MULTI OBJECTIVE OPTIMISATION FOR THE MINIMISATION OF LIFE CYCLE CARBON FOOTPRINT AND LIFE CYCLE COST USING NSGA II: A REFURBISHED HIGH-RISE RESIDENTIAL BUILDING CASE STUDY

Simona Vasinton[1], Rokia Raslan[1]
[1] Institute for Environmental Design and Engineering , University College London, London, UK

ABSTRACT

This paper presents the application of Multi Objective Optimisation to a design decision-making process, which aims to minimise Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) from cradle-to-grave of a refurbishment intervention over a period of 60 years. The purpose is to compare the LCCF and LCC of the un-refurbished and refurbished solution of the case study with the optimal solution obtained using a multi-objective computational method.

Results show that the application of this method in the decision–making process can achieve considerable carbon emission savings, while relatively smaller savings were recorded in terms of LCC. The LCCF of the optimal solution was 21% less than the refurbished solution and 67% less the un-refurbished solution. Compared to the LCCF assessment, the LCC analysis showed a smaller gap of about 5% between the refurbished and optimal solution, and about 16% between the un-refurbished and optimal solutions.

INTRODUCTION

The Role of the Built Environment and the Importance of Refurbishing: the UK Case

Globally, the building sector accounts for approximately 40% of energy demand and 30% of Green House Gas (GHG) emissions. Consequently, the energy efficiency improvement of the existing stock has been recognised as a key research aim (UNEP, 2009). In particular, in Europe the residential sector, which constitutes 75% of the existing stock, has been identified as a main area of focus for these efforts (UNEP, 2009; BPIE, 2011).

Within this context, the UK Government aims to reduce GHG emissions by 80% by 2050 in line with EU policy (EPBD, 2010). To achieve this, the transformation of the stock using available knowledge and tools to design cost and energy optimal solutions over their whole lifecycle is required (UNEP, 2009). The benefits of retrofitting the residential stock are significant due to its old age, low replacement rate and high-energy demand (BPIE, 2011).

The use of advanced tools and innovative approaches to aid the delivery of sustainable interventions is now a growing trend. In recognising this, an innovative approach involves applying Multi Objective Optimisation tools during the design decision-making process to minimise the Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) of a refurbishment intervention over a certain time and according to specific boundary conditions (Karimpour, et al., 2014; Cabeza, et al., 2014; Chau, et al., 2015).

Research Background: LCA and LCCA in the Building Sector.

Life Cycle Assessment is a procedure used to evaluate the environmental impacts associated with a product, process, or service over its life span in a ‘cradle-to-grave’ approach. LCA consists of four main phases (ISO 14044, 2006; 14040, 2006):

- *Goal Definition and Scoping.* Definition of the purpose, context and study methodology.
- *Life Cycle Inventory Analysis (LCI).* Identification and quantification of the direct and indirect use of energy, water and materials and related environmental releases of the activities and processes involved.
- *Life Cycle Impact Assessment (LCIA).* Assessment of the human and ecological effects of resource usage and associated environmental releases.
- *Interpretation.* Analysis of the outcomes

Life Cycle Cost Analysis (LCCA) provides a framework for estimating the lifetime economic performance of a product (BSRIA, 2006; Cabeza, et al., 2014). The level of breakdown depends on the aim of the study (Islam, et al., 2015; Asiedu, et al., 2015) and can be divided into acquisition, operational, maintenance and disposal stages.

Because of the high degree of complexity of buildings (presence of subsystems, etc.), the application of LCA and LCCA in this sector is more complex and still experimental, but is rapidly growing (Diakaki, et al., 2009; Bribian, et al., 2009; Islam, et al., 2015). Currently, most studies aim to achieve the maximum reduction of carbon (CO_2) emission over a building’s life thorough the identification of the optimal balance between the associated Embodied Carbon (EC) and Operational Energy (OE) related CO_2 (Ramesh, et al., 2010; Karimpour, et al., 2014; ; Cabeza, et al., 2014, Chau, et al., 2015; Islam, et al., 2015). In general, the Life Cycle Energy or Carbon Assessment, a simplified approach to LCA, is applied (Cabeza, et al., 2014;

Karimpour, et al., 2014; Chau, et al., 2015). Life Cycle Carbon Emission Assessment considers all the CO_2-equivalent emission output from a building over different life cycle phases (Chau, et al., 2015). The Life Cycle Carbon Footprint (LCCF) of the product is described as the sum of GWP (Global Warming Potential) values in CO_2e of each environmental impact category (Schwartz, et al., 2015).

