Integrated Building Life Cycle Carbon and Cost Analysis Embedding Multiple Optimisation Levels

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Abstract

Because the optimisation of various building components and structural systems is often performed in isolation, this study developed an integrated approach for the optimisation of building life cycle carbon emissions and costs embedding multiple analysis levels. The functionalities of the proposed approach were tested in a realistic building scenario. Results demonstrated significant variations in the lifecycle carbon performance (more than 50%) and minor variations in the cost performance (10%) between the optimised building solutions. It was suggested that project teams could effectively use the proposed approach to understand the relationships between high-performing building configurations during the early design stages.

Introduction and Aims

Since the 1960's various computational optimisation techniques have been developed and extensively used by academics and practitioners (Yang, 2011). Specifically in the built environment, optimisation models have only been more commonly implemented since the late 2000`s to improve the performance of buildings: energy use, Heating, Ventilation and Air Conditioning (HVAC) systems, envelope (Islam, Jollands, Setunge, Ahmed, & Haque, 2014; Alaidroos & Krarti, 2015; Hasan, Vuolle, & Siren, 2008; Congradac & Kulic, 2009; Bichiou & Krarti, 2011; Nguyen, Reiter, & Rigo, 2014).

Optimisation algorithms were also widely applied in the context of buildings refurbishment for the evaluation of different design scenarios (Gustafsson, 2000; Bojic, Miletic, & Ljubisa, 2014; Han, Srebric, & Enache-Pommer, 2014; Chantrelle, Lahmidi, Keilholz, El Mankibi, & Michel, 2011; Ostermeyer, Wallbaum, & Reuter, 2013). Furthermore, the assessment of building life cycle carbon impacts has also begun to attract attention particularly for early design and decision-making purposes in new and reburbished buildings (Schwartz, Raslan, & Mumovic, 2018; Wang, Xia, & Zhang, 2014).

In building structures, mathematical optimisation was predominantly used to obtain efficient and economic design solutions without compromising the mechanical properties of the entire structural system (Bendsoe & Sigmund, 2004). Only recently, the consideration of life cycle carbon and other sustainability related concepts has started to be adopted within structural optimisation applications (Eleftheriadis, Mumovic, & Greening, 2017).

In recent studies, the relationships between the structural systems and other building components (form, layout, services, etc.) were evaluated to understand how material and carbon efficient structural solutions can be more effectively obtained during the early stages of a project. Eleftheriadis et al. (2018) and Dunant et al. (2018) have found that the optimisation of concrete and steel framed building structures, which constitute the most common structural material typologies, are mainly affected by the specification of the column grids, which are often determined by the project architects. These significant findings suggest that improved optimisation procedures that integrate structural and building level analysis are necessary.

However, the layout optimisation of structural systems is not a new concept. Noteworthy studies include Nimtawat & Nanakorn's (2010) layout optimisation of horizontal floor plans for a given column and wall arrangement and Sharafi, Hadi & Teh's (2012) column layout optimisation for a given rectangular plan in reinforced concrete buildings. These studies nevertheless, do not critically evaluate how the optimised structural designs would affect the spatial configurations or the life cycle carbon performance of the building. Typically, this level of analysis is conducted discretely or with limited practical applications as recognised by Schwartz, Raslan, Korolija & Mumovic (2017).

The aforementioned literature review confirmed that the detailed life cycle carbon optimisation of buildings is disaggregated and typically performed in multiple levels. Thus, this paper investigates how these different analysis levels (spatial, structural and building) could be integrated in a sensible manner to obtain more carbon efficient designs. The main aims of the paper are threefold:

1. Develop an integrated computational approach that optimises building life cycle carbon performance at multiple levels (structure, internal layout, and building components).
2. Test the proposed approach in a practical numerical scenario and evaluate the optimisation results in every level of the analysis.
3. Discuss contextual parameters that could facilitate the future implementation of such approaches in real projects.

Methods and Computational Components

Figure 1 shows the approach proposed in the paper to enable the integration of different optimisation levels. The rationale behind this sequential approach is to offer an automated design procedure that can improve the cost and life cycle carbon performance of buildings and help project teams identify efficient solutions during the early design stages.

