Comparative numerical analysis for cost and embodied carbon optimisation of steel building structures

Stathis Eleftheriadis*[1], Cyrille F. Dunant[2a], Michal P. Drewniok[2], William Rogers-Tizard[3] and Constantinos Kyprianou[4]

[1]*Department of Computer Science, University College London, Gower Street, London WC1E 6BT, UK*
[2]*Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK*
[3]*Price & Myers, 37 Alfred Place, London WC1E 7DP, UK*
[4]*Steel Construction Institute, Silwood Park Campus, Ascot SL5 7QN, UK*

(Received keep as blank , Revised keep as blank , Accepted keep as blank)

Abstract. The study investigated an area of sustainable structural design that is often overlooked in practical engineering applications. Specifically, a novel method to simultaneously optimise the cost and embodied carbon performance of steel building structures was explored in this paper. To achieve this, a parametric design model was developed to rapidly analyse code compliant structural configurations based on project specific constraints and rigorous testing of various steel beam sections, floor construction typologies (precast or composite) and column layouts that could not be performed manually by engineering practitioners. Detailed objective functions were embedded in the model to compute the cost and life cycle carbon emissions of different material types used in the structure. Results from a comparative numerical analysis of a real case study illustrated that the proposed optimisation approach could guide structural engineers towards areas of the solution space with realistic design configurations, enabling them to effectively evaluate trade-offs between cost and carbon performance. This significant contribution implied that the optimisation model could reduce the time required for the design and analysis of multiple structural configurations especially during the early stages of a project. Overall, the paper suggested that the deployment of automated design procedures can enhance the quality as well as the efficiency of the optimisation analysis.

Keywords: structural optimisation; steel frames; cost; carbon; design

1. Introduction

Concerns about the life-cycle sustainability in buildings are rising, both within the UK and globally. Current structural engineering practices consider the minimisation of material usage to reduce financial costs only. Indeed, optimising structural systems to minimise embodied carbon emissions is currently a complex task, as the relationships between the cost and the embodied carbon of a structure are either difficult to analyse or take an impractically long time to quantify. Additionally, structural engineers often investigate only a limited number of options for a building scheme, which are chosen based on their past experience and empirical rules of thumb. Thus, buildings structures tend to be designed and constructed using knowledge and insights from previous

∗Corresponding author, Ph.D., E-mail: ucabele@ucl.ac.uk
[a] Ph.D., E-mail: cfd@cam.ac.uk

decisions, as opposed to bespoke decision development. Whilst this generally leads to functioning designs, in many cases there would have been better options available in terms of material system, floor construction or grid spacing. This paper explores effective ways to support structural design decisions through rigorous and automated optimisation mechanisms utilising embodied carbon and cost principles implemented in real buildings.

1.1 Relevant Literature & Context

To meet the CO_2 emission targets set by the 21st Conference of the Parties (COP21) (2016), enhancements in the material production and use across different industries is necessary. In the construction industry, the embodied carbon emission of structural frames can reach up to 20–30% of the assumed 50-year life-time carbon footprint of a building (Moussavi Nadoushani & Akbarnezhad, 2015; Dimoudi & Tompa, 2008; Luo, Yang, & Liu, 2016). This figure is set to be increased in the near future, as the number of buildings that are designed to achieve carbon-neutrality during their operation has significantly increased in recent years. Thus, it is expected that the appropriate selection and optimisation of structural materials and systems would help reduce the whole-life embodied carbon emissions of buildings (Eleftheriadis, Mumovic, & Greening, 2017; Oti & Tizani, 2015). In England, almost 1/3 of the buildings by floor area are non-domestic buildings (Department for Business, Energy & Industrial Strategy, 2016; Department for Communities and Logal Government , 2017). Furthermore 66% of all non-domestic framed multi-storey buildings and 71.6% of the multi-storey offices are steel framed structures (BCSA, 2017). Therefore, there is a big opportunity to mitigate the lifecycle embodied carbon emissions of those structures.

Although steel structures are designed according to standards that define minimum safety limits, their material efficiency is rarely addressed by the codes and thus often ignored in practice. This could create inherent inefficiencies in the way building structures are designed, constructed and maintained. Moynihan and Allwood (2014) investigated 23 real steel-framed buildings, and concluded that the unused mass in the structure could reach nearly 46% of the buildings total mass due to over-specification of the steel members. Furthermore, Dunant *et al.* (2018) in their study confirmed that 35-45% of the steel by mass for the steel frame is not required in terms of structural efficiency. Moynihan and Allwood (2014) suggested that the unused mass in steel frames is caused mainly by the design rationalisation which normally occurs at the detailed technical design stage (RIBA, 2013), where layout, building materials and structural systems are already specified.

Mathematical techniques for structural performance optimisation already exist since the 1970. Even though such techniques could be applied to member sizing (Dunant, Drewniok, Cullen, Eleftheriadis, & Allwood, 2018; Eleftheriadis, Mumovic, Greening, & Chronis, 2015), shape and topology problems (Frans & Arfiadi, 2014) or entire buildings (Tsavdaridis, Kingman, & Toropov, 2015; Stromberg L. , Beghini, Baker, & Paulino, 2012; Stromberg L. , Beghini, Baker, & Paulino, 2012), in practice, they are rarely implemented. In the occasions where the structural system of a building is optimised using these techniques, the computational analysis tends to be time-consuming and unable to influence critical design decisions. Furthermore, there is a limited scope in the optimisation of the structure at a late project stage as its design efficiency is largely affected by parameters that cannot be amended any more (e.g. column grid) (Dunant, Drewniok, Cullen, Eleftheriadis, & Allwood, 2018).

To maximise the effectiveness of the existing techniques, material optimisation in building structures needs to occur during the preliminary or tender design stages. At these stages, decisions associated with the construction type or structural layout are key to improve the overall material efficiency of the steel frame. After the tender stage, most of the engineering analysis focuses on the integration of the structure with the mechanical and electrical services or the completion of the construction detail schedules.

Typically, the structure is optimised for cost after the design is finalised during the developed and detailed technical design stages. This favours material utilisation as the cost of the steel and fabrication typically accounts for 30-40% each of the total frame for steel structures (BCSA & TATA Steel, 2015). Such optimisation has been described for welded steel structure (Jarmai & Farkas, 1999), steel frames with semi-rigid connections (Hayalioglu & Degertekin, 2005), design, fabrication, and manufacturing (Sawada, et al., 2006; Heinisuo, Laasonen, & Haapio, 2010; Haapio, 2012), and entire steel structures (BCSA & TATA Steel, 2015). Whether an extensive optimisation programme will be implemented is limited by the project constraints (Prager, 1970; Beghini & Sarkisian, 2014) and often excludes any environmental impact analysis.

