Refurbish or Replace: Optimising Refurbished and New Building Designs for Life Cycle Carbon Footprint and Life Cycle Cost Minimisation

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Abstract

The refurbishments and replacements of existing buildings can significantly contribute to CO_2 emissions reductions in the built environment. This paper presents and tests a novel approach for supporting the decision-making process in assessing the performance of refurbished buildings and their replacements, to achieve life-cycle CO_2 emissions reductions in the most economically viable way.

The proposed method, incorporating generative design scripting, dynamic thermal simulations and Genetic Algorithms optimsiation, successfully identified a set of pareto-optimal models, which achieved minimal life cycle carbon footprint and a minimal cost. Findings indicate that optimal refurbishments can achieve between 7-38% lower CO_2 emissions, over an assumed life span of 60 years, and cost between 5-20% less than optimal replacements.

Introduction and aims

The built environment is responsible for around 40% of global energy consumption and associated CO_2 emissions(European Commission, 2013), where the UK is one of the world's highest CO_2-emitting countries (Olivier et al., 2013). Following the 1992 Kyoto protocol and the Paris 2015 UN Climate Change committee , the UK government committed to reducing at least 80% of its CO_2 emissions, compared to its 1990 baseline figures, by 2050 (Department of Energy and Climate Change, 2011). The building industry, therefore, can significantly contribute to achieving this aim.

While much of the effort for improving building energy efficiency is focused on new buildings, the environmental performance of existing buildings can have an important role in achieving reduction targets. In the UK, new buildings account for only 1% of the total building stock every year (Power, 2008), while around 75% of the housing stock in 2050 has already been built (Sustainable Development Commission, 2007).

To achieve the UK government's reduction targets in an economically viable way, a mechanism that supports a more detailed investigation process to determine the most efficient reduction pathway, either the refurbishment of existing buildings or their demolition and re-building, is required. To address this need, this study presents an innovative approach for the evaluation of the Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) of optimal refurbishment and replacement of existing buildings, and for the first time presents a comparative analysis to identify a preferable design alternative, when examining some of their passive and geometric properties (build-ups, spatial arrangement and window-to-tall ratio).

Background: refurbish or replace?

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 (Power, 2008; Ding, 2013; Goldstein, el al., 2013), the different alternatives offer potential performance improvements at different stages of the building's life. While refurbished buildings allow the re-use of some parts of the existing structure and savings through the structure's embodied CO_2 and costs, new buildings have a better potential for improving operational efficiencies (mainly for space heating), as the result of a better design (orientation, window-to-wall ratio, use of materials etc.).

While a number of studies have recommended refurbishments over replacements, as refurbishments are often perceived as more environmentally and economically responsible, evidence to support this is still debatable and the actual benefits of either option are still not clear (Bell et al., 2014, Bullen & Love. 2010, Goldstein et al., 2013, Power 2008). One possible reason for this is that the nature of the problem makes it hard to gather evidence and reach an agreed upon conclusion: Most studies evaluate the benefits of each design alternative differently. Bullen & Love (2010) show that while the choice between refurbishment and demolition is often driven by economic reasons, environmental aspects have a growing impact on this decision.

In a systematic literature review, where a comparison between the LCCF of new and refurbished case study buildings was carried out in an attempt to identify the preferable alternative, Schwartz et al. (2018) note that it was not possible to reach an ultimate conclusion due to the variety in building uses, the climates at which the buildings were built at and the differences in construction technologies and materials.

When minimising the scope of analysis to typical refurbished and new residential buildings in the UK and Ireland only – regions with similar climate and construction industries (Figure 1) – the analysis showed that although refurbishments seem to perform generally better than new buildings, some new buildings still achieved better performance than the best refurbished alternative. The figure suggests that there is a room for a comparison between the performance of optimal designs in the two scenarios, to identify which optimal design solution performs best.

As a clear conclusion could not be established, this study presents and tests a comprehensive, life-cycle-based approach, which enables a detailed comparison between the benefits of the refurbishments of existing buildings and their replacements.

