Multi-Objective Genetic Algorithms for the Minimisation of the Life Cycle Carbon Footprint and Life Cycle Cost of the Refurbishment of a Residential Complex`s Envelope: A Case Study

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ABSTRACT

Life Cycle Analysis (LCA) is an environmental assessment and management framework that aims to simplify the decision-making processes of manufacturing and consumption, with regard to their environmental impact. In the built environment, LCA is often used as a comparative tool that helps in choosing one design alternative over another. Most LCA studies compare a limited number of design alternatives due to the complexity of the method.

The main goal of this study is to examine the various Life Cycle aspects of a refurbishment of a case study, and explore the potential of using Multi Objective Genetic Algorithms (MOGA) with Dynamic Thermal Simulation Tool (EnergyPlus) to find optimal refurbishment measures in terms of Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) over an assumed life span of 60 years.

Results show that MOGA successfully identified optimal design solutions, when taking into account both basic design aspects such as window-to-wall ratio or envelope build-ups, but also more detailed ones, such as thermal bridges insulation and the use of different fuel types for energy generation.

Author Keywords

Multi-objective Genetic Algorithm; Building Performance Optimisation; LCA - Life Cycle Analysis; LCCF – Life Cycle Carbon Footprint; LCC – Life Cycle Cost.

INTRODUCTION

The building industry is responsible for approximately 40% of the global energy consumption, 40% of global raw aggregates, gravel and sand and 25% of wood [1, 2, 3, 4]. In the built environment, energy is used throughout the different phases of a project, starting from material extraction through to building components manufacturing, construction, usage and demolition [5].

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LCA (Life Cycle Assessment) is a method that offers a holistic approach for assessing the potential impact of products and process on the environment throughout their lives in what is referred to as a 'cradle to grave' approach [6, 7]. The inputs of an LCA study are units of resources and substances, and its outputs are the environmental impacts (called Impact Categories). In the built environment, LCA impact categories are usually converted into a single value – CO_2e (CO_2 Equivalent) – which measures the Global Warming Potential - GWP [8]. This type of analysis is referred to as Life Cycle Carbon Footprint (LCCF).

In order to achieve the maximum carbon emission savings throughout a building`s lifetime, the optimal balance between the Embodied Carbon (carbon that had been invested during construction) and Operational Energy Carbon (carbon emissions associated with in-use burning of fossil fuels) needs to be found.

In acknowledging the value of existing buildings, the demand for refurbishment has increased. Improving the performance of existing buildings, while keeping the additional embodied carbon and cost to a minimum, has become a key challenge in reducing the Life Cycle impact of buildings.

This study examines the impact of the refurbishment of a case study building on its LCCF (Life Cycle Carbon Footprint) and the LCC (Life Cycle Cost). In particular, the study aims to answer the following questions:

- Can computational optimisation methods with Dynamic Thermal Simulation Tools be utilized to find the optimal refurbishment measures, in terms of LCCF and LCC?
- What LCCF and LCC improvement rates can be achieved by using optimisation methods?

BACKGROUND AND LITERATURE REVIEW

Carbon in Buildings

In order to mitigate building carbon emissions from, it is essential to first identify their sources. As carbon emissions are the result of the burning of fossil fuel, an aggregation of energy consumption in the building must be carried out.

The inputs and outputs of LCCF in buildings are therefore a combination of two components [9]:

Embodied Energy (EE)

EE is the required energy for the manufacturing of a building product, including the energy associated with the extraction of raw materials, transport to factories and manufacturing (also called “cradle to factory gate”), as well as transport to site (“gate to site”) and energy consumption for construction on-site [5]. Various case studies indicate that EE is responsible for 9-46% of the total Life Cycle energy consumption in low-energy buildings, and for 2-38% in conventional ones. [10, 11].

A common method for calculating Embodied Carbon is using Embodied Carbon Factors from pre-calculated Inventories. In the UK, one of the most popular pre-calculated databases is the Bath Inventory of Carbon and Energy (Bath ICE [5]) developed at Bath University.