Furthermore, the embodied carbon analysis of building structures has begun to attract attention amongst researchers. Vukotic *et al*. (2010) investigated how the different life cycle stages influence the assessment of buildings structural elements embodied carbon. They found that the material selection and sourcing as well as the waste handling at the end-of-life phase were more significant than the labour transportation and construction/demolition processes. On the other hand, Foraboschi *et al*. (2014) specifically analysed the impact of different structural floor types in the embodied energy impacts of tall buildings. They have found that structural solutions with the least weight do not necessarily correspond to the optimum embodied energy solutions. Lately optimisation studies have also begun to investigate the cost and embodied carbon performance as well as the cost-carbon trade-offs for the entire structure. In steel framed buildings, previous research exhibited that the cost and carbon performance of an optimised structure could be improved by 12-18% and 6-8% respectively when compared to actual design alternatives (Eleftheriadis, Dunant, Drewniok, & Rogers-Tizard, 2017). Similar analysis that combined the cost and embodied carbon performance of the structure was also performed in other material types such as reinforced concrete (Eleftheriadis, et al., 2018).

1.2 Paper Objectives & Structure

The previous literature review recognised possible synergies between building structures analysis with lifecycle sustainability concepts. In a different literature review, it was also found that despite the continuous development in the domain, practical engineering and sustainability models are still underutilised (Eleftheriadis, Mumovic, & Greening, 2017). In addition, two key limitations in the existing design optimisation practices of steel frames were also reported (Eleftheriadis, Mumovic, & Greening, 2017): The first involves the concurrent estimation and analysis of the structure's cost and embodied carbon footprint. For a comprehensive structural optimisation the two objectives need to be consolidated. The second consideration relates to the analysis speed. Design decisions in actual projects are dynamic, and the impact of parameters variations must be computed fast enough to ensure that the correct combination of design parameters is selected.

To address the limitations and gaps recognised in the literature, the paper presents a novel computational approach that allows the development of a wide range of structural design configurations that are pre-optimised for their cost and carbon performance and are expected to support early decision-making as design benchmarks. The solution space which is generated by the rigorous computational analysis could be used by engineering practitioners to explore specific areas of interest. The scope of the research is to offer new insights on how a rigorous evaluation of the cost-carbon relationships of available designs in the solution space could help structural engineers recognise and obtain more optimised designs which could be used for further development during the detailed design stages.

The performance metrics in the study include the costs and embodied carbon emissions of the structure. Comprehensive functions were established using a customised cost and carbon model containing elements such as the raw materials, fabrication, design, fire protection, and erection. The proposed model was validated in an actual building scenario. To verify the feasibility of the generated designs by the automated analysis, a comparative assessment was performed utilising results obtained from a trial-and-error analysis which was conducted by structural engineering practitioners.

The paper is organised as follows: In Section 2, the detailed mechanisms of the research are described, including the engineering design principles and the relevant cost and carbon data assumptions. In Section 3, the group of precast and composite configurations designed by the engineering practitioners are analysed and the relationships between the various cost and embodied carbon components are evaluated. Uncertainty analysis is also performed to examine the sensitivity of the specified solutions against the cost and carbon data. Design configurations computed with the automated design procedure are analysed in Section 4. In Section 4, the overall performance of the methodology in finding cost and carbon efficient structural solutions is also analysed. Critical and future expositions are finally discussed. The paper concludes in Section 5.

2. Research Methods

The paper's method extends the computational paradigm developed by Eleftheriadis *et al*. (2017) to optimise steel frames considering not only precast but also composite floor systems. These two systems were selected in this study because they are commonly used in typical steel buildings. Thus, understanding the cost and embodied carbon behaviour of these systems could be extremely valuable in several practical circumstances. The general representation of the research workflow is presented in Fig 1.

A comparative optimisation analysis is performed herein to evaluate the cost and carbon performance of structural solutions generated from two different design approaches. The first one, which is the traditional route, involves the manual generation of feasible solutions using a trial-and-error approach based on engineering practitioners' experience and proprietary software (Tekla Structural Designer). Due to time constraints only a discrete set of solutions can be generated with this approach. The design characteristics (weight, area of steel, number of elements, etc.) of the verified designs were manually exported to calculate the equivalent cost and embodied carbon emissions using Excel spreadsheets.

The second design approach involves the automatic computation of the entire solution space assuming the same constraints with the ones used by the structural engineers in the first approach. A parametric design model was built for that purpose to ensure code-compliant (Eurocode 3 and 4) structural solutions. The design characteristics of the solutions are automatically queried in cost and carbon functions that were embedded within the model to ensure rapid analysis. The different alternatives that are generated by the two approaches comply with Eurocode's limit state requirements. The objective of the design optimisation in both instances is to facilitate early stage designs, thus, the design factors involve column grids, floor type and depth, member/section types. If these factors are optimised at the beginning of a project it is expected that more efficient structural designs will be obtained at more developed design stages (Dunant, et al., 2018).

Besides the large discrepancies in the total number of design solutions generated by the two optimisation streams, the analysis time also differs. More specifically, the traditional optimisation procedure is a time-consuming process which could take days to complete depending on the complexity of the project. This means that the manual optimisation workflow could be a costly procedure with limited practical use. On the other hand, the developed parametric model can generate thousands of design configurations in a fraction of the time. This is a significant novelty of the study as it allows rapid optimisation using multiple input parameters. Overall, it is expected that the outputs from this model could help engineering practitioners reduce the time required for the analysis of optimised design alternatives.

For the cost and the embodied carbon analysis for each of the computed design solutions, the following design data from the two optimisation streams are required: 1) the total steel weight by member type, 2) the total steel surface area, 3) the total volume of the precast planks, 4) the total volume of the in-situ concrete, and 5) the total weight of the reinforcing steel. The data are integrated with customised cost and carbon inventories. In the traditional optimisation analysis this process involves manual data entries, whereas in the automated parametric model, the computations of the cost and the carbon are performed instantly by querying the necessary material and cost/carbon data directly in the model. The final results are collated and the relationships between the cost and the carbon performance of the engineering-based designs and the designs generated by the computational model are evaluated.