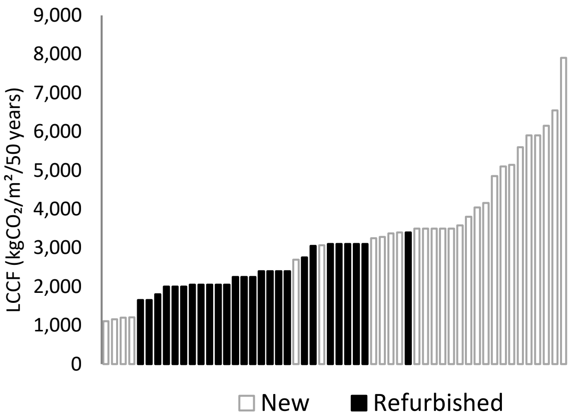

Figure 1: The Life Cycle Carbon Footprint (LCCF) of refurbished and new residential case-study buildings in the UK and Ireland (Schwartz et al., 2018)

Life Cycle Studies in the built environment

Life Cycle Studies (LCS) methodologies are based on the Life Cycle Assessment (LCA) framework - an environmental assessment and management framework that aims to minimise the environmental impact of production processes (ISO 14040, 2006). Life cycle studies are comparative methods – their aim is choosing the best option out of a set of alternatives by comparing the performance of different 'System Units' - a product or a service, or a building in the built environment. The main comparative component is called the 'Functional Unit' – a reference unit that quantifies the performance characteristics of the product (In the built environment – often a 1m^2 floor area).

In 2011, the European Standards Technical Committee CEN/TC 350 developed a series of standard addressing the "sustainability of new construction works". Among those is EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method (BS ISO, 2011).

EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - is the adaptation of ISO 14040 to the built environment. The standard defines four main stages in the life cycle of buildings: product, construction, usage, end-of-life. A fifth stage – recycling – is added when possible. The protocol describes the sub-processes involved in each stage (Table 1).

There are various ways to obtain the relevant data for the different building life cycle stage. These are extensively covered in (Hammond and Jones, 2011; Bull et al., 2014; Schwartz et al., 2016) and others.

CO_2 emissions associated with space and water energy use are normally calculated by using thermal simulation tools.

Table 1: Buildings environmental life cycle EN 15978:2011

A1-A3 Product			A4-A5 Construction		B1-B7 Use							C1-C4 End of life			
1	2	3	4	5	1	2	3	4	5	6	7	1	2	3	4
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal

Life Cycle Cost is a framework for assessing the costs performance of buildings and construction works. It aims to assist clients by calculating not only the initial capital investment of construction projects, but also their future operational cost flows, over a defined time period (Bourke et al., 2016). Similarly to LCA, LCC uses flows of input resources (costs of materials and energy), and sums up all costs involved in the construction, maintenance and operation of the building (Woodward 1997; Reidy et al., 2005; Gluch & Baumann 2004).

BS ISO 15686-5 - Building and constructed assets - Service life planning. Life-cycle-costing is a British standard that details the principles of life cycle costing for buildings and construction assets. Table 2 shows the stages of the LCC analysis.

When future costs in different design scenarios are not of similar proportions of the life cycle cost (e.g., when comparing the cost of a future small-scale repair with that of a major refurbishment), inflation might have a significant impact on results. While environmental impact assessments are not assumed to degrade over time, the value of money might inflate or deflate in the future. For this reason, BS ISO 15686-5 recommends bringing future costs to a present-day value by using discounting.

The discounted value of future costs, net the future incomes (e.g., interest) is called Net Present Value (NPV). NPV is expresses by the following equation:

$$NPV = \sum_{i=0}^{n} \frac{Vi}{(1+r)^i} \quad (1)$$

Where:
NPV = Net Present Value
n = period of analysis in years
i = Present
Vi = Cost in year i
r = Real discount rate

Methodology

This study integrates various applications and methods that were introduced previously by Schwartz et al. (2016) and Schwartz et al. (2017), and carries out, for the first time a complete analysis that links a full LCA, optimisation algorithms, generative design programming and thermal simulations, to carry a comparative life cycle performance analysis of refurbished and replacement buildings.

In accordance with the LCA methodology, a recursive comparative case study analysis was used in this study. Here the calculated LCCF and LCC of optimal models of refurbished case studies was compared with that of their replacements.

To perform a comparative analysis between a large number of design alternatives and efficiently select an optimal design solution, optimisation algorithms were used. These are search techniques that enable a rapid and efficient scan for solutions to given problems.

To compare the performance of refurbished buildings with that of new ones, a sufficient number of new design alternatives had to be generated, modelled, simulated and evaluated. For this, an algorithm for that automates the generation of buildings layout has been developed.