The overall objective of the analysis is to optimise the following three levels:

1. The structural system and the column grid.
2. The spatial and interior spaces of selected building zones.
3. Building components such as wall build-ups and window areas.

The optimisation begins with a general building outline, which is specified in the project brief and complies with clients' or other planning requirements. This pre-optimisation phase was mainly used to obtain the overall dimensions of available building plots and other general service constraints such as building cores or vertical circulation (staircase, lifts, etc.) areas.

The geometric data for the building collected during the pre-optimisation phase were directly utilised in the first level of the analysis (Level 1), which involved the structural column topology as well as other design characteristics of the structure (floors and columns). Only the superstructure was included in the optimisation to simplify the computations. Thus, the foundations and the structural cores were excluded from the scope of the optimisation.

Multiple structural configurations were computed and evaluated based on their embodied carbon and cost performance. The focus of this paper is reinforced concrete (RC) buildings that cover a large proportion of residential and office stock in the UK. Thus, the engineering analysis and verification was performed according to the necessary building codes for RC structures (Eurocode 2 – EC2).

Selected optimised structural configurations were used as input parameters in the subsequent analysis. At Level 2, the structural column grids were used to generate the appropriate architectural zones for the building interior layouts. This is an important functionality of the proposed approach that provides realistic design constraints (column spacing) for the computation of the internal spatial configurations of the building.

In reality, an inverse procedure is typically implemented. The internal layouts in most buildings are articulated first by the architects with limited considerations about the implications in the performance of the structural system. For example, unnecessary large spans might make the design of internal layouts easier but they often result in large inefficiencies in the structure. Herein, it is suggested that a more balanced approach between the spatial requirements and the structural performance could yield more efficient structural and architectural designs solutions overall.

The realistic spatial layouts computed at Level 2 were embedded within a dynamic energy optimisation model at Level 3 to recognise building components such as the window-to-wall ratio and wall build-ups with the minimum life cycle carbon emissions and costs. The designs emerging from the proposed multilevel approach are expected to be optimised for their structural and building design components as well as for their structural and architectural layouts.

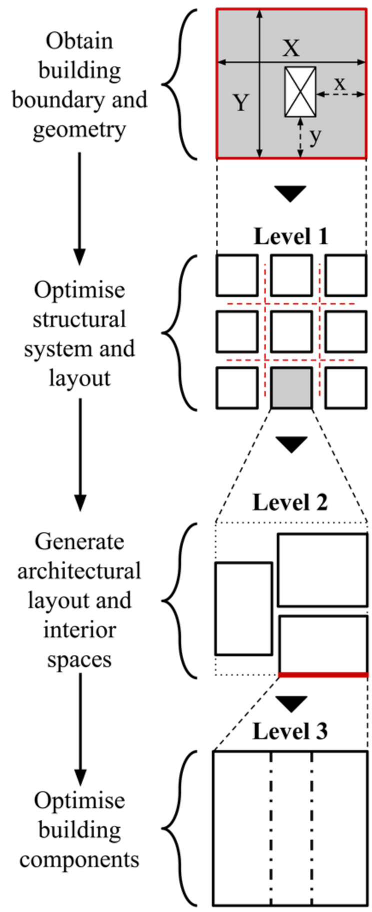

Figure 1: Optimisation approach showing the three analysis levels implemented in this paper.

To perform the analyses at the aforementioned levels various computational components were developed. The following sections describe the main functionalities and the associated algorithmic processes of the developed computational components.

Level 1 Structural Layout and System

The core algorithmic components from the multilevel and multi-objective optimisation approach proposed by Eleftheriadis et al. (2018) were implemented in the paper to perform the relevant structural optimisation computations. The optimisation model uses state-of-the-art Finite Element (FE) analysis utilising on the Non-Sorting Genetic Algorithm II (NSGA-II) algorithm supported by custom constructability functions to compute realistic and practical structural configurations: 1) Column grid, 2) Slab thickness and column sizes, 3) Slab and column reinforcement specifications. Material quantities from the structure are combined with the relevant carbon and cost factors in the corresponding objective functions to compute the optimised structural solutions visualised on the Pareto front.