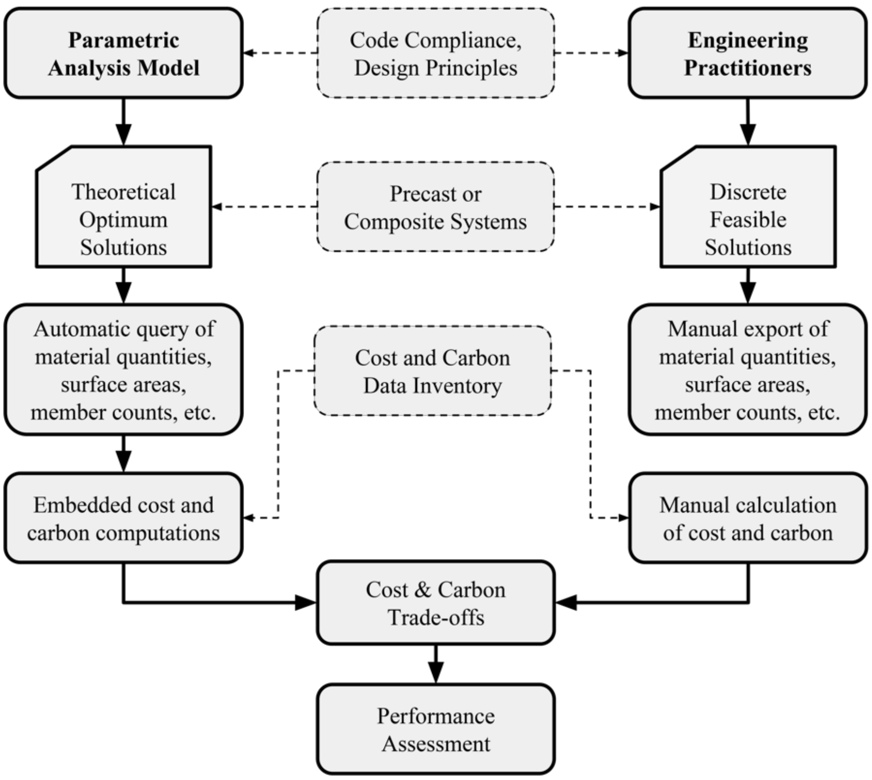


Fig. 1 Research workflow demonstrating the comparative optimisation approach of the paper

2.1 Cost & Carbon Data Inventories

The cost and carbon data for the relevant material and structural types were consolidated in inventories after a rigorous review of the literature. Widely available data sources were used in the study to increase practicality and reduce maintenance requirements. For the cost inventory, detailed data from Spon's Architect's and Builder's Price Book 2017 (AECOM, 2016) were used where necessary. The cost functions were related to the structural analysis as beam-level information was used to derive total lengths, total weights, number of elements and total surface area for painting and floor area. The function utilised cost factors for rolled steel sections, precast units, connections, fire protection, transportation, erection. The total cost of the structural system is given in total £ or £ per m^2 gross floor area.

The embodied carbon component utilised Life Cycle Assessment (LCA) concepts and particularly notions from the CEN/TC350 framework. The scope of those standards follows a modular approach to buildings life cycle impacts based on the corresponding life cycle stages starting from product and construction stages to use and end-of-use stages. The detailed material carbon inventory is shown in Table 1. The carbon functions also use material quantities, member count and steel areas to compute the embodied carbon of the structural steel, coating, precast concrete units, rebar and screed. The outputs from the carbon model are given in total $kgCO_2e$ or $kgCO_2e$ per m^2 gross floor area.

Table 1 Carbon inventory data and system boundaries for the materials used in the study. Lifecycle stages according to TC350 Framework (Moncaster & Symons, 2013)

Lifecycle Stages ($kgCO_2e/kg$)		Material Type					Reference
		Steel Beams	Steel Decking	Rebar	Precast Concrete	Ready-mix Concrete	
A1	Raw material	1735	2520	1270	200	200	(SteelConstruction.info, 2017)
A2	Transport						
A3	Manufacturing						
A4	Transport	No data available	No data available	No data available	No data available	No data available	N/A
A5	Construction	No data available	No data available	No data available	No data available	No data available	N/A
B	Use Stage	Not included	Not included	Not included	Not included	Not included	N/A
C1	Deconstruction	20	20	19	5.6	5.6	(SteelConstruction.info, 2017)
C2	Transport	40	40	42	2.2	4.2	(SteelConstruction.info, 2017)
C3	Waste Processing	0	0	0	2.3	2.2	(SteelConstruction.info, 2017)
C4	Disposal	0	0	0	-9.5	-4	(SteelConstruction.info, 2017)
D	Benefits and loads beyond the system boundary	Not included	Not included	Not included	Not included	Not included	N/A

2.2 Engineering Design Approach

The designs generated by the engineering practitioners were carried out using Tekla Structural Designer software in full accordance with Eurocode 3 (Steel) and Eurocode 4 (Composite) where applicable. In each design option, steel members were appropriately selected with the aim of achieving the section with the minimum possible weight to suit both ULS and SLS requirements – aiming for a utilisation ratio as close to 1.0 as possible. Columns as well as beams were altered where necessary. For the designs generated by the engineering practitioners the following parameters were varied:

- Floor type, between precast planks or steel-concrete composite.
- Floor depths. For precast this involved simply varying the depth of the planks in standard 50mm increments (and allowing for secondary beams were necessary). For composite various depths between 120mm and 150mm were checked for both re-entrant and trapezoidal decking types. The gauge of the decking was varied with the spacing of the secondary beams.
- Floor finishes. Composite options were assumed to have a high quality floated finish and therefore no screed was allowed for. For the precast options, typically a 75mm topping screed was added (as is usually necessary to provide an acceptable finish), however this was removed for comparison in two of the options.
- Beam spacing. For both precast and composite floor types, several variations of floor beam arrangement were considered, representing what were believed to be the various realistic patterns.

