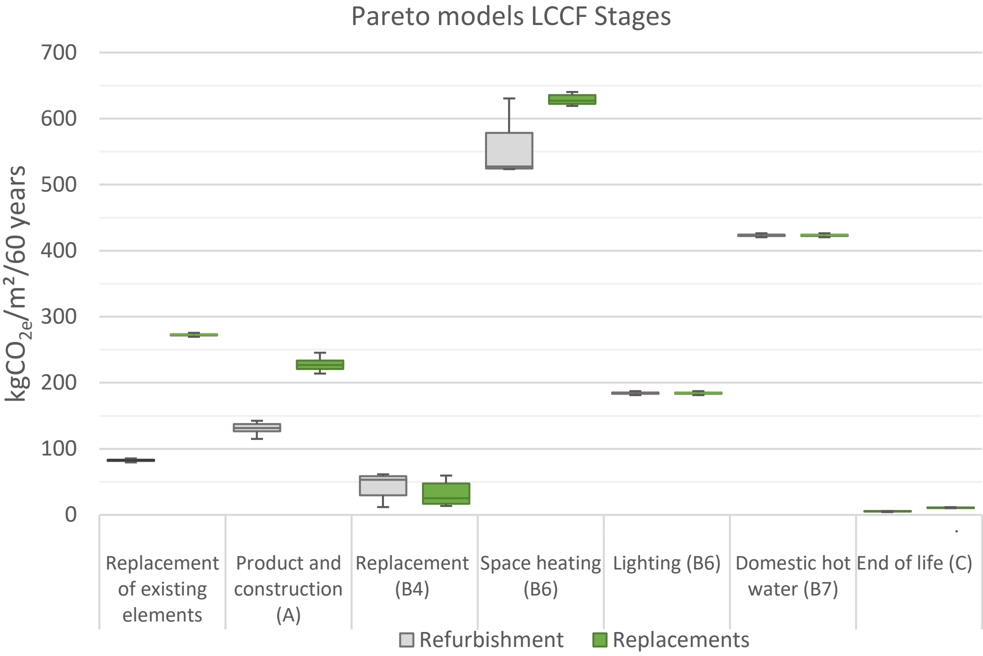

Figure 13: Bungalow refurbishment and replacements life cycle CO_2 stages breakdown

B. Life Cycle Cost

A comparison between the life cycle cost of the refurbishment and replacement pareto optimal models (Figure 14) shows that the main contributor to the buildings life cycle cost is the initial investment (Stage A in Figure 14). It also shows that spending on replacements throughout the buildings' lives (stage B4) is within a similar range of the life cycle spending on space heating,

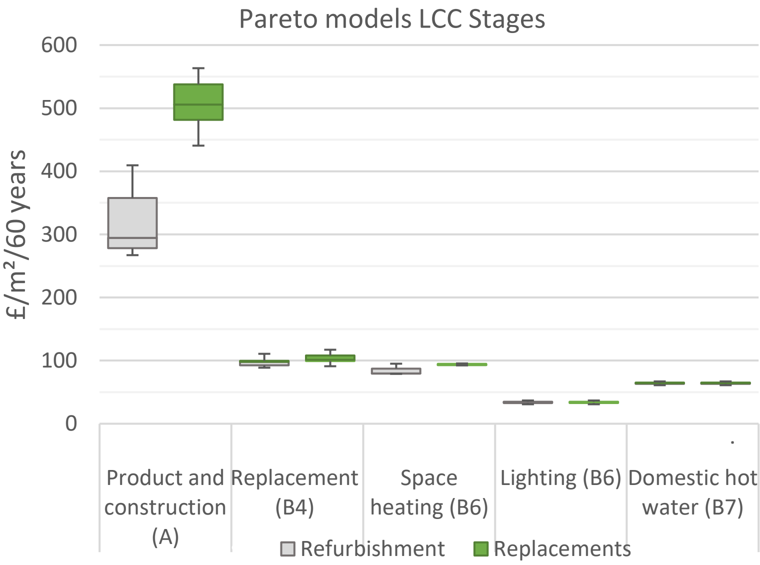

Figure 14: Terrace house refurbishment and replacements life cycle cost stages breakdown

C. Embodied and Operational Performance

Finally, when comparing the ratio of the embodied and operational CO_2 and cost outputs for the different scenarios, Figure 15 shows that, the buildings` main LCCF contributor is the operational stage, (82% for the refurbishment and 70% for the replacement). This is attributed both to lower absolute embodied emissions and to slightly poorer thermal properties in the refurbishment scenarios. When it comes to LCC, however, these trends are reversed: the initial capital investment contributes most to the buildings LCC (70% refurbishment and 80% for replacement). It is suggested that the reason for this opposite trend is due to the relatively low costs of energy, compared with its emission rates, as well as due to the skewed projection of operational costs over time.