Operational Energy (OE)

Operational Energy in buildings is the energy that is used for maintaining the thermal and environmental conditions and includes such aspects as heating, cooling, domestic hot water and lighting [12]. OE is usually calculated by using Building Performance Simulation tools. Once OE consumption is calculated, it is multiplied by carbon emissions associated with each fuel type, thus the choice of fuel may have a significant impact on LCA results [13, 14].

Components of LCA

ISO 14040:2006 (Environmental Management — Life Cycle Assessment — Principles and Framework) is regarded to be one of the most commonly used LCA frameworks in the LCA industry. It consists of four steps:

1. Goal and Scope – Determination of the goals, boundaries, assumption and limitations.
2. Life Cycle Inventory (LCI) – Specification of input and output inventories of energy flows of all systems and sub-systems of production.
3. Life cycle impact assessment (LCIA) – Evaluation of the different components in the inventory and their impact on the environment.
4. Interpretation –The formulation of conclusions and recommendations based on the LCIA.

Optimisation and Genetic Algorithms (GA)

Parametric simulation has in recent years been used in built environment research to improve building energy performance. As the basic method involved in parametric simulation is considered to be both time and resource consuming [15], to make the process more efficient, optimisation algorithms have been incorporated within them. Optimisation, in mathematical programming aspects, is the task of finding a solution which is both feasible and when it is the best of all other possible alternatives. [16]. Finding a solution for an optimisation problem might be a complicated task, especially if the given problem has a large number of possible scenarios to cover.

Genetic Algorithms (GA)

The principle behind GA is based on the theory of natural selection and evolution. The elements of a basic GA are:

- The generation of a set of possible solutions to a problem. Each solution is a result of a unique set of properties ('genes').
- The evaluation of the success of each solution, and comparing it to the other solutions.
- The selection of a set of the best solutions on which mathematical manipulations are applied to the 'genes'. These are based on principles inspired by evolution (mutating, breeding and crossover) to create a new, fitter, set of solutions to the problem.

Non-dominated Sorting Genetic Algorithm 2 – NSGA2

To enable the realization of the two objectives of this study (LCCF and LCC), a Multi-objective GA was used. Previous studies state that NSGA2 is one of the most widely used Multi-objective GAs [17] and is less prone to local optimums than other optimisation algorithms [18].

NSGA2 is based on the concept of Pareto Dominance; where for a given set of solutions for multiple-objective problem, one solution option is considered to be better than another (or, Pareto dominates it). This occurs when all solutions presented for one option are deemed as good as the other option for all objectives, and at least one solution is deemed better [19].

Figure 1 shows a two-dimensional Pareto optimal front, where individual 'B' is better than 'A' along the x axis and individual 'A' is better than 'B' along the y axis. They dominate each other for different objectives. Individual '2', however, is better than 'B' for both axes. No other individual dominates it on either axis. The goal of NSGA2 is to find a set of solutions which are not dominated by any others [18].

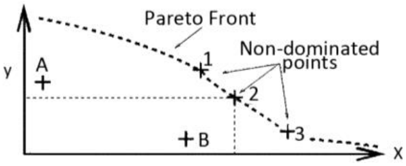

Figure 1. Pareto front. [19]

Building Performance and LCA Optimisation

Various studies have used GA to minimise building life-cycle impacts. While studies [20] have shown that a multi criteria GA can be used for the minimisation of the life cycle environmental impact and cost of a 1000 m^2 case study office building, the methodology used involved the utilisation of a steady-state simulation toolkit for Operational Energy calculations (i.e. a simplified and general calculation method), instead of a more detailed

Dynamic Thermal Simulation (DSM) tool. Another study [21] used optimisation algorithms on the refurbishment of a semi-detached house to optimise refurbishment associated costs, energy consumption and thermal comfort within the building. The study used a simplified optimisation algorithm that only allowed for the alteration of a very limited set of numerical values (e.g. U-Values), rather than physical elements within the building (window-to-wall ratio / shading elements, etc.). It concluded that for more complicated optimisation problems - Evolutionary Multi-Objective Algorithm should be used.