2.3 Parametric Model Design Approach

The detailed description of the parametric model which was used in the paper for the computation of the entire solution space can be found in Eleftheriadis *et al*. (2017). The model utilises a Monte Carlo methodology which was developed in C++ to specify and analyse all code-compliant design combinations for any typical building layout evaluating the steel member sizes, the floor construction type and the configurations for the columns and beams. The engineering analysis was limited to the floor of the structure. The design principles associated with the optimisation of the structure were modified from the model proposed by Eleftheriadis *et al*. (2017) to consider the additional compliance checks required for the calculation of the composite beams. A customised tool with visualisation components (Graphic User Interface – GUI) was used to access and process the relevant data from the parametric model.

2.3.1 Composite Design Principles

The parametric model does not cover light steel deck or composite slab design. It is Eurocode permitted design for bespoke decks to determine bare steel resistance and shear bond (composite action with concrete) resistance properties by a test procedure as given by EN 1993-1-3 Annex A and EN 1994-1-1 Annex B respectively. Deck manufacturers often carry these tests and provide the maximum capabilities for each deck type, in the form of custom built owned software or published load span tables, for different scenarios. In this study, load span tables were included in the model and a choice was made for the most appropriate slab design based on the grid arrangement.

The design of the horizontal composite beam members, for both primary and secondary ones, is made in two stages. Initially a construction stage design is carried where concrete is taken as a wet variable load along with an additional construction variable load of 0.75kN/m^2. The beam is treated as a bare steel one and checks are made on bending, shear and shear buckling capacity. When the beam is treated as a secondary one the deck is assumed to provide lateral torsional buckling resistance where for the primary case the check is carried for its unrestrained length (that of between the secondary beams). Serviceability limit checks at construction include a stress limit calculation for steel and a calculation of deflection which will be treated along with additional variable deflections a normal stage following the P359 guidance (SCI, 2011).The second stage of the design is treating the horizontal members as composite beams at normal stage once concrete has cured.

Additional checks are made for vertical shear, shear buckling and longitudinal shear for reinforcement and concrete crushing. A total deflection check is made with a recommended limit of Length/250 by calculating the sum of construction stage deflection, permanent and variable deflection at normal stage. A variable deflection check with a recommended limit of Length/360 is made only on the variable deflection at normal stage. A natural frequency check on the beams is made following the simplified rules of P354 (SCI, 2016) and demonstrated in P359 (SCI, 2011) with a recommended user input limit of 4Hz for office and residential buildings.

2.3.2 Precast Design Principles

The precast design analysis is limited to the design of the individual steel members, as opposed to the precast concrete. Proprietary load/span data from UK manufacturers were tabulated and incorporated into the model. The model calculates both standard precast Hollowcore planks and composite precast Hollowcore planks. The composite here refers to the use of a structural topping screed and steel mesh working in conjunction with the precast planks to increase their span capability. Where this is done, a minimum screed depth is automatically included within the design loadings on top of any other superimposed dead loads. A suitable plank depth is selected based on the span and overall loading, and this is applied to the beams.

All steel beams are designed in accordance with Eurocode 3 and are treated as simply supported, with the assumption that the planks are installed on the top flange of the beams, to avoid any torsional effects. The design of the steel beams is essentially straightforward, with notional checks are carried out to ensure they have adequate bending and shear resistance, and that deflections and frequencies are within code-specific limits. There is currently no use of shear studs to make the beam work compositely with the precast planks. There is also no allowance for construction loads, and the model takes no account of the potential for temporary torsional effects due to plank installation sequence. The design also assumes that no additional allowance needs to be made for disproportionate collapse, and that any tying required to achieve the required robustness will be achieved through reinforcement dowels between the planks or the steel-steel connections.

3. Engineering Optimisation Analysis

The same building case from Eleftheriadis *et al*. (2017) was used in the paper to perform the necessary optimisation and verification analyses. The tested building consists of a 2 storey school block, with a single line of seven uniform classrooms with corridor down one side and circulation cores at either end. A typical floor layout is shown in Fig 2. For simplicity, only the classroom and the corridor spaces were optimised excluding the staircase zones on both ends of the block. The generated designs depend on the engineers' perception of optimality and as a result only a discrete set of solutions can be realistically specified. Imposed loads were fixed at the standard value for classrooms at 3.0 kPa + 1.0 kPa for partitions on the classroom level (first floor) and 0.75 kPa for the roof. Additionally, the cladding loads were ignored whilst the overall structural depth was unrestricted.

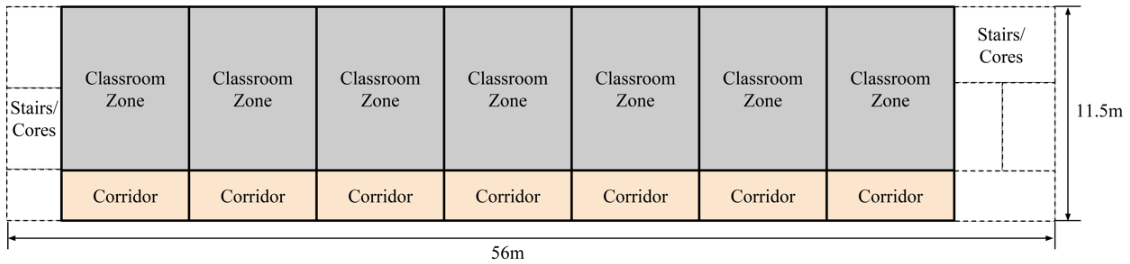
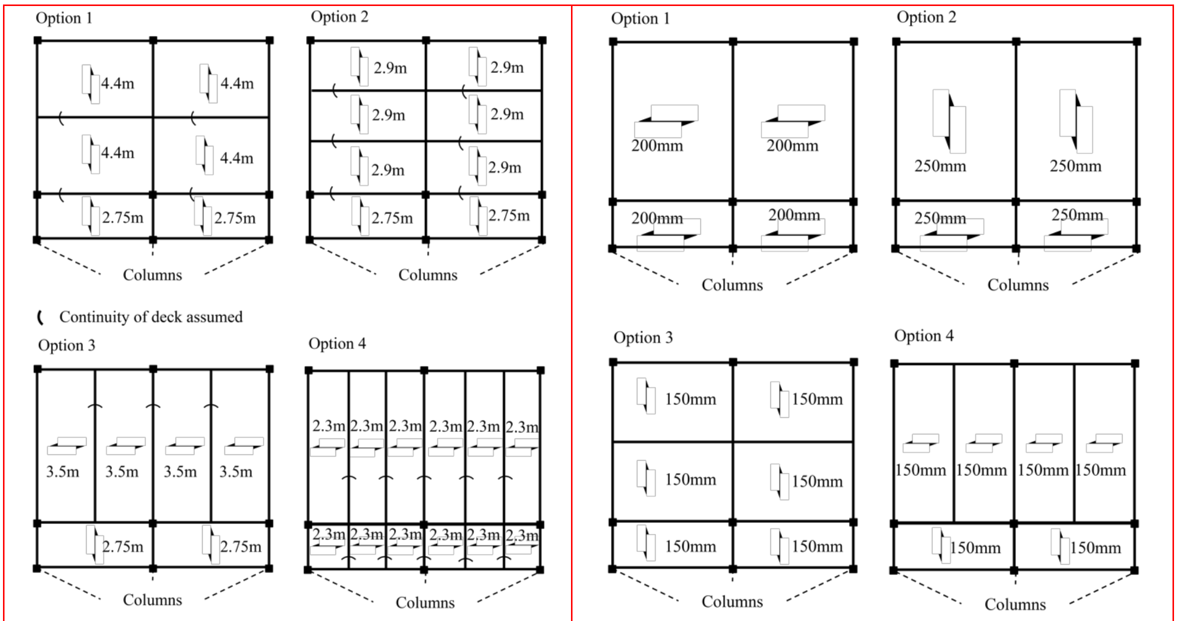