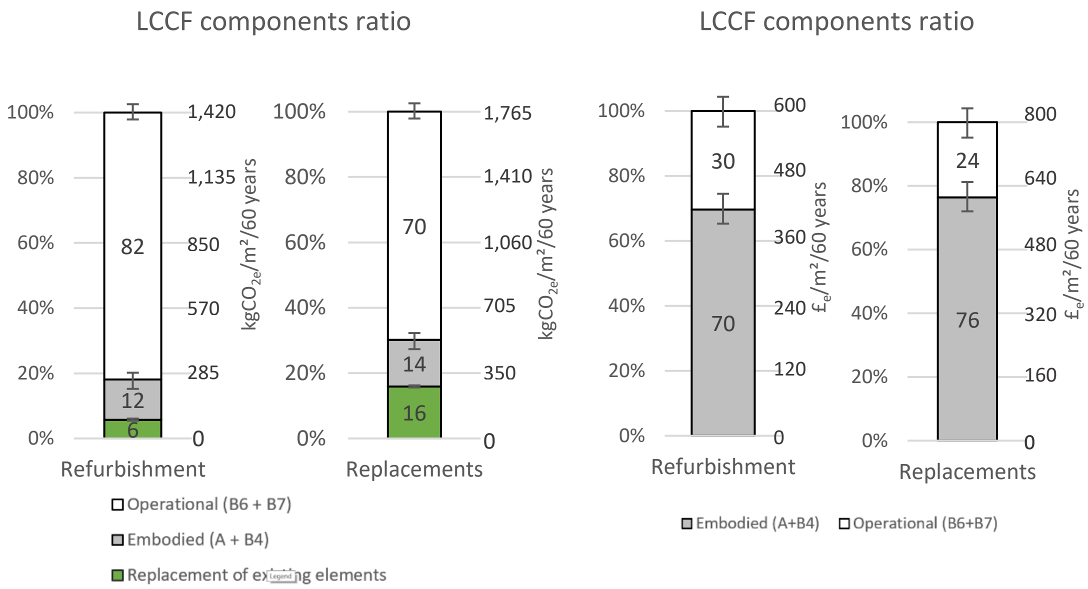

Figure 15: Refurbishment vs Replacement: life cycle performance breakdown

6. Discussion

6.1. Payback Time

While the analysis has shown that refurbishments have resulted with favourable life cycle performance over an assumed 60 years, a further investigation was performed to determine when these trends would reverse, i.e., at what time would a replacement perform better than a refurbishment. Analysis showed that:

- For the Terrace house, optimal replacements could out-perform refurbishments, in terms LCCF, after around 80 years.
- For the Bungalow houses, optimal replacements could out-perform refurbishments, in terms LCCF, after around 250 years.

6.2. Best Short-Term Carbon Reduction

As the UK has committed to minimise emissions by the year 2050, there is a need in achieving emissions reduction in a rapid way, an analysis was carried to identify the preferable scenarios for quick savings on the short term.

. An examination was, therefore, carried to compare the impact of the optimal refurbishments and replacements and evaluate their short-term (20 years) environmental impact, rather than their life cycle performance. Figure 16 shows that refurbishments were shown to have significantly better performance in the short term: 20 years after refurbishments are carried out, they emit between 65-75% CO_{2e}, compared to replacements (510, and 620 $kgCO_{2e}/m^2$ for the refurbishment of a terrace house and bungalow, respectively, and 650 and 930 $kgCO_{2e}/m^2$ for their replacements). The main reason for this difference is associated to the embodied CO_{2e} emissions due to the replacement of existing materials – which needs to be transported to landfills, as well as the embodied CO_{2e} which is required for the actual construction. This embodied CO_{2e} is significantly lower in refurbishments, as building foundations and structure – highly CO_{2e} intensive elements –need to be procured in a replacement scenario.