In LCCF assessments, two main components must be considered: the Embodied Carbon (EC) and the Operational Carbon (OC) (Karimpour, et al., 2014; Chau, et al., 2015). Embodied Carbon (EC) is the sum of the CO_2 emissions related to the whole life cycle from the production to the demolition excluding the operational phase. Operational Carbon (OC) is the sum of the CO_2 emissions associated with daily operational processes such as heating (e.g. Chau, et al., 2015). Exclusively focusing on the reduction of OE is not sufficient to meet zero carbon targets. Furthermore, trends suggest that OE will diminish as a result of the spread of sustainable design solutions and EC will increase due to the use of energy-intensive materials in energy savings measures (Mandley, et al., 2015; Cabeza, et al., 2014).

Multi-Objective Optimisation

Multi-objective optimisation (MOO) involves computational mathematical optimisation methods that use one or more objective functions (Karmellos, et al., 2015). Its application in combination with energy simulation for the evaluation of building designs has mainly taken place in the last two decades (Evins, 2013; Nguyen, et al., 2014). Currently, most MOO studies focus on the building envelope and have energy and construction costs as objective functions (Evins, 2013; Penna, et al., 2015).While a number of methodological approaches in terms of tools, algorithms and objectives can be used, the most commonly used tools are EnergyPlus or TRNSYS and GenOpt or Matlab (Nguyen, et al., 2014; Evins, 2013).

The dominant method is genetic algorithms (GA), one of the multi-objective evolutionary algorithms (MOEA), based on the principles of natural selection and survival of the fittest (Schwartz, et al., 2015; Yu, et al., 2015).

The Non-dominated Sorting Genetic Algorithm II (NSGA II) is a specific class of GA based on Pareto-dominance (Deb, et al., 2002; Yu, et al., 2015). Here the non-dominated or Pareto-optimal solutions, which are equally good when compared to other solutions of that set, are identified from a random population forming a locus or ‘Pareto-front’. The set of identifed Pareto-solutions are paired randomly, bred and mutated to generate a new generation of better solutions. The process is iterated until the maximum number of generations is reached. Due to this process, NSGA-II mantains the population diversity and avoids the loss of excellent individuals (Yu, et al., 2015).

Research Aim and Objectives

The aim of this study is to compare a traditional refurbishment and an un-refurbished option for a case study building in terms of their impact on the Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) over a period of 60 years, with the optimal solution determined using a multi-objective computational method. The specific objectives are:

- To investigate the feasibility of carrying out a LCCF and LCC assessment of a refurbishment intervention in the UK context.
- To explore the applicability of using multi-objective computation to minimise the LCCF and LCC of a refurbishment intervention.
- To assess the gap in terms of LCCF and LCC between a traditional refurbishment intervention (where no advanced optimisation tools were used in the decision-making phase) and an optimized solution obtained using the MOO approach.

STUDY METHODOLOGY

The case study

The research involved the analysis of a single case study, considered typologically representative of contemporary high-rise residential buildings. Ferrier Point is a 23-storey post-war public sector residential tower located in east London (Figure 1-a). Over the years, the internal space configuration of the typical floor plan has not changed. In the 1980s the building was subject to minor refurbishments and in 2008 a deep retrofit intervention was undertaken (Figure 1-b). The main interventions included windows upgrade, external wall insulation and the installation of a central gas heating system and PVs on the external façade.

Figure 1 Ferrier Point,(a) pre- and (b)post-refurbishment

Research Design and Simulation Tools

The modelling process was divided into three phases: pre-processing, optimisation and post-processing as illustrated in Figure 2.

Model construction and specifications

SketchUp v15.3.331 (Trimble, 2015) and the Open Studio Legacy plug-in (US DOE, 2015) were used to create the model geometry and for an initial definition of the thermal zones. The file was then exported as an .idf format file for editing in EnergyPlus v8.2 (US DOE, 2015).

A typical floor plan was used to account for the various storeys. As the overall difference in results for the ground and top storey were considered minimal, these were not modelled. The LondonTRY weather file was used for simulations and relevant default NCM schedules were customised in an aim to create a more realistic representation of space use patterns.