Table 2: Buildings life cycle cost (BS ISO 15686-5)

1	Construction- total development costs
2	Maintenance – cost of maintenance or refurbishments
3	Operation – operting the facility
4	End-of-life - costs for demolition and disposal

Study design

Figure 2 presents the stages of the design of this study:

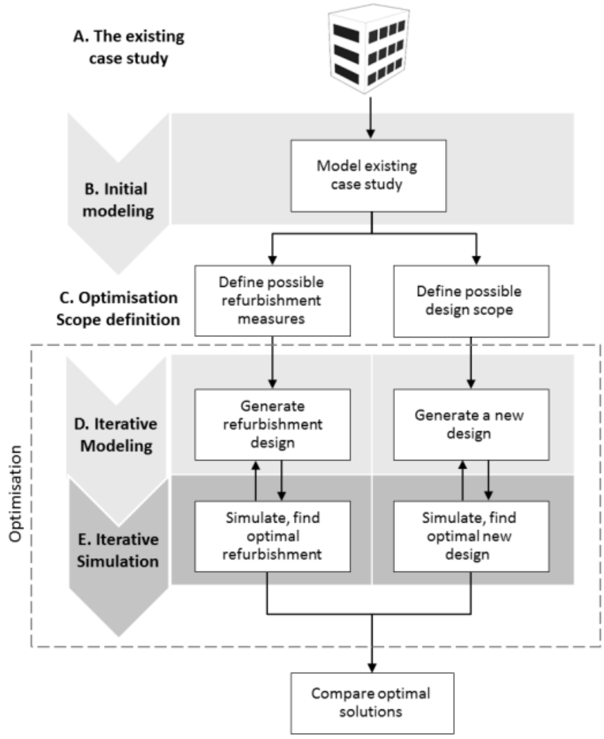

Figure 2: Study design

A. Firstly, an existing case study building is selected, its properties are identified and a detailed description of its geometrical properties, thermal properties and usage profiles is set out.

B. Based on the building properties listed in the previous stage, the building was then modelled in EnergyPlus, using Sketchup and the legacy OpenStudio plug-in. This was found to be the easiest way to construct an initial .idf file.

C. The scope of the refurbishment and replacement scenarios is defined, in accordance with the EN-15978:2011 protocol. This includes the description of several possible construction measures, both for the refurbishment and the replacement scenarios. For the replacement scenario - the embodied CO_2 of the original building is calculated, to be accounted for when calculating the replacements LCCF. The overall possible volume for a new development is then defined, as well as allowed building materials, build-ups and building service systems (aligned with building regulations and the program of the existing building).

D. The search for an optimal refurbishment and replacement, in terms of LCCF and LCC then takes place. In both design scenarios, this was done by using a designated Non Sorting Genetic Algorithms - II (NSGA-II) application. GA in general, and NSGA-II, in particular, are of the mode widely used optimisation techniques across the built environment discipline. A study by Nguyen et al. (2014) shows that compared with other GA applications, NSGA-II can achieve a more accurate solution, faster and more efficiently.

The search for optimal designs included the process of controlling various parameters in the .idf file, sending the models to simulation, retrieving simulations outputs and automatically analyse results.

For the replacement scenario, as a very large number of building designs which might be of various forms or shapes should potentially be evaluated, a designated algorithm for the automated generation of spatial arrangements and building layouts was generated.

The application – Parametric Lay-Out Organisation generaTOr (PLOOTO) – generates new building designs in a .idf format, and enables a quick and easy integration of the model in NSGA-II application. This allows an efficient, life cycle optimisation of replacement buildings to be carried.

PLOOTO was developed and validated in Schwartz et al. (2017).

E. Lastly, the performance of the optimal refurbishments and optimal replacements is analysed and compared, and the favourable design solution is identified.

Study execution

The case study building

The selected existing case study building for this exercise was an architype of a typical two-storey London terrace house. This building architype was chosen as it is one of the most common forms of residential unit in London (Oikonomou et al., 2012). The ground floor includes the living spaces (living room, kitchen, dining room and corridor/stairwell), while the bedrooms are all located at the first floor.

It was assumed that the original construction of the building included a double-brick build-up for the external walls, non-insulated ground floor slab and single glazed timber frame windows. For the purpose of simulation, partition walls were considered as adiabatic surfaces.

Figure 3 shows the floorplans of the original existing terrace house case study building.

Study scope

Based on EN 15978:2011, the study examined building performance at various stages of their life cycle. Table 3 shows the life cycle stages that were considered in both the LCCF and LCC evaluations.