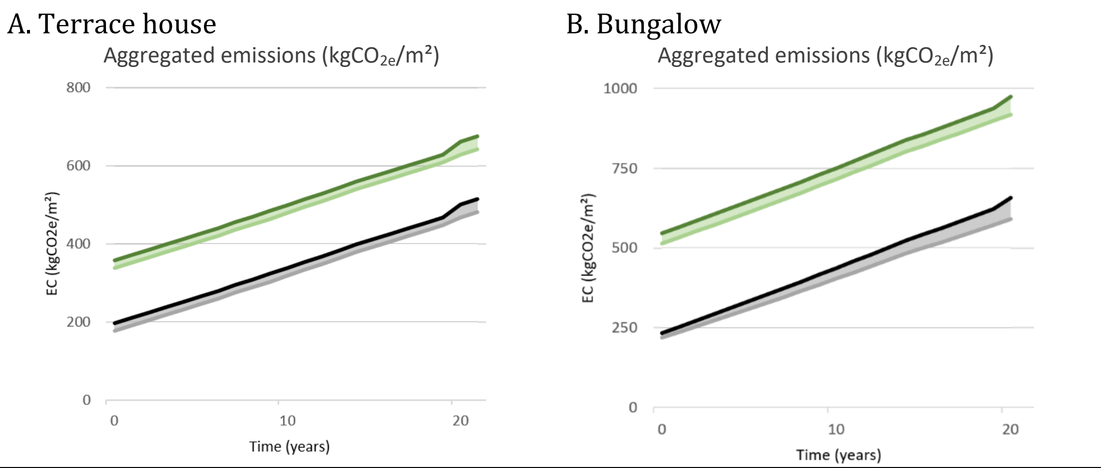

Figure 16: Short term (20-years) refurbishment/replacement LCCF comparison

6.3. Refurbishment or New Built?

While the analysis above has shown that when comparing the life cycle performance, refurbishments were found to perform better than replacements (when the embodied carbon of the materials replacements were considered in the calculations), an analysis was carried to compare refurbishments and new built buildings (not a replacement scenario, but simply a new built). This may inform stakeholders in allocating resources into either refurbishment projects or the construction of new developments elsewhere.

The analysis in Table 12 compares the LCCF of refurbishments (in which the embodied carbon of the replaced elements was accounted for) with complete new built buildings. The analysis shows that in this case, the performance of new buildings is around 5% better than that of refurbishments. It is noted that while these findings indicate that new-built tend to perform better than refurbishments, due to the variability in designing the design scenarios – this may not be a sufficient difference to determine that new-built will necessarily perform better.

		Refurbishments ($kgCO_{2e}/m^2$)	**New buildings ($kgCO_{2e}/m^2$)**
Terrace	Embodied	180	210
	Operational	949	864
	Total	**1,130**	**1,074**

Table 12: Embodied and Operational performance comparison - (Embodied emissions = life stage A, operational emissions = life stages B4, B6 and B7)

6.4. Study Limitations

Theis study is based on the principle of a comparative analysis of case studies. To carry out a comparison between the performance of different scenarios, the study compared buildings with similar characteristics (i.e., similar floor areas, number of rooms and ceiling heights). It is acknowledged that in a real-life scenario, homeowners and developers may wish to extend their properties and build additional rooms. This scenario was beyond the scope of this study.

It is also noted that limitations exist within the life cycle protocols (EN 15978:2011and ISO 15686-5). For example, this study assumed that the expected life span of a building, based on the BRE`s Green guide for specification [45] was 60 years, which may, of course, be different in reality.

Furthermore, the embodied carbon and materials costs figures that were used in this study may be different in materials in the future. This is also true when it comes to operational energy carbon emissions and costs, which may change with decarbonisation of the grid or other changes in the energy markets.

Other limitations relate to any modelling and simulation issues, such as potential differences between modelled and actual energy consumption figures. It is also noted that while the study used a series of layouts that had been generated in an automated manner, it did not cover all possible design solutions, and that there, while not very likely – there might be other design solutions with better performance.

7. Summary & Conclusions

By examining the outputs of the two case study buildings analysis, the following findings are summarised:

7.1. Refurbish or Replace?

For both case studies, and under the study scope and assumptions, the refurbishment scenario was found to be favourable when comparing the life cycle performance of the refurbished and replacement buildings. It is pointed out that these cases depend on the specific design scenarios that had been tested in this study, as each study might have different scope and potential refurbishment and replacement designs which might significantly affect results.

It is pointed out that the authors acknowledge that the debate around the refurbishment or replacement of existing buildings is a multi-layered one. While some layers are more tangible and quantifiable (e.g., economics, environmental), others might be more subjective (e.g., cultural, social and historic values). The authors believe that the decision for the refurbishment or replacement of buildings should not rely on environmental or economic analysis only, but that a wider discussion should take place in such cases. The authors hope that this study could add to this discussion by introducing scientific evidence to the decision making process.

7.2. Embodied and Operational Performance

The study has shown that for all case studies, the embodied CO_2 of the optimal replacements were around double than those of the optimal refurbishment. Furthermore, results show that for all case studies, the operational-related CO_2 emissions had the largest contribution to the buildings LCCF: around 80-85% in the case of refurbishments and between 65-70% in the case of replacements. For all case studies, initial capital costs had the largest contribution to the buildings LCC: around 70-75% in the case of refurbishments and around 76-80% in the case of replacements.

7.3. Short Term Savings

This study compared the environmental impact of refurbishments and replacements in a short term, to evaluate the need for quick reductions in carbon emissions. The study concludes that the evidence in favour of refurbishments is even stronger on a short-term scale.

8. Acknowledgements

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Appendix A – EPD Sources

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