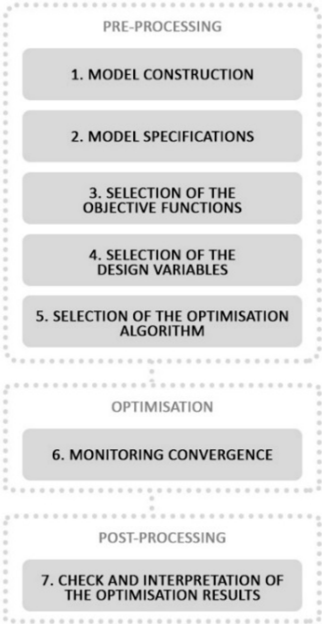

Figure 1 Research Design

Selection of the objective functions, design variables and the optimisation algorithm

The MOO was carried out using the NSGA II algorithm through the calculation of total and partial results (Table 1). As specified, the study focused on the main refurbishment interventions. The design variables taken into account and the ranges of values analysed are reported in Table 2. As the tower consists of two main vertical volumes connected by a central hallway block, the insulation thickness was analysed separately for the two blocks (Figure 3). Two groups of windows were identified based on orientation: N-NE and S-SW (Figure 3).

Simulation and Monitoring convergence

The simulations were run using jEPlus+EA v1.5_beta_05 (De Montfort University, 2015) in combination with SQLite (Hwaci, 2015). A precompiled excel spreadsheet was used to link the energy, cost and carbon emission inputs to the design variables. The main settings are reported in Table 3.

Table 1 Primary and Secondary Objective Functions

	Functions	Unit
LCCF	Life Cycle Carbon Footprint	$kgCO_2/m^2$
LCC	Life Cycle Cost	£/m^2
ECO_2	Embodied Carbon Footprint	$kgCO_2/m^2$
OCO_2	Operational Carbon Footprint	$kgCO_2/m^2$
EC	Embodied Cost	£/m^2
OC	Operational Cost	£/m^2
OCO_2 (Heating)	Operational Carbon Footprint (Heating energy demand)	$kgCO_2/m^2$
OC (Heating)	Operational Cost (Heating energy demand)	£/m^2

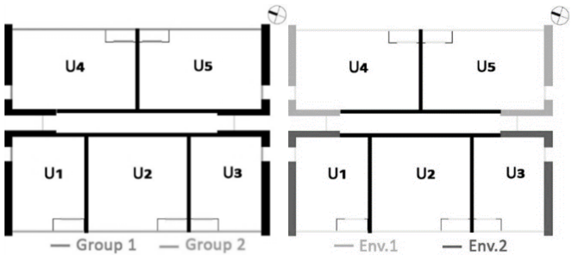

Figure 2 Envelope and windows classification in the parametric project

Table 2 Design variables and number of jobs

Parameter	Design variable	Classification	Unit	Value	Properties
P1	Insulation thickness	Env.1	mm	100 - 150 - 200 - 250	0.035 W/mK
P2		Env.2	mm	100 - 150 - 200 - 250	0.035 W/mK
P3	Heating fuel		-	NaturalGas, Electricity	N/A
P4	PV on the south façade, wall 1	-	%	0 - 100	N/A
P5	PV on the south façade, wall 2		%	0 - 100	N/A
P6	External windows glazing type	Group.1	-	double - triple	1.6 - 1.0 W/m²K
P7	(Living room and bedroom)	Group.2	-	double - triple	1.6 - 1.0 W/m²K
P8	External windows glazing type	Group.1	-	single - double - triple	3.7 -1.6-1.0 W/m²K
P9	(Balcony)	Group.2	-	single - double - triple	3.7 -1.6-1.0 W/m²K
P10	Interior window glazing type	Group.1	-	single - double - triple	3.7 -1.6-1.0 W/m²K
P11	(Kitchen)	Group.2	-	single - double - triple	3.7 -1.6-1.0 W/m²K
	Tot. JOBS	-	-	*41,472*	

Table 3 jEPlus+EA simulation settings

Parameters	12
Space research	41,472
Mutation	0.2
Cross-over rate	1
Tournament selection size	2
No. of generations	Varied to assess possible result differences (sec 3.1)
Population size	Varied to assess possible result differences (sec 3.1)

LCCF and LCC assessment

A simplified approach to LCA based on the standard ISO 14040 framework was applied (ISO, 2006):

Goal and Scope: The aim of the study was to analyse the impact of the refurbishment on the LCCF and the LCC from cradle-to-grave (Figure 4) of a refurbishment intervention. The lifetime of the analysis was assumed to be 60 years (BRE, 2015) and 1 m² of floor area the functional analysis unit.

Life Cycle Inventory: An inventory of materials used in the refurbishment was compiled, with relevant sources and calculation methods used listed below.