The refurbishment scenario

The refurbishment scenario is based on the same layout as that of the existing building. It was assumed that all building outfits have been stripped down, and

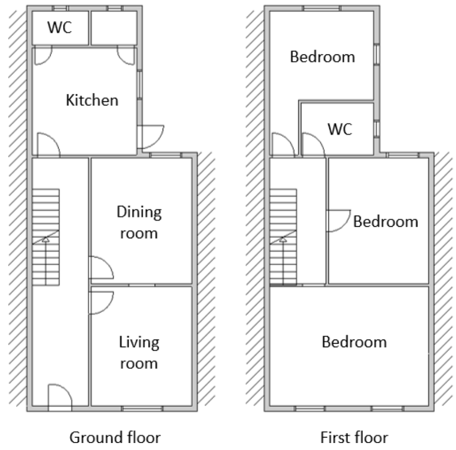

Figure 3: Terrace house case study (adapted from Oikonomou et al., 2012)

Table 3: Study Scope, based on EN 15978:2011 (as described in Table 1)

Objective	EN 15978:2011 Stages
Life Cycle Carbon Footprint	A1-A5, A4, A5, B4, B6-B7, C1-C4
Life Cycle Cost	A1-A3, B4, B6-B7

that only the brick (for the external and partition walls) and the construction elements (foundation, ground floor concrete slab and internal partitions and ceiling timber construction) were retained. This means that their embodied CO_2 and costs were not considered in the analysis.

As part of the optimisation process, a range of possible refurbishment build-ups is suggested, each with different embodied CO_2 and cost values, as well as component life-expectancy. It is important to note that each build-up alternative was made to meet the standards for improving retained thermal elements, as described in approved document L1B: Conservation of fuel and power in existing buildings (HM Government, 2010).

To enable the optimisation process and thermal simulations, the case study building was divided into independent thermal zones, as presented in Figure 4. As part of the generation and optimisation process, the algorithm, automatically assigned build-ups to different building surfaces (external/internal walls, windows, roof etc.), and calculated the embodied CO_2 and cost of those surfaces.

The replacement scenario

For the replacement scenario, it is assumed that the entire existing building is demolished and removed. As part of the optimisation process, a range of new build-ups is suggested, each with different embodied CO_2 and cost values, in accordance with the limiting fabric parameters, as given in approved document

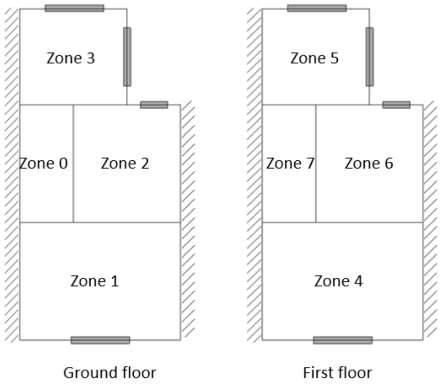

Figure 4: Refurbishment scenario – thermal zones

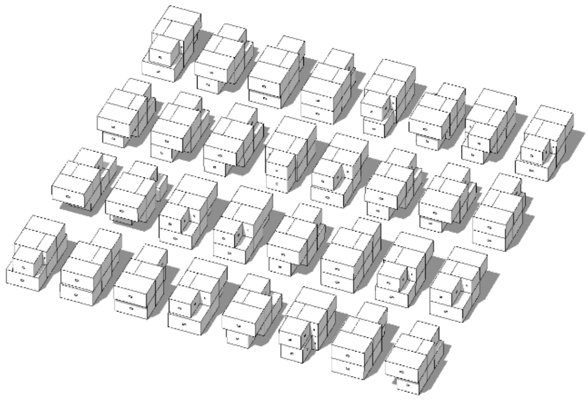

Figure 5: PLOOTO outputs – the 32 new-build designs

L1A: Conservation of fuel and power in new dwellings (HM Government, 2016). To evaluate the life cycle performance of the replacement scenario, new building designs had to be generated and simulated using PLOOTO. Any new design had to be of a similar program, size and volume as those of the original existing building. Therefore, based on the original building, possible room dimensions were identified and a proximity matrix was set, to describe room sizes and adjacencies (as shown in Table 4). These inputs were then used in PLOOTO for the generation of different floor layouts and spatial arrangements. PLOOTO was stopped once 32 building configurations had been generated (Figure 5), as it was at this threshold that designs typologies started to repeat, and as there were marginal differences between new models.

Optimisation results

For verification purposes, three optimisation runs were carried out and analysed. As all pareto fronts were identical – only one set of results is presented in this paper.