Fig. 2 Typical floor layout of the tested building case

3.1 Layout Configurations

In total, 29 configurations were developed by the project structural engineers over a period of two weeks. However, it is worth noting that this scale of analysis rarely occurs in actual projects. In fact, the number of solutions tested by engineers in real projects is significant lower due to tighter time constraints. This is a common approach across many engineering practices. From the 29 configurations, 18 were with composite decking and 11 included precast planks. Fig 3 demonstrates the layout configurations for the various composite and precast designs as implemented by the structural engineers.



(a) Composite | (b) Precast from Eleftheriadis *et al.* (2017)

Fig. 3 Framing arrangements for the tested building as examined by the practicing structural engineers

The practitioners identified 4 realistic framing options for each of the construction types. The geometric constraints set by the classroom-corridor arrangement were critical for the development of their layouts. For the precast options, 4 configurations of Option 1, 3 configurations of Option 2, 2 configurations of Option 3 and 2 configurations of Option 4 were tested using Hollowcore floor type with variable depth (150mm or 200mm). On the other hand, 2 configurations of Option 1, 6 configurations of Option 2, 4 configurations of Option 3 and 6 configurations of Option 4 were tested for the composite designs with multiple Comflor decking types. Table 2 outlines the 29 tested configurations including the relevant design labels, the floor type and the floor thickness.

Table 2 Composite design configurations as developed by the engineering practitioners

Design Label	Type	Framing arrangement	Decking Type/Plank Type	Floor Thickness (mm)	Screed Depth (mm)	Floor Area (m^2)	Precast Concrete (m^3/m^2)
C1	Composite	Option 1	Comflor 60-1.2mm	130	-	644	0
C2	Composite	Option 1	Comflor 60-1.2mm	140	-	644	0
C3	Composite	Option 2	Comflor 46-1.2mm	120	-	644	0
C4	Composite	Option 2	Comflor 46-1.2mm	150	-	644	0
C5	Composite	Option 2	Comflor 51-1.0mm	120	-	644	0
C6	Composite	Option 2	Comflor 51-1.2mm	150	-	644	0
C7	Composite	Option 2	Comflor 60-0.9mm	120	-	644	0
C8	Composite	Option 2	Comflor 60-0.9mm	150	-	644	0
C9	Composite	Option 3	Comflor 51-1.2mm	120	-	644	0
C10	Composite	Option 3	Comflor 60-0.9mm	130	-	644	0
C11	Composite	Option 3	Comflor 60-1.0mm	130	-	644	0
C12	Composite	Option 3	Comflor 60-1.2mm	150	-	644	0
C13	Composite	Option 4	Comflor 46-0.9mm	120	-	644	0
C14	Composite	Option 4	Comflor 46-0.9mm	150	-	644	0
C15	Composite	Option 4	Comflor 51-0.9mm	120	-	644	0
C16	Composite	Option 4	Comflor 51-0.9mm	150	-	644	0
C17	Composite	Option 4	Comflor 60-0.9mm	120	-	644	0
C18	Composite	Option 4	Comflor 60-0.9mm	150	-	644	0
P1	Precast	Option 1	Hollowcore	200	75	644	0.125
P2	Precast	Option 2	Hollowcore	250	75	644	0.138
P3	Precast	Option 3	Hollowcore	150	75	644	0.100
P4	Precast	Option 4	Hollowcore	150	75	644	0.138
P5	Precast	Option 1	Hollowcore	200	75	644	0.125
P6	Precast	Option 2	Hollowcore	250	75	644	0.138
P7	Precast	Option 3	Hollowcore	150	75	644	0.100
P8	Precast	Option 4	Hollowcore	150	75	644	0.100
P9	Precast	Option 1	Hollowcore	200	75	644	0.125
P10	Precast	Option 1	Hollowcore	200	0	644	0.125
P11	Precast	Option 2	Hollowcore	250	0	644	0.138

3.2 Cost and Carbon Performance

The material outputs and listing from the 29 designs were used to calculate the equivalent embodied CO_2 and cost for each of the options using the cost and carbon models previously described. Fig 4 and 5 show in ascending order the embodied carbon and cost results respectively for the entire structure including the breakdown of the relevant structural components

.