THE CASE STUDY

For this study, a council housing complex in the city of Sheffield in the United Kingdom was used. The complex was built in the late 1950s and was recently refurbished by Hawkins Brown Architects.

The original building was regarded as being poorly-built. The original envelope consisted of un-insulated brick and exposed-concrete structure which was considered to be one of the main architectural features in the original design, but lead to significant thermal bridges which can result in higher energy consumption and the formation of mold in interior spaces. The exposed concrete was also a main feature in the refurbishment and was therefore kept intact, while the facades of the building were re-clad. In doing so, the designers not only kept the original appearance of the building, but were also able to minimise its life cycle environmental impact. However, in keeping the concrete exposed, the risk of creating thermal bridges increased.

The case study building uses waste combustion district heating system for space and water heating, which is considered to be a very efficient supply system.

METHODOLOGY

Research Design and Tools Used in the Study

In order to carry the optimisation process, this study used EnergyPlus as the DSM tool. The study was implemented in the following steps:

1. Model preparation: An initial .idf (Input Data File) file which includes all the required geometric data for a thermal simulation (coordinates of walls, roof, floors, thermal zones etc.) was created in Google Sketchup 8.0.
2. Model specification: The thermal parameters of the model (U-Values, weather file data, HVAC etc) were set in EnergyPlus.
3. Optimisation preparation: The definition of the GA objectives and genes was undertaken in jEPlus (v.1.5). This java-based parametric simulation manager, designed for EnergyPlus, allows batch simulation, and was responsible for generating models following the genes.
4. Run optimisation and results analysis: The jEPlus project was imported to jEPlus+EA – a platform that allows the manipulation of the batch simulation and the performance of a GA optimisation studies. The GA code was run in jEPlus+EA, which was also used to control the population size, number of generations, crossover rate, etc.

Model Construction and specification

The study focused on the optimisation of the building envelope, as this has a major impact on the passive performance of the building. In exploring the thermal qualities of the various components of the envelope, the study specifically focused on U-Values, window-to-wall ratios and thermal bridge insulation. The genes for the GA were therefore defined as:

- Insulation thickness
- Wall build-ups
- Window-to-wall ratio
- Thermal bridge insulation

The shaded surfaces in Figure 2 indicate the materials and building components that could be manipulated by the GA. This led to a total of 55,296 possible combinations (Table 1). A total of 1125 individuals were simulated – a population of 9 individuals during 125 generations. The code had a mutation rate of 0.2 and a cross-over rate of 1.0. Table 2 shows the building component build-ups and GA genes. The CIBSE "UK-ManchesterTRY" weather-file was used for the thermal simulations as it was considered to be the closest and most reliable available weather data.

THE CASE STUDY`S LCA

In adhering to the ISO 14040 framework, the LCA study was implemented as follows:

Goal and Scope

The goal of the study is to examine the use of optimisation methods using Dynamic Thermal Simulation Tools to minimise the LCCF and LCC of a case study building. Furthermore, the study also examines the improvements, generated by the optimised LCCF and LCC. As such, all steps from cradle to grave were taken into account and carbon emissions were calculated through a mixture of calculated and assumed coefficients (Table 3).

Based on similar studies [10, 11], a 60 year building life span was defined. In the analysis, the whole building was treated as the system unit, and the functional unit for the analysis was 1 m2 of the building floor area.

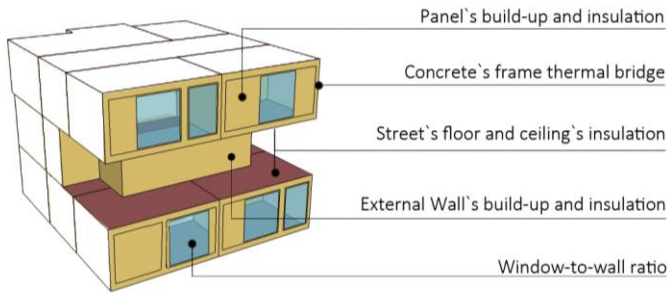

Figure 2: The building elements for the GA optimisation

Gene`s name	Possible value
Panel Insulation, Street insulation	50, 100, 150 [mm]
Exterior Insulation	50, 100, 150 [mm]
Bricks	0, 100 [mm]
Thermal bridges Insulation	0,50,100 [mm]
Window South-West Bottom	25, 50, 75, 100 [%]
Window South-West Middle	25, 50, 75, 100 [%]
Window South-West Top	25, 50, 75, 100 [%]
Window North East Bottom	25, 50, 75, 100 [%]
Window North East Top	25, 50, 75, 100 [%]
Total Number of combinations	55,296