Building components: The hybrid variation $kgCO_2$ calculation described in Schwartz et al. (2015) was used, where component weight was converted into $kgCO_2$ emissions using the ICE database (ICE, 2011). As per the cradle-to-gate boundary conditions, these were increased using percentages derived from previous studies (Schwartz, et al., 2015) to take into account transport (2%), construction (7%) and disposal (2%) emissions. As it was not possible to quantify the amount of components used to switch from an electric to gas heating system, only the impact due to fuel type was considered.

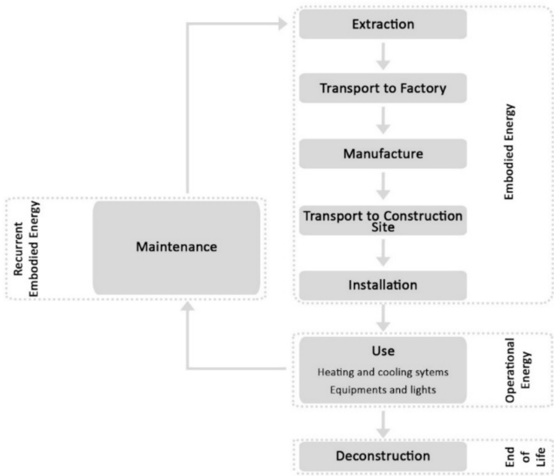

Figure 3 Boundary conditions of the LCCF assessment

Table 4 Energy conversion factors and costs

Energy type	Carbon emissions	Cost
	$kgCO_2$/kWh	£/kWh
Electricity	0.519	0.17
Natural gas	0.216	0.05

Operational Energy: Operational energy was calculated using EnergyPlus v8.2 and converted into CO_2 using the NCM carbon conversion factors (Table 4) (EPBD, 2014).

Recurrent Embodied Energy: The lifespan values of the construction materials were derived from NBS specifications, the National Association of Home Builder and CIBSE Guide M (CIBSE, 2008). Based on these, specific equations were produced for the calculation of the LCCF and LCC. In regards to the LCCF, the general equation (1) which refers to the i-component/system/ technology was modified according to the specific case (eqs 2-3).

(1) $$\text{LCCF}=\sum_{i=1}^{n} ECi * Y/Li \; + OC - OC\ renewable$$

Where:	OCi = operational energy of the i-system (kgCO2)
i = component/system/technology	Y = life time of the assessment (years)
ECi = embodied carbon of the i-component ($kgCO_2$)	Li = life span of the i-component or system (years)

(2) *LCCF = [(ECins * Y/Lins) + (EC rainscreen * Y/Lrain.) + (EC finishes * Y/Lfinishes.) + (EC win * Y/Lwin) + (EC pv * Y/L pv)] + (OE heating + OE equi./light + OE renewable)*

(3) $$LCCF = [(Fi\ x\ Ti\ x\ Di)\ x\ (1+Mi)]x \sum_{j}^{mj} Aij\ x\ \frac{Y}{Li} + [(Fr\ x\ Tr\ x\ Dr)\ x\ (1+Mr)]x \sum_{j}^{mj} Arj\ x\ \frac{Y}{Lr} + [(Ff\ x\ Tf\ x\ Df)\ x\ (1+Mf)]\ x \sum_{j}^{mj} Afj\ x\ \frac{Y}{Lf} + [Pw\ x\ (1+Mw)]\ x \sum_{j}^{mj} Awj\ x\ \frac{Y}{Lw} + [Pp\ x\ (1+Mp)]\ x \sum_{m}^{mj} Apj\ x\ \frac{Y}{Lp} + Y\ \{[(S+W)\ x\ EH] + [(E-X)\ x\ EE]\}$$

Where:	F = embodied carbon ($kgCO_2$/kg)	L = life span of the component (year)
i = insulation	P = embodied carbon ($kgCO_2$/m²)	S = space heating energy (kWh/year)
r = rainscreen	T = thickness (m)	W = water heating energy (kWh/year)
f = finishes	D = density (kg/m³)	EH= heating fuel carbon emissions ($kgCO_2$/kWh)
w= window	M = waste (%)	E = electricity for equipment & lighting (kWh/year)
p = pv panels	A = area (m²)	EE= electricity carbon emissions ($kgCO_2$/kWh)
	Y = life time of the assessment (year)	X= electricity produced by the PV system (kWh/year)

The LCC analysis was carried out considering the following costs (4):

(4) $LCC = Cmaterial + Cinstallation + Coperation + Cmaintenance + Cdisposal$

Costs were calculated according to Spons Guide for Architects (AECOM, 2014) and using manufacturer data. Energy costs were derived from the UK Government Energy Price Statistics (2014) (DECC, 2015) (Table 8). The labour cost for component installation was taken into account in this study, while design costs were not. The costs over the whole lifetime were calculated using Equations 5 and 6 as in Islam, et al. (2015). The inflation rate was assumed to be 2.7% (average of the past 10 years) (RateInflation, 2015) while the discount rate was assumed to be 3.0% as indicated in The Green Book (HM Treasury, 2015).