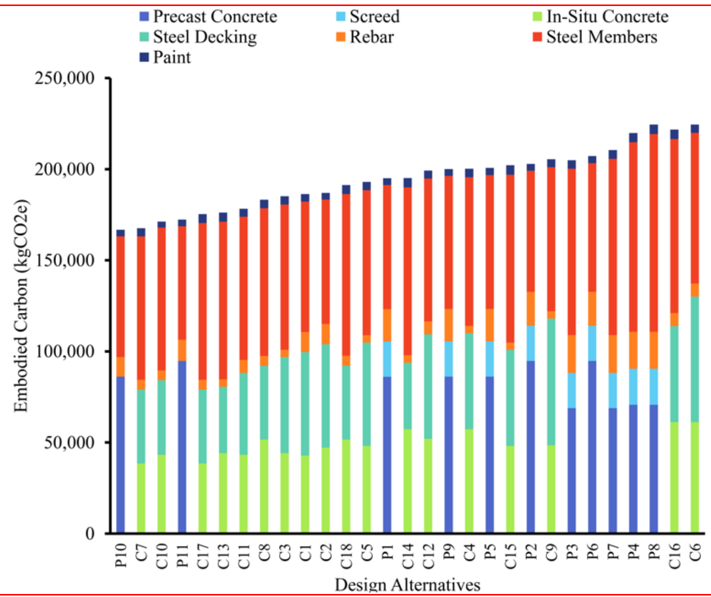


Fig. 4 Embodied carbon performance of the 29 designs generated by engineering practitioners

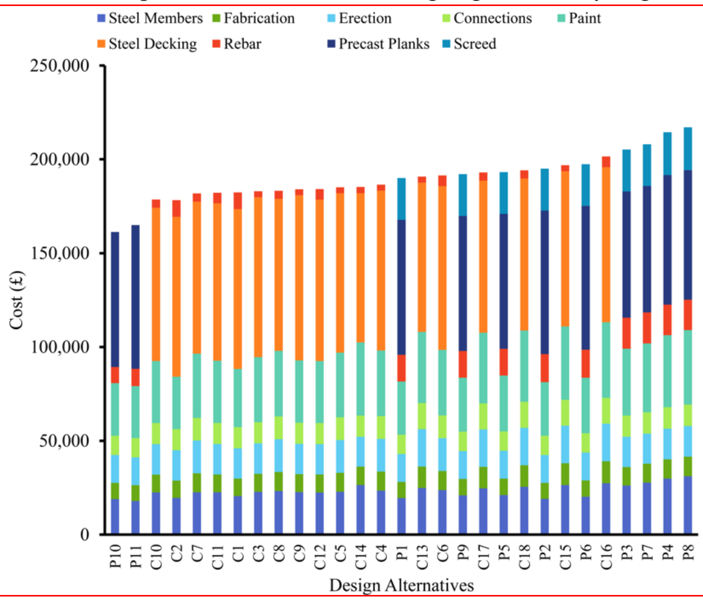


Fig. 5 Cost performance of the 29 designs generated by engineering practitioners

The box plots in Fig 6 show the overall carbon and cost performance of all the composite and precast designs. The first observation from the results indicate that even though the most carbon and cost efficient solution is a precast design (P10), as a general trend the composite solutions appear to be more carbon and cost efficient than the precast solutions. The composite options were made up using combination of 4 variables. These include the layout option, the decking type, the decking gauge, and the slab depth. Regarding the cost performance, the layout option was seen to have a large impact, with the 4 most costly composite options all being different variations of Option 4. This could be because of the closely spaced beam arrangement for this layout, which meant that trapezoidal sections were not utilised to their full potential. It can be seen that the shallower sections C13 & C14, were not as inefficient as the other Option 4 layouts.

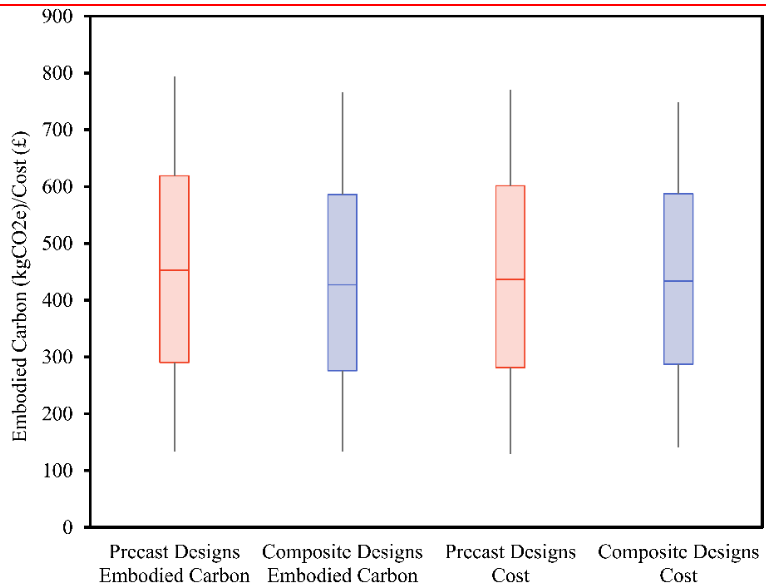


Fig. 6 Box plots showing the overall cost and embodied carbon performance per m^2 of flo or are for the composite and precast designs implementing the minimum, the 1st quartile, the median, the 3rd quartile and the maximum values from the entire solution set

In terms of the carbon performance, the composite cases with the highest embodied carbon were C6, C16, C9 and C15. All of these designs correspond to variations of decking type Comflor 51 which is a re-entrant composite floor type. Typically, this decking type results in a higher volume of concrete per m^2, which could be a contributing cause towards the high embodied carbon values. It is interesting that these 4 cases contained 3 different layout options, showing that although the layout was important for cost, in this instance it had less of an impact on the carbon performance.

The layout Option 1 was only possible with certain decking types, as it had a standardised grid spacing of 4.4m, which was greater than the maximum span for the shallower decks. It can be seen in cases C1 and C2 that by using these longer spanning decking types, the material was used efficiently, and the cost was typically reduced. The other two lowest cost options were C7 and C8. These both utilised the same deeper decking profile (Comflor 60) which allowed them to use less material and work more efficiently.

It can be seen that this material saving also helped to reduce embodied carbon, and C7 and C8 were found to be both cost and carbon efficient options. At the lower end of the scale in terms of carbon, C7, C10 and C17 were all found to have Comflor 60 decking types as well. This highlights the importance of material saving in carbon efficiency and shows that material tonnage was important at both ends of the carbon scale. When comparing the precast and composite options together it is clear that the precast options were generally most costly. However, once the screed was removed, and the corresponding steel weight savings were accounted for, the precast actually had the potential to be the most cost efficient solution. This can be observed in Fig 5, where the design configurations P10 and P11 appeared to be the cheapest options amongst the entire design set.