Table 1: Genes and their possible values

Panel	Exterior Wall	Interior Wall	Window
Metal surface	Cement board	Plaster board	Clear glass
Brick	Brick	Rock Wool	13mm Air gap
Rock wool	Rock wool	wool	Clear glass
Plaster board	Plaster board	Plaster board	

Interior floor	Street ceiling	Street floor	Concrete frame
Timber	Timber	Timber	Concrete
Ceiling air space	Ceiling air space	Rock wool	Rock wool
Concrete	Concrete	Concrete	Plaster board
Rock wool	Rock wool	Rock	
Plaster board	Plaster board	Plaster board	

Table 2: Build-ups. In gray – GA`s genes

Life Cycle Inventory (LCI)

An inventory of the environmental impacts of building materials used in the refurbishment was established, based on the architectural drawings and specifications. The carbon inventory was based on various assumptions:

- Embodied Energy – Since the GA generates a large number of models, the total area of each building component (walls/floors/windows etc.) in each simulation had to be calculated automatically for each model. The total areas were then multiplied by the relevant carbon factors using Bath ICE [5]. Costs were calculated in a similar way, based on Spons` Guide for Architects [22].

  Waste rates, carbon due to transport and construction, Recurrent Embodied Energy (for refurbishments) and 'End of Life' carbon (demolition) were also taken into account, as shown in Table 3, based on assumptions used in previous studies [13, 23, 24, 25]. The percentages in Table 3 refer to total material EC, which was regarded to be 100%. This is the value that had been calculated automatically for each model in the "Building Material + Waste" section in that table.
- Energy in use – Operational Energy was calculated in EnergyPlus. Energy outputs were then converted to carbon emissions using the National Calculation Methodology`s (NCM) carbon conversion factors [26]. Energy costs were taken from the UK Government Energy Price Statistics [27].
- The district heating system has a very low carbon emission factor value of 0.057 kg CO_2/kWh [14, 29]. In order to examine the life cycle impacts of the refurbishment under a more generic fuel type, two LCA optimisations were undertaken; one in which the primary energy was the waste combustion district hearting, and the other in which the primary energy was the more conventional gas boiler, which has a carbon conversion factor of 0.21kgCO_2/kWh [28].
- The cost of heating energy is the same, whether heating is produced by waste or natural [29].

Life Cycle Impact Assessment (LCIA)

In order to minimise the LCCF and LCC of the building, the GA code had to calculate both values for each and every model it generated. The calculations were split into two parts. The first summed up the Embodied Carbon and cost, and the second calculated the Operational Energy related carbon and cost.

The LCCF was calculated based on the following equation:

$$LCCf = \sum_{i=0}^{ni}(Ki \times Ti \times Di \times (1 + Mi) \times (\sum_{j}^{mj} A\,ij)) + Y(((S + W) \times EH) + (E \times EE)) \quad (1)$$

Where:

i = Number of material

Ki = Material`s Embodied Carbon (kgCO_2/kg)

Ti = Material`s Thickness (m)

Di = Material`s Density (kg/m3)

Mi = Material`s additional energy coefficient – includes embodied energy in waste, transport construction and demolition (%).