Life Cycle Impact Assessment: The Global Warming Potential was considered as the impact category.

(5) FC = PC x (1+f)n

Where:
FC = future cost (£), f = decimal inflation rate
PC = Present cost (£), n = years

(6) $DPV = \frac{FC}{(1+d)^n}$

Where:
FC = future cost (£), n = years , d = decimal discount rate, DPV = discounted present value (£)

RESULTS AND DISCUSSION

Sensitivity Analysis

A sensitivity analysis was carried out to assess the potential extent and magnitude of the impact of the number of generation, the population size and the number of objective functions on results (Table 5).

In the cases where two objective functions were used, these referred to the LCCF and LCC while in the other cases, where eight objective functions were used, even the partial results were calculated as reported in Table 1. The analysis highlighted that 60 generations were sufficient to reach convergence and that the defined algorithm functioned better with a smaller number of objective functions. As the Pareto solution results almost overlapped in simulation 3 and 4, simulation 4 results were chosen as representative in order to carry out considerations about both partial and total results.

Optimisation Results

The comparison of the optimisation results of the un-refurbished and refurbished solutions highlights the considerable gap between LCCF and LCC over 60 years (Figure 5). A more detailed analysis of optimisation results indicates a substantial difference between the electric and gas heating (Figure 6).

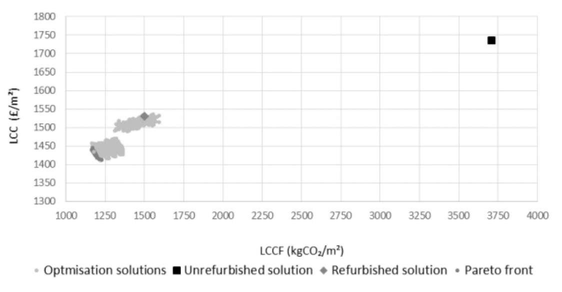

Figure 5 Comparison of the optimisation results (sim. 4 with the un-refurbished and refurbished solutions)

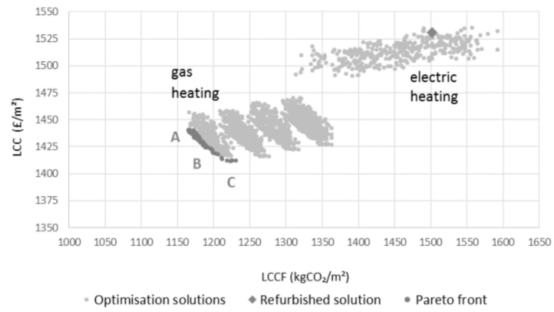

Figure 6 Optimisation results (simulation 4)

In general, results shows that thicker insulation is recommended on both the South West and North East facades and that windows (which have lower thermal performance and higher costs) can be used for the kitchen on both the south and north sides. The external windows for the bedrooms, living room and the balcony varied depending on the specific combinations of parameters. The installation of the maximum percentage of PV panel area and switching from an electric to a gas heating system are recommended as in the traditional intervention. Values for selected solutions are listed in Table 6.

Table 5 Simulation summary

simulation n°	population	generations	jobs	type	n° of obj.	time (h)	Convergence
1	8	120	960	Local	2	16	~60
2	8	80	640	Local	2	11	~60
3	8	80	640	Local	8	11	~60
4	32	80	2560	Local	8	40	~60

Table 6 Selected Pareto solutions (T= triple glazing, D= double glazing, S= single glazing).

Solution	Description	Unit	A	B	C
P1	*Insulation thickness_envelope 1**	mm	250	150	150
P2	*Insulation thickness_envelope 2**	mm	250	200	150
P3	*Heating fuel*	-	NaturalGas	NaturalGas	NaturalGas
P4	*PV on the south façade, wall 1*	%	100	100	100
P5	*PV on the south façade, wall 2*	%	100	100	100
P6	*External windows glazing type (Living room and bedroom)*	-	T	D	D
P7		-	T	T	D
P8	*External windows glazing type (Balcony)*	-	D	D	S
P9		-	T	S	S
P10	*Interior window glazing type (Kitchen)*	-	S	S	S
P11		-	S	S	S
LCCF		*kgCO_2/m²*	*1,166*	*1,193*	*1,219*
LCC		*£/m²*	*1,440*	*1,425*	*1,412*

In regards to the EC and ECO_2, results illustrate the significant role of the operational phase. For both, the Pareto solutions obtained using LCCF and LCC as objective functions (Figure 6) correspond to the solutions with the lowest operational CO_2 and costs (Figures 7-8).