Even though the model incorporated engineering analysis that is typically performed during the detailed design stages (especially the reinforcement computations in the slab), the intention of the optimisation was to support primarily early scheme designs. With that in mind, some functionalities relevant to the geometric assessment were simplified and complex building geometries could not be effectively modelled at this stage of the research.

Complex buildings would have to be broken down to simpler parts to successfully optimise them. Additionally, at this stage of the research the slab reinforcement computations do not consider punching shear. The implementation of that functionality significantly increased the computational time and thus it was de-activated. However, this limitation is not considered as significant, as the analysis focused on early stage designs, which often do not consider punching shear reinforcement in the slabs.

Level 2 Spatial Layout

Based on the optimal columns grid specified at Level 1, a set of spatial configurations was generated using PLOOTO (Parametric Layout OrganisatiOn generaTOr) - a software application that generates various spatial arrangements and building layouts, that can be further investigated in thermal simulation analysis. The application, which was first described in Schwartz, Raslan, Korolija & Mumovic (2017), receives a series of constrains and limitations as input parameters (i.e. number of floors in the building, number of required thermal zones, plot dimensions, acceptable rooms size etc.), as defined by a user, and outputs a series of geometrical solutions in the format of an .idf file, which is suitable for energy analysis with EnergyPlus. The generated model already contains relevant thermal properties and life-cycle performance data. The geometry can then be imported and examined in any CAD tool that can read .idf formats. The generated designs were subsequently used in the optimisation process at Level 3, which develops a series of Pareto-optimal models.

Level 3 Building Level

At this level, design properties were defined for the build-ups of the different envelope components, and a set of allowable window-to-wall ratios and window orientations. A multi-objective optimisation, using a designated NSGA-II algorithm, which has been developed for the purpose of this study, was then carried out. The optimisation procedure was used to evaluate the relationships between different layouts, build-ups window-to-wall ratios and window orientations, to find the optimal combinations that will minimise the Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC), whilst taking into account the embodied carbon and costs of the building structural elements computed at Level 1. LCCF methodology and scope followed standard BS EN 15978:2011, and LCC scope followed the BSRIA Life Cycle Costing guide (Churcher & Tse, 2016).

Numerical Analysis and Results

Building Scenario

A prototypical building scenario was used in the paper to perform the required numerical testing and analysis of the various optimisation computations. A square plot of 22m×22m was used assuming a central zone of 7.5m×7m, which is designated as the vertical circulation zone.

Structural Optimisation Results

The embodied carbon computations followed a cradle-to-gate approach using product-specific Environmental Product Declarations (EPD) and cost data (labour and materials) from Eleftheriadis et al. (2018). Table 1 summarises the cost and embodied carbon emissions for the optimised structural configurations on the Pareto front. It can be seen that small trade-offs (4-5%) exist between the optimum cost and optimum carbon designs, which suggests that carbon efficient designs can be obtained with minimum cost penalties.

Table 1: Cost and embodied carbon emissions for the Pareto front solutions obtained from the structural optimisation analysis at Level 1

Design	Structural Cost (£/m^2 of floor area)	Structural Carbon (kgCO_2/m^2 of floor area)
1	111.1	135.0
2	111.7	132.1
3	112.1	133.2
4	112.3	133.5
5	112.7	133.0
6	113.0	132.8
7	113.7	133.5
8	114.4	134.2
9	115.9	137.0

Design 1 was selected for further analysis in Level 1 & 2 due to economical reasons as it was the cheapest option. The column layout for a typical floor of the selected option is shown in Figure 2, whilst the design characteristics are summarised in Table 2. Figure 3 shows a detailed breakdown of the cost and embodied carbon emissions for the selected Design 1. It is evident that the slab carbon emissions and costs take up to 80-85% of the structures emissions and costs, which highlights the importance of an optimised slab design.

Results suggest that the emissions associated with the concrete in the slabs are the biggest contributor of the emissions in the structure (more than 60%). Furthermore, the following observations regarding costs can be made. The slab formwork is almost equally as important as the cost of the concrete in the slab. On the other hand, the formwork is the largest cost contributor in the columns.

From this, it can be concluded that formworks play a significant role in the cost performance of the entire structure.