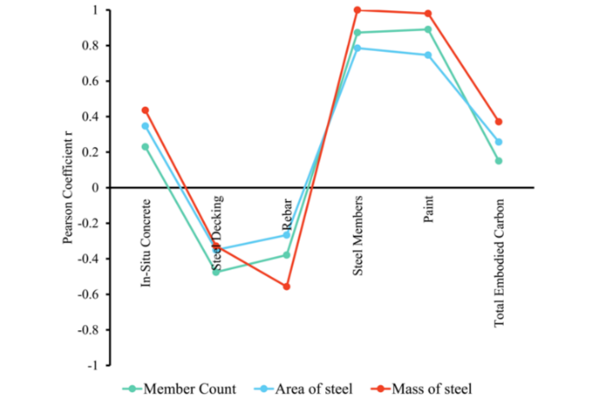
Regarding the carbon performance, the results were slightly more varied, however there is still a clear trend for the precast options at the higher end of the scale. It should be noted that these observations do not necessarily imply that any composite design will be more efficient than the precast equivalent. In fact, there were a number of very inefficient composite solutions. However, generally an optimised composite option was found to be more cost and carbon efficient than the optimised precast option when the cases with "no screed" were not included.

In all tested cases, the steel member contribution to the cost was significantly lower than the precast planks or the decking. This indicates that for the cost optimisation of the structure more emphasis should be put onto optimising the floor systems, rather than the steel elements supporting them. In terms of the carbon performance the steel members take up to 35-55% of the entire structure's emissions in both construction types. This suggests that the prioritisation of the steel members design parameters could affect the way the cost and carbon optimisation models are deployed in real projects. For that purpose, an in-depth analysis of the relationships between the steel member count, the total weight of the steel members and the surface area of the steel members with the embodied carbon and the cost results is performed in this section. Fig 7 presents the correlation analysis for the cost and embodied carbon components as computed for all the precast and the composite designs. The total member count, area of steel and mass of steel were obtained from the structural engineers' models and used to compute the Pearson coefficients (r).

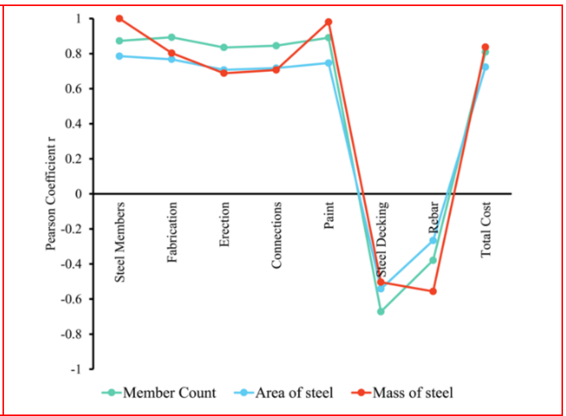
It is observed that the impact of these three parameters in the cost and carbon results of the precast and composite components varies considerably. In some instances, strong positive correlation can be observed (in the cost of fabrication, erection, connections and paint for the precast designs), whereas in others strong negative correlation occurs (precast planks cost and carbon). For the composite solutions, the three design parameters associated with the steel members appear to have a small impact on the total embodied carbon emissions. Specifically, the steel member count has the smallest correlation (0.1507), whilst the mass of steel has the largest correlation (0.3714). On the other hand, a strong positive correlation was identified between the three design parameters with the total cost and carbon of the precast designs and the total cost of the composite designs.

3.3 Uncertainty Analysis

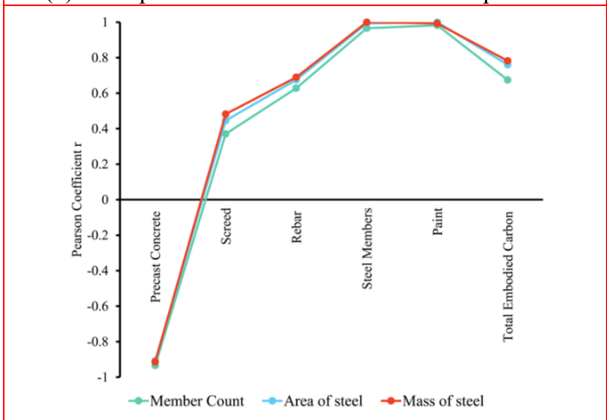
An uncertainty analysis was performed to analyse the influence of different embodied carbon factors in the obtained results to ensure the robustness of the performed analysis. The uncertainty of the embodied carbon factors is a significant limitation of previous LCA approaches thus it was studied by many authors in the past. A detailed review on the subject can be found in Pomponi & Moncaster (2017). Herein, 10% and 5% uncertainty factors were tested using a Gaussian distribution. Fig 8 shows the variability of the cost and embodied carbon solutions as computed by the uncertainty analysis. The graph shows a uniform distribution of the cost and carbon results of up to 25%.



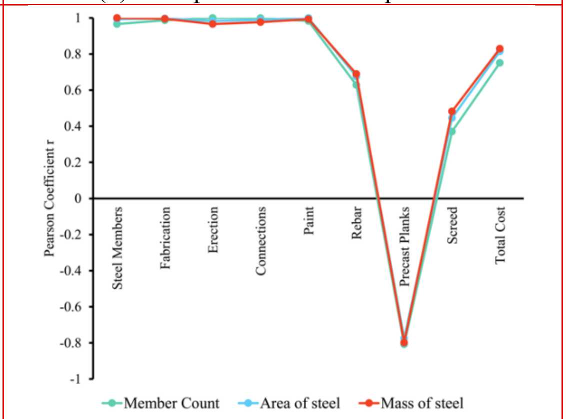
(a) Composite Embodied Carbon Components



(b) Composite Cost Components



(c) Precast Embodied Carbon Components



(d) Precast Cost Components

Fig. 7 Correlation between the steel member count, area of steel and steel weight with the cost and carbon performance of the 29 designs

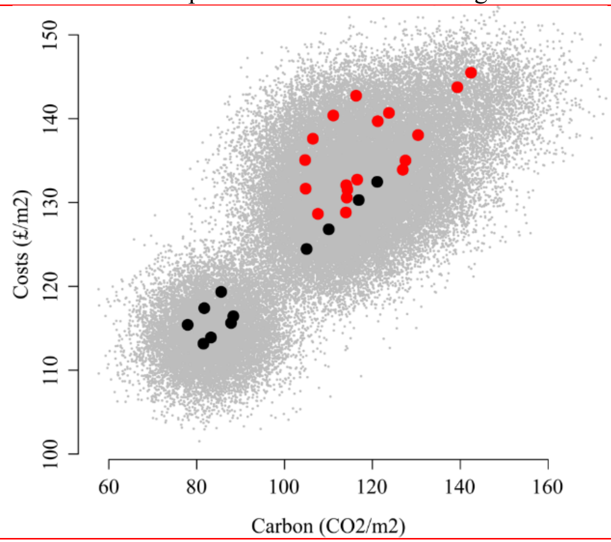


Fig. 8 Uncertainty analysis for the 29 design configurations. The composite designs are sh own with the red nodes and the precast designs with black nodes.