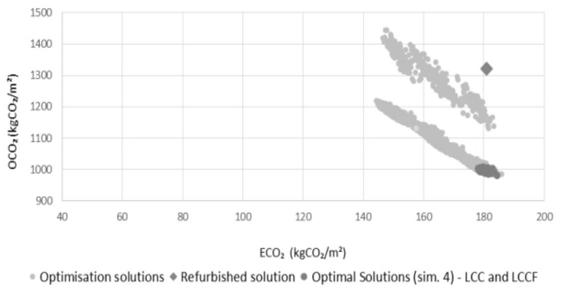

Figure 7 Optimisation results (simulation 2) Operational and Embodied CO_2

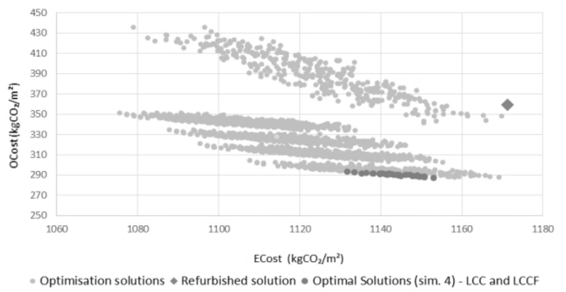

Figure 8 Optimisation results (simulation 2) Operational and Embodied Costs

Un-refurbished, Refurbished and Optimal Solution

To allow for the comparison of optimisation results for the un-refurbished and refurbished solutions, the Pareto solution B (Figure 6 and Table 6) was assumed to be representative. Results show an 80% reduction in the Operational CO_2 emissions due to the heating system. Furthermore, a reduction of 70% between the optimal solution and the refurbished solution and a difference of about 95%, between the optimal solution and the un-refurbished building can be observed (Figure 9). Further analysis of results in Figure 9 highlight the following:

- For Total Operational CO_2 emissions, these trends are similar to the light and equipment energy demand and are not affected by parameter variation. The minimal differences are mainly due to the presence of the PVs in the refurbished and optimal solutions.
- The Embodied CO_2 is about four times greater in the refurbished and optimal solutions compared to the un-refurbished solution, with a difference of approximately 140 kgCO_2/m^2. The gap is not as significant, as most of the main components of the intervention were assumed to have a lifespan greater than the lifetime of the assessment.
- The optimal solution is always lower in terms of partial (ECO_2 and OCO_2) and total results (LCCF). The LCCF of the optimal solution is approximately 21% less than the refurbished solution with a variation of about 320 kgCO_2/m².

This analysis suggests that most of the differences between the un-refurbished solution and the optimal and refurbished solutions can be attributed to the use of gas instead of electricity as the primary fuel source.

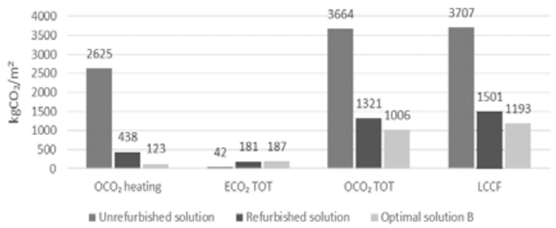

Figure 9 Operational CO_2 due to the heating system, Total Operational and Embodied CO_2, and LCCF

Further examination of the Operational and Embodied Costs, highlight similar trends as those above. Fuel type has a significant impact on the reduction of costs. The optimal solution presents slightly higher (~12%) Embodied Costs compared to the refurbished solution, however over the whole lifecycle this option is considered to be more convenient (Figure 10).

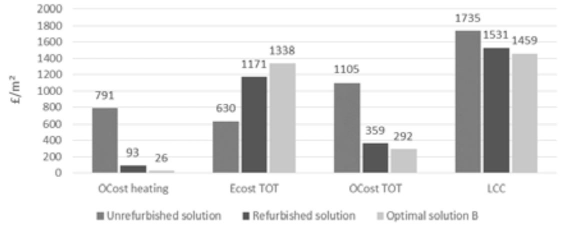

Figure 10 Operational cost due to the heating system, Total Operational and Embodied Cost, and LCC.