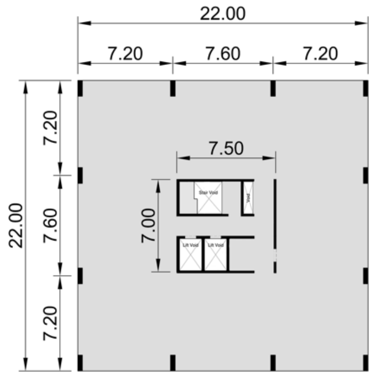

Figure 2: Typical floor plan showing the column grid in meters of the optimised Design 1.

Table 2: Design characteristics of selected Design 1

Slab thickness (mm)	275
Column sizes (mm)	12columns of 1200×350
Reinforcement rate (kg/m^3)	93
Total structural weight per floor (tonnes)	318
Slab Reinforcement Bars	Ø Varies
Column Reinforcement Bars Diameter (mm)	Ø16

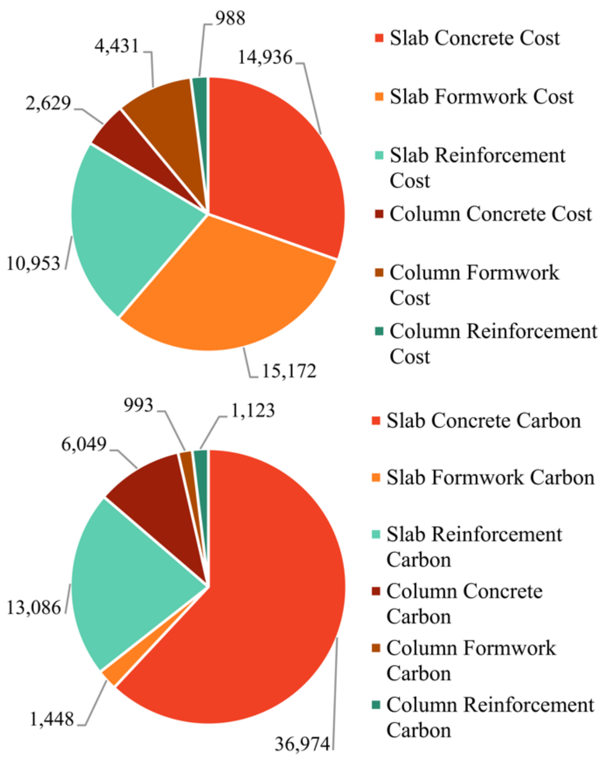

Figure 3: Cost (£) and embodied carbon ($kgCO_2e$) breakdown for Design 1.

Spatial Generation Results

Based on the structural optimisation results, the layout for a selected segment of the building (Figure 4) was generated and its life cycle performance was later optimised. The selection was done to utilise the unobstractred space between the optimised column grid.

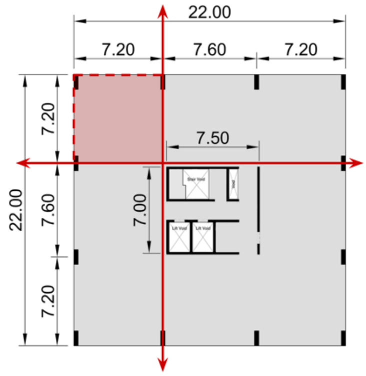

Figure 4: Zone selection for the generation of spatial configurations in PLOOTO.

As one of the main aims of this study was testing the processes and workflow of an overall buildng performance optimisation (structure, form and materials), the chosen case study building is a relatively simple one. To test the robustness of the spatial arrngement program, in this process, PLOOTO was evaluated for its ability to find all possible spatial arrangements of the given design task.

For this, a simple arrangement task was designed, where 3 thermal zones of different uses, each with a set of fixed possible dimentions, were identified (as described in Table 3 and Figure 5). The rooms then had to be distributed across a part of the building within a restricting dimentions 720×720 cm.

Table 3: Room design restrictions for PLOOTO computations.