Table 4: Possible room sizes and room adjacencies

Thermal Zone			Width		Length		Adjacent to
			Min	Max	Min	Max	
Ground floor	0	Core (stairs)	160	240	360	440	1,2,3
Ground floor	1	Living	600	600	360	440	0
Ground floor	2	Dining	360	440	360	440	0,3
Ground floor	3	Kitchen	360	440	360	440	0,2
1st floor	4	Bedroom	600	600	360	440	7
1st floor	5	Bedroom	360	440	360	440	7
1st floor	6	Bedroom	360	440	360	440	7
1st floor	7	Core (stairs)	160	240	360	440	4, 5, 6

Figure 6 (left) shows the optimisation of the refurbishment scenario. The figure shows that a pareto front, with the size of 5 pareto-optimal models, was found. The LCCF of the pareto-optimal models ranges between around 920 - 1000 $kgCO_{2e}/m^2$, and the LCC ranges between 410 – 485 £/m^2. An examination of the GA convergence rate (Figure 7, left) shows that the systems converged after between 7 to 8 generations. Figure 6 (right) illustrates the outputs of the replacement optimisations. Results show a clear pareto front with 12 pareto-optimal models. The LCCF, in the case of the replacement, ranges between around 1040 - 1100 $kgCO_{2e}/m^2$ and its LCC ranged between 520 – 590 £/m^2. The system converged after 12 generations.

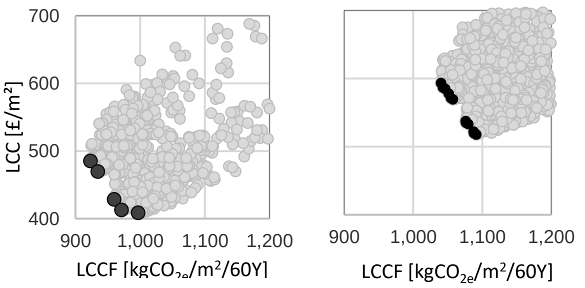

Figure 6: Optimisation results – refurbishment (left) and replacement (right)

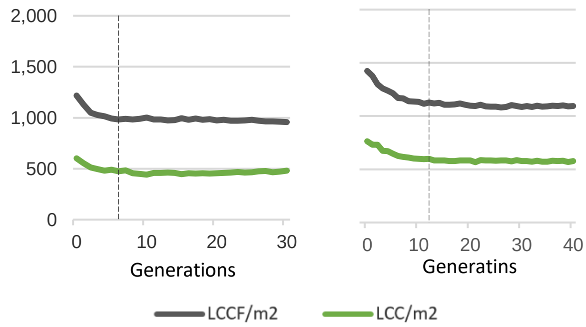

Figure 7: Optimisation convergence: refurbishment (left) and replacement (right)

Discussion and conclusions

This paper aimed to present and test a framework, through which an analysis could be carried out to determine which design alternative presents the more favourable option– an optimal refurbishment of existing buildings or their optimal replacement, in terms of the life cycle CO_2 and costs.

For the technical context (generative design and optimisation), this study has shown that the proposed method and framework can successfully reach a set of pareto-optimal models, for the optimisation of both refurbishment schemes and for their replacements. The tools that had been developed for this study (both PLOOTO and the NSGA-II application) were successful in carrying the optimisation and find a set of pareto optimal models. The study results reached the same outputs when executed on three different occasions. This supports the robustness of the approach and the tools that were used for running the optimisations.

For the building performance context, this study has shown that under the assumptions and scope of this study, the refurbishment scenario was found to be favourable, when comparing the life cycle carbon footprint and life cycle cost of the refurbished and replacement buildings (Figure 8). It is noted that the results compare optimal solutions: This does not mean that all refurbishments are better than all replacements: when comparing the entire search spaces of the refurbishment and replacements, Figure 6 shows that some replacements can have better performance than some refurbishments, however, these depend on the specific designs and they do not represent the optimal solutions.

Further research and development opportunities arise as the result of this study:

A. Technology:
   - This study made use of a designated generative design program. The integration between generative design in buildings and research is still at its infancy. It is expected that further research will take advantage of similar computational applications.
   - It is suggested that by incorporating Building Information Modelling (BIM) technologies, the streamline of the process that was presented in this study will become easier and the more user-friendly.

B. Life cycle performance:
   - More buildings can be tested using the proposed method, to develop a better understanding of the performance of refurbishments and replacements.
   - To further explore the life cycle performance in buildings, the proposed method can be used for the development of a regression model, that will enable to evaluate building performance and identify preferable designs.
   - This study used LCCF and LCC as the optimisation objectives. Other performance indicators, such as energy performance, lighting, comfort etc., should be can be examined in future studies.

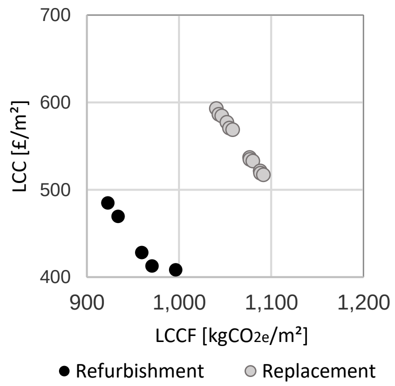

Figure 8: Refurbishment and Replacement pareto-front comparison

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