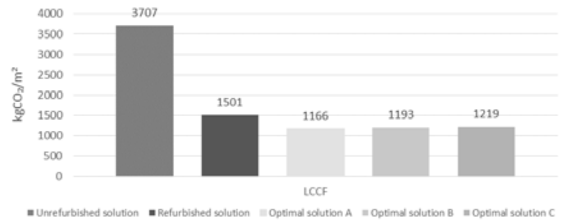

Figure 11 Comparison of LCCF for the un-refurbished, refurbished and optimal solutions (A,B and C).

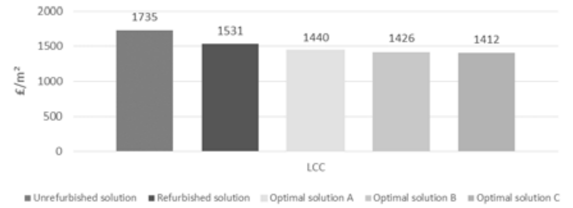

Figure 12 Comparison of LCC for the un-refurbished, refurbished and optimal solutions (A,B and C).

Overall, the LCCF and LCC of the optimal solution was slightly lower than the refurbished one, with reductions of 20% and 7% respectively (Figures 11-12). In Table 7 both the refurbished and optimal solutions had longer cost and shorter CO_2 emission payback times, with the optimal solution generally slightly lower. Despite an initial higher embodied carbon investment, annual CO_2 savings were higher for the optimal solution.

CONCLUSIONS AND RECCOMENDATIONS

The application of multi-objective optimisation for the minimisation of LCC and LCCF using EnergyPlus, jEPlus and jEPlus+EA provided an effective means by which to assess different design solutions.

The use of optimisation in combination with LCA analyses to support the refurbishment decision-making process based on the use of reliable data can provide valuable feedbacks in terms of highlighting options that combine achievable costs and carbon emission savings with potentially significant benefits in the case of large scale refurbishment projects. In regards to the specific case analysed in this study highlighted a substantial difference in terms of LCC and LCCF, between the un-refurbished building and the refurbished and optimal solution especially in the operational phase attributable to the change from electric to natural gas heating. Furthermore, while a total replacement was considered at the end of their operational life for most components, two of the main components were assumed to have a lifespan greater than the lifetime of the assessment. It should be noted that assuming more realistic replacement rates that depend on the state of component deterioration may lead to significantly different results.

The work highlighted the challenges in applying LCA to the building sector due to the relative novelty of the approach and the high degree of complexity of buildings as the subject of analysis. These are:

- The majority of calculation complexities as well as the accuracy of assessments relate to the gathering of reliable data as well as finding representative references.
- The most significant software limitation was the limited ability to effectively analyse more than three objective functions using the current algorithm.
- For modelling inputs, in the case of refurbishment interventions, measurements of occupant behaviour may allow for a more realistic model. Close cooperation between the professionals involved in the project and more accurate product certifications may allow for more precise assessments.
- Various challenges in defining a standardized method for LCCF and LCC for the building sector emerged. The method developed and applied in this study can be used for further cases but should be modified for the features of each specific case.

Finally, further work will focus on assessing the impact of the uncertain data on results and establishing mechanisms for gathering more reliable data,

Table 7 Comparison of LCC for the un-refurbished, refurbished and optimal solutions (A,B and C).

		Refurbished	**Optimal solution B**
Annual Carbon savings	$kgCO_2/m^2$	39.1	44.3
Embodied Carbon	$kgCO_2/m^2y$	180.8	187.4
Payback Time	*years*	*5*	*4*
Annual Cost savings	£/m²	12	14
Embodied Costs	£/m²y	1171	1133
Payback Time	*years*	*94*	*84*

REFERENCES

AECOM, 2014. Spon’s Architects’ & Builders’ Price Book 2015. Boca Raton:CRC Press.

Asiedu, Y. & Gu, P., 2015. Product life cycle cost analysis:State of the art review. International Journal of Prod. Research,36(4),pp.883-908.

BPIE, 2011. Europe’s buildings under the microscope - A country-by-country review of the energy performance of buildings, Brussels: Buildings Performance Institute Europe (BPIE).

Bribian, I., Aranda Uson, A. & Scarpellini, S., 2009. Life cycle assessment in buildings: State-of-the-art & simplified LCA methodology as a complement for building certification. Building & Environment, Vol 44, p. 2510–2520.

BRE , 2015. FAQ’S - The Green Guide [Online] . Bre, UK. From: http://www.bre.co.uk/green guide/ page.jsp?id=2089 [Acc: 3 July 2015].