Room	Possible size (mm)
1	720×480
2	480×240
3	240×240

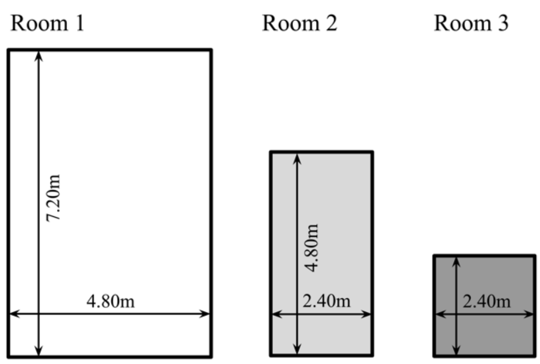

Figure 5: Dimensions of the three possible thermal zones.

For this particular design task, when the orientation of the model is fixed, only four spatial arrangements exist, as described in Figure 6. The program successfully managed to generate all possible spatial arrangements.

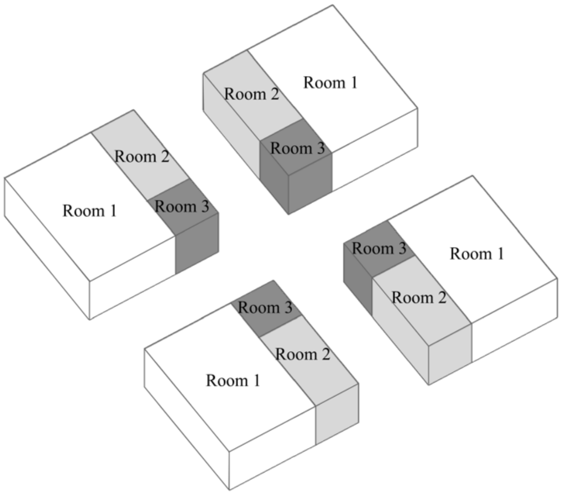

Figure 6: The four possible spatial arrangements.

Building Optimisation Results

Following the structural optimisation and the spatial arrangement generation, a total building design optimisation was carried (N=122,880 models).

Table 4 shows the building properties that were taken into account in the optimisation study, and the number of possible parameters for each design property. The optimisation process was carried out through a designated optimisation application, which used the principles of NSGA-II (Non Sorting Genetic Algorithms optimisation II). The application receives a number of EnergyPlus .idf files as input, and subsequently modifies a series of design properties, as indicated in Figure 7.

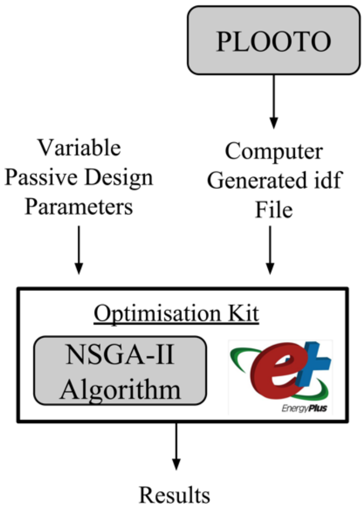

Figure 7: Final building optimisation approach.

To run the optimisation procedure, UCL Legion hub (an internal cloud computer infrastructure) was used. The optimisation was executed three times, with various combinations of number of generations and number of model per generation (ranging from between 30 – 60 models per generation and 10 to 20 generations). This was done to increase the confidence in finding the set of Pareto-optimal solutions. All runs had similar search space and identical Pareto fronts.

Table 4: Possible parameters and search space size

Parameter		Number of possible options
Layouts		4
Zones in each layout		3
Windows per zone		1
Structural solution		1
Possible Window-to-wall ratio		2 (25%, 75%)
Build-ups	External wall	5
	Ground floor	4
	Internal wall	2
	Ceiling	3
	Window types	2
Total of 122,880 combinations		

Figure 8 shows the results of the optimisation for the given building scenario, after running the optimisation with 60 models (individuals) over 10 generations. Results show that all Pareto-optimal models had a 25% window-to-wall ratio. All had the same external wall build-up, as well as internal wall and ceiling build-ups. Table 5 shows a summary of the LCCF and LCC for the optimised building design and construction.