Ai = Material`s Area (m^2)

j = Number of surfaces of the i`th material

Y = Number of years

S = Space heating energy (kWh)

W = Water heating energy (kWh)

EH = Carbon emissions due to heating fuel (kgCO$_2$/kWh)
E = Electricity energy (kWh)
EE = Carbon emissions due to electricity fuel (kWh)

Equation 1: LCCF Calculation

Similarly, LCC was calculated by the equation:

$$LCC = \sum_{i=0}^{ni}(Ci \times (1 + Li) \times (\sum_{j}^{mj} A\,ij)) + Y(((S + W) \times CH) + (E \times CE)) \qquad (2)$$

Where:
i = Number of material
Ci = Material`s Cost (£/m^2)
Li = Material`s additional energy coefficient – includes embodied energy in waste and transport
Ai = Material`s Area (m^2)
j = Number of surfaces of the i`th material
Y = Number of years
S = Space heating energy (kWh)
W = Water heating energy (kWh)
CH = Cost of heating energy (£/kWh)
E = Electricity energy (kWh)
CE = Cost of electricity (£/kWh)

Equation 2: LCC Calculation

Results and Interpretation

Four optimisation projects were simulated, using a cloud simulation service and an i7 Intel processor with 6.0 GB installed memory. Each project had a population size of 9 individuals and tested 125. It took around 6 hours to simulate using the cloud service, and 10 hours using the PC.

Optimisation Results

Figure 3 shows the progress of the typical optimisation run in this study.

The graph shows that the code achieved significant improvements in LCCF and LCC after 25 generations, and then reached the optimal solutions after approximately 75 generations. This shows that using NSGA2 for LCA optimisation can work and save many hours of simulation (1,125 models were simulated in each optimisation run, instead of the original 55,296 models).

The use of GA therefore presents the opportunity to examine the performance of numerous buildings and compare their performance. Each dot on the graph below represents a model with different set of genes.

Embodied / Operational Carbon - Waste Combustion District Heating

Figure 4 shows the embodied and operational carbon in the waste combustion district heating scenario. The following conclusions can be drawn from it:

- The embodied energy of the refurbishment was between 210-290 kgCO$_2$/m^2. In the case of a very efficient heating energy source, it has a relatively big impact on the overall LCCF (between 20-30%). Even though the building was only being refurbished (i.e. a large quantity of carbon has already been invested in its initial construction), these results echo previous studies [10, 11].
- The analysis of GA results shows the impact of insulating the thermal bridge and the thickness of the wall insulation on operational-related carbon emissions, as most optimal models had an insulated thermal bridge and the thickest available insulation.
- GA also showed that the majority of optimal individuals had minimal north facing windows. This can be attributed to the fact that northern windows do not have significant solar gains. Effectively, this means that these windows embody more carbon than saved.
- Interestingly, results show that none of the optimal individuals used any brick. This is likely due to the fact that since it has high embodied energy and makes relatively little contribution to building performance, it was therefore not considered beneficial from a life-cycle point of view.

LCCF + LCC: Waste Combustion District Heating

Figure 5 shows the multi-criteria optimisation process in the scenario of a waste combustion district heating system, where fitness criteria are LCCF and LCC.

Boundary	LCA	LCC	Source/Value
Building Materials + waste	√	√	Sketchup, Bath ICE
Transport	√	√	3%
Construction	√	-	7%
Energy in use	√	√	Energy Plus
Demolition	√	-	2%
Maintenance	√	√	Various values by material

Table 3: LCA boundary

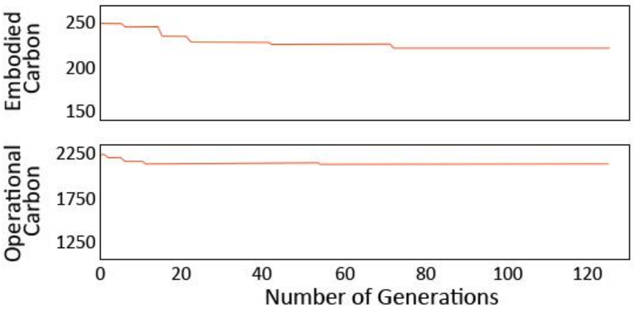

Figure 3: Optimisation`s progress

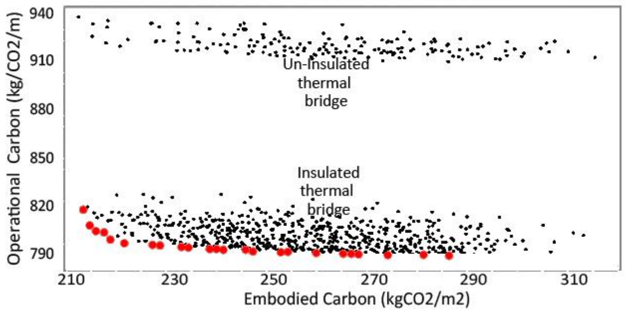

Figure 4: Embodied and Operational carbon emissions optimisation – Waste Combustion District Heating