BSRIA, 2006. What is whole life cost analysis? [Online].BSRIA,UK. From:https://www.bsria. co.uk/news/article/1886/ [Acc:4 June 2015].

Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) & life cycle energy analysis (LCEA) of buildings & the building sector: A review. Renewable & Sustainable Energy Reviews. Vol 29, pp.394-416.

Chau, C., Leung, T. & Ng, W., 2015. A review on Life Cycle Assessment, Life Cycle Energy Assessment & Life Cycle Carbon Emissions Assessment on buildings. Applied Energy, Vol 143, pp. 395-413.

CIBSE, 2008. Guide M - Maintenance engineering & management, Norwich. CIBSE Publications.

Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T., 2002. A Fast & Elitist Multiobjective Genetic Algorithm: IEEE Transactions On Evolutionary Computation, 6(2), pp. 182-197.

DECC, 2015. gov.uk [Online]. Available from: https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics [Acc: 3 July 2015].

Diakaki, C. & Kolokotsa, D., 2009. Life Cycle Assessment of Buildings. In: A Handbook of Sustainable Building Design & Engineering. UK.:Earthscan.

EPBD, 2010. European Directive 2010/31/EC on the Energy Performance of Buildings (EPBD). Official Journal, 18 06, Iss L 153 13.

EPBD.2014. National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in Wales), s.l.: Building Research Establishment.From: http://www.ncm.bre.co.uk /filelibrary/NCM_Modelling_Guide_2013_Edition_06April2014.pdf [Acc: 9 June 2015].

Evins, R., 2013. A review of computational optimisation methods applied to sustainable building design. Renewable & Sustainable Energy Reviews, Vol 22, pp. 230-245.

HM Treasury. 2013 The Green Book-Appraisal & Evaluation in Central Government. London.

Islam, H., Jollands, M. & Setunge, S., 2015. Life cycle assessment & life cycle cost implication of residential buildings—A review. Renewable & Sustainable Energy Reviews, Vol 42, pp.129-140.

ISO, 2006. ISO 14040:2006-Environmental management - Life cycle assessment - Principles & framework.

ISO, 2006. ISO 14044:2006-Environmental management - Life cycle assessment - Principles & framework.

Karimpour, M., Belusko, M., Xing, K. & Bruno, F., 2014. Minimising the life cycle energy of buildings: Review & analysis. Building & Environment, Vol 73, pp. 106-114.

Karmellos, M., Kiprakis, A. & Mavrotas, G., 2015. A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: Model, software & case studies. Applied Energy, Vol 139, pp. 131-150.

Mandley, S., Harmsen, R. & Worrell, E., 2015. Identifying the potential for resource & embodied energy savings within the UK building sector. Energy & Buildings, Vol 86, pp. 841-851.

Nguyen, A., Reiter, S. & Rigo, P., 2014. A review on simulation-based optimisation methods applied to building performance analysis. Applied Energy, Vol 113, pp. 1043-1058.

Penna, P., Prada, A., Cappelletti, F. & Gasparella, A., 2015. Multi-objectives optimisation of Energy Efficiency Measures in existing buildings. Energy & Buildings, Vol 95, pp. 57-69.

Ramesh, T., Prakash, R. & Shukla, K. K., 2010. Life cycle energy analysis of buildings: An overview. Energy & Buildings, 42(10), pp. 1592-1600.

Rate Inflation, 2015. RateInflation. [Online]. From:http://www.rateinflation.com/. [Acc: 05 July 2015].

Schwartz, Y., Raslan, R. & Mumovic, D., 2015. Implementing Multi Objective Genetic Algorithm for Life Cycle Carbon Footprint & Life Cycle Cost Optimisation: A Building Refurbishment Case Study.(in print).

Stephan, A., Crawford, R. & De Myttenaere, K., 2012. Towards a comprehensive life cycle energy analysis framework for residential buildings. Energy & Buildings, Vol 55, pp. 592-600.

TRIMBLE, 2015. SketchUp. www.sketchup.com/

U.S.DOE, 2015. http://apps1.eere.energy.gov/ buildings/energyplus/openstudio.cfm

UNEP, 2009. Buildings & climate change: a summary for decision-makers, Paris: UNEP

University of Bath. Inventory of Carbon & Energy V2.0. [Online] [Acc: 16 April 2015.] http://www.environmenttools.co.uk /directory/tool/name/inventory-of-carbon-&-energy-ice-university-of-bath/id/780.

Yu, W. Et Al., 2015. Application of multi-objective genetic algorithm to optimize energy efficiency & thermal comfort in building design. Energy & Buildings, Vol 88, pp. 135