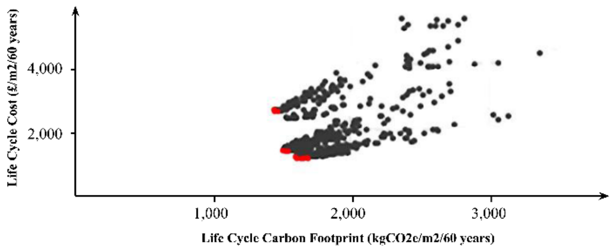

Figure 8: Final building optimisation approach.

Table 5: Optimised building design solutions from the Pareto front analysis

Design	Life Cycle Cost ($£/m^2$/60 years)	Life Cycle Carbon Footprint ($kgCO_2/m^2$/60 years)
1	1,507	2,621
2	1,507	2,618
3	1,512	2,606
4	1,513	2,603
5	1,577	1,439
6	1,577	1,436
7	1,584	1,434
8	1,584	1,431
9	1,590	1,430
10	1,590	1,428
11	1,666	1,216
12	1,666	1,213
13	1,673	1,209
14	1,674	1,206

Results show that all Pareto-optimal models had LCCF value of between 1,500-1,675 $kgCO_2m^2$/60 years. The majority of models reached LCC values off between 1,200 – 1,440 £/m^2/60 years, with the exception of two models that used more expensive window frames materials, and reached LCC of around 2,600 £/m^2/60 years.

Discussion

This paper has presented an open and collaborative building optimisation approach where insights from different design analysis levels can support project teams' expertise in the development of more efficient and sustainable building designs. Further developments on the technological, organisational and individual dimensions will make such integrated optimisation procedures more applicable and effective in the future.

In the technological level, the past decade new digital applications such as Building Information Modelling (BIM) and advanced parametric modelling have disrupted and radically changed the way design teams design, plan, construct and maintain building and infrastructure projects.

These applications will continue to grow in the future offering a shared architecture for integrated optimisation approaches like the one presented in this paper. As a result, improvements in the following three areas could continuously become more relevant:

1. Digital collaboration and organisation that consolidate numerical optimisation assessments organised in multiple levels.
2. Effective integration of rich cost information and carbon data obtained from the optimisation and the lifecycle analyses at building and structural levels.
3. Virtual Reality (VR) or Augmented Reality (AR) systems that would allow the analysis and visualisation of large amounts of data generated from the performed computations.

Furthermore, the study argues that besides the necessary technological developments, improvements in the current decision-making processes would be essential to obtain this degree of analysis.

Necessary parameters for an integrated organisation structure in more interactive virtual environment platforms would involve:

1. Explicit project criteria during the early design development.
2. Efficient decision processes embedding multiple design criteria.
3. Enhanced communication and integrated decision platforms.
4. Decision models that consider the dynamic relationships between the project team members.

The familiarisation of the new structure and the exchange of information between the various decision-makers are required to overcome cognitive limitations at individual level.

Improvements on the current design practices at individual level are also necessary to ensure designers become more familiar with automatically generated solutions. The adoption of such automated procedures could radically improve the work efficiency of project teams as repetitive tasks could be reduced or eliminated.

Additionally, automated design procedures like the one proposed herein could help engineers and architects identify potential design solutions and configuration that could not be instantly recognisable during the early phases of the project. In this automated design context, the role of the design team would be to critically evaluate the outputs from such integrated models and assess their practical applicability based on previous experience. As a result, through deeper human-computer interactions the entire design decision-making process of building project could be amplified in the future.

Conclusions

The paper presented an integrated approach for the optimisation of building life cycle carbon and cost performance considering multiple analysis level. Three interconnected analysis levels were incorporated in the optimisation: the first one consisted of the structural system of the building; the second one included the internal layout of designated building zones whilst the third one covered detailed building element components.

A numerical example was used to test the functionalities of the proposed optimisation in the context of a real building. The relationships between the cost and the carbon emissions at both structural and building levels were succesfully computed and analysed. At structural level, small trade-offs (2-5%) between the cost and the embodied carbon emissions of the entire structure were identified. On the other hand, the optimisation of life cycle carbon emissions and costs for the entire building highlighted that large trade-offs (10-50%) exist when the operational carbon emissions were also considered.

Contextual limitations across different technological, organisational and individual dimensions were critically discussed whilst future implementation strategies were reviewed.

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