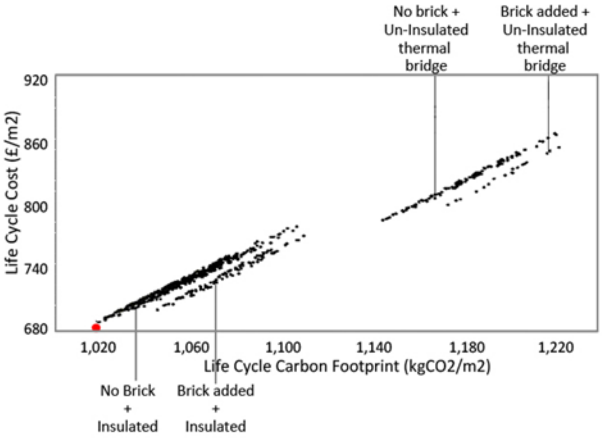

Figure 5: LCCF and LCC optimisation – Waste Combustion District Heating

Results show that GA successfully found an individual model with the best LCCF and LCC. Four groups of individuals clearly appear on the graph; individuals with and without additional brick wall, and individuals with and without thermal-bridge insulation. Results also show that:

- The optimal individual chose the smallest windows in all facades (minimal embodied carbon).
- Individuals with a brick layer have lower Operational Energy consumption than individuals without it. However, it seems that this layer embodies more carbon than it saves throughout the building’s life.
- GA shows that insulating the thermal bridge reduces LCCF and LCC by around 10-15%.

Embodied / Operational Carbon: Natural Gas Heating

The performance of the building under the natural gas heating fuel scenario is illustrated in Figure 6. This shows that:

The total embodied carbon of the optimal cases is similar to that of the previous case, however, in this scenario, as the OE related emission values are 2-3 times higher than those of the waste combustion district heating system scenario, the refurbishment embodied carbon is around 10% of the buildings LCCF.

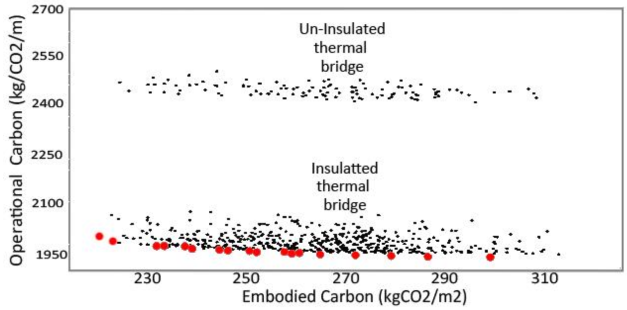

Figure 6: Embodied and Operational carbon emissions optimisation – Gas boiler

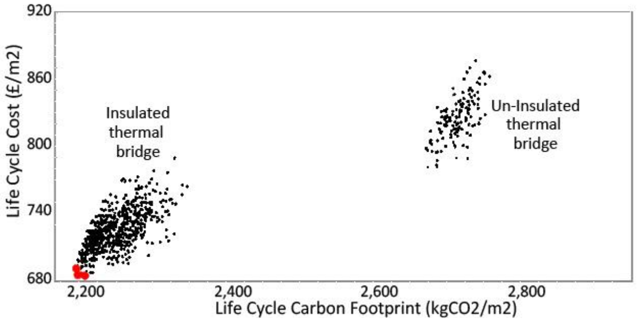

Figure 7: LCCF and LCC optimisation – Gas Boiler

- Similar to the previous scenario, GA results show the impact of insulating the concrete frame (thermal bridge) has on Operational Energy consumption. Almost all optimal individuals had the thickest available insulation and none used the brick.
- The building with the lowest LCCF and LCC values had the smallest north-facing windows and allowed various combinations for the south-facing windows.

LCCF + LCC: Natural Gas Heating

In the natural gas heating fuel scenario, where the fitness criteria are LCCF and LCC, results show that the multi-criteria GA successfully found optimal individuals (Figure 7). Two groups of individuals are clearly shown on the graphs – individuals with and without insulated thermal bridges.

- Even when OE related carbon account for around 90% of the building`s LCCF, the optimal individuals have the smallest available windows in all facades.
- GA shows that the optimal individuals chose the thickest available insulation, as it seems that adding insulation

saves more carbon than it embodies, and that insulating the concrete structure can bring to a reduction of between 10-20% in the LCCF and LCC in this scenario.

- Using a brick wall is still a more significant investment than what it can save (both in terms of carbon and cost).

Optimised Individuals` Carbon Payback Times

Carbon payback times were calculated for the optimised individuals for both primary-energy-source scenarios. Table 4 shows that the optimised solutions can be paid back much quicker. In addition, Table 4 shows that the payback time (in terms of whole-life carbon emissions) of a refurbishment of buildings that use waste-combustion district heating is very long, and therefore might not be worth the investment.

The reason for the difference between Figures 5 and 7 is the fact that the two scenarios used different fuel types. While Figure 5 shows the case of using a very efficient (low carbon emitting) district heating system, Figure 7 shows a less efficient (or more carbon-emitting) gas boiler scenario. The Y axis in both graphs shows that whole-life cost of the building, where Operational Energy costs are not affected by the different energy generation technology (district heating / gas boiler) [29].

The X axis, on the other hand, shows the building`s whole-life carbon emissions. When the Operational Energy is very low (i.e, in the district heating case) – the significance of building Embodied Carbon becomes more prominent as compared to its Operational-Energy-Related emissions.

In this case study, the building whole-life cost was substantially affected by the building Embodied Cost. In the case of the district heating, both axes are highly influenced by the Embodied component (Figure 5 suggests a stronger relationship than in Figure 7).

CONCLUSIONS

This study examined the optimisation of the LCCF and LCC of a refurbishment of a large residential complex. The main aim of the study was to examine the use of multi-criteria GA with Dynamic Thermal Simulation Tool as an optimisation method in LCA studies of buildings. The goal of implementing the optimisation code was to find the optimal building envelope properties that minimise the environmental impact of the refurbishment and the cost of its materials.

The study has shown that GA successfully found optimal solutions for the various examined scenarios. The study also examined the carbon emission savings and their payback times. Optimisation results indicate that the optimal models had the smallest available windows, which may be attributed to the fact that window Embodied Carbon is higher than the Operational Energy-related carbon that they save. For the same reason, bricks were not used in any optimal individual. The study also illustrates the impact of insulating thermal bridges on LCA, as well as the potential impact of various primary fuel types and heating systems on building LCA.

Further Studies

Even though the study successfully found optimal refurbishment measures for the case study, it is important to note that different buildings are likely to have different results. To draw a more generic set of conclusions that can be considered to be more widely applicable, a larger range of case studies should be examined.

In addition, while this study illustrated the benefits of using optimisation methods with Dynamic Thermal Simulation Tools for minimsing various life-cycle aspects in buildings, the simulation and optimisation process is still a complicated and a time-consuming process. It is still not possible to carry an optimisation study in a single simulation environment. A further examination of the communication between the different tools (3D modeling, thermal simulation and GA optimisation) is therefore required.

		Optimal design
Annual energy savings from original non-refurbished building (kWh/m^2/y)		70
Waste combustion district heating	Operational Carbon savings (kgCO$_2$/m^2/y)	4.0
	payback time (years)	79
Natural gas-based heating system	Operational Carbon savings (kgCO$_2$/m^2/y)	15.3
	payback time (years)	20

Table 4: Optimised individuals savings and payback times

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