4. Automated Design Optimisation

4.1 Solution Space Analysis

In this section the relationships between the cost and the carbon performance of the optimised designs are analysed. The results obtained from the previous section are evaluated against the solutions generated from the computational model. Fig 9 shows the solution space for the tested building using the cost and embodied carbon results for the 29 designs generated by the structural engineers and the computational model. From the analysis of the graph it can be observed that a rather linear relationship exists between the cost and the embodied carbon for both the precast and the composite designs. This could suggest that a cost-effective solution could also reduce the embodied carbon of the structure. In practical terms, this could be a good motivation for structural engineers to further reduce the costs of the structural system in a project.

However, in the composite solutions a small cost-carbon trade-off exists between designs C7 and C10. Design C7 is approximately 2% more carbon efficient but it is 3% more expensive than design C10. Additionally, an interesting observation can be made about solutions C10 and C2. Even though their costs are very similar, their corresponding carbon emissions vary considerably. In fact, design C10 is 9-10% more carbon efficient than design C2. In general, the evaluation of these relationships could be particularly useful in actual decision-making processes as designs could be assessed in a comparative manner and not in isolation. However, it is hypothesised that the optimisation analysis from the designs developed by the structural engineers potentially offers a limited view of the entire solution space for the given problem. The solutions generated by the parametric process are used herein to develop a better understanding of the cost-carbon relationships for the entire solution space.

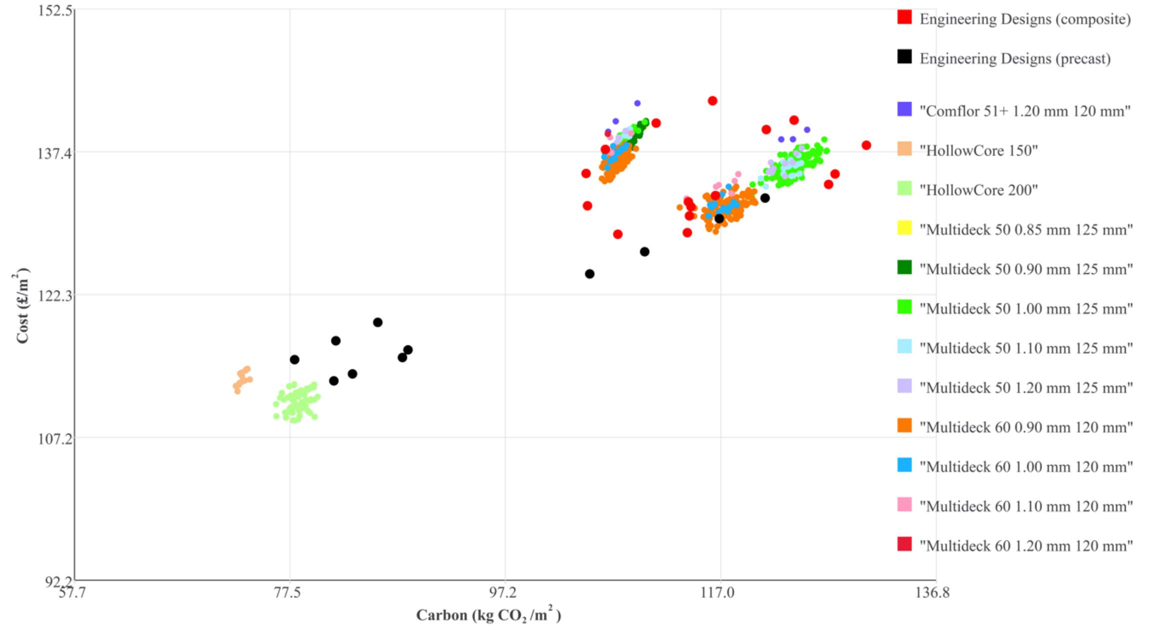


Fig. 9 The solution space for the tested building case with the optimised solutions from th e structural engineers and the automated design analyses

Fig 9 highlights the design clusters generated by the automated optimisation procedure which are organised by their corresponding floor construction types (composite and precast). Overall, it is observed that a similar clustering occurs in both optimisation analyses (automated and manual). These results verify that realistic design configurations can be obtained from the automated procedure. This provides significant evidence about the technical feasibility of the solutions generated by the automated model in practical problems. Furthermore, it can be observed that new optimised designs can be obtained from the automated optimisation. This validates the initial hypothesis of the paper about the engineers' ability to partially examine and optimise the entire solution space. In this example even though the engineers have effectively mapped a large proportion of the solution space, more efficient precast solutions were identified by the computational model. These new optimised solutions can further reduce the cost and embodied carbon emissions of the solutions optimised by the structural engineers by approximately 10% using the Hollowcore 200 and 150 clusters.

4.2 Discussion

Taking a comprehensive optimisation approach, the study demonstrated the value of rigorous engineering analysis in the cost and carbon optimisation of steel frames. The paper exposed the potential benefits that automated design procedures could have in the development of robust and sustainable structural design configurations in actual building cases. A post-optimisation assessment took place after the numerical optimisation analyses. The results from the automated procedure were presented to the engineers who participated in the study for further examination of the developed solutions.

Two main elements of the automated optimisation analysis were highlighted by the structural engineers. The first one involved the optimisation quality. The quality of the optimisation analysis was significantly enhanced by the new knowledge acquired by the structural engineers during the articulation of the entire solution space regarding the precise cost and carbon relationships of the designs. The computation of the entire solution space offered valuable information about new design alternatives the engineers did not previously consider. Additionally, it enabled new insights on the detailed relationships between the two objective functions.

The second dimension involved the optimisation efficiency. The structural engineers were particularly impressed by the analysis speed as more than 1,000 designs were computed in less than 5 minutes. Additionally, the assessment of the design characteristics (layouts, member sizes, etc.) verified that the obtained solutions were practical solutions the engineers could use in actual projects. The capability of the tested model to perform this rapid analysis allowed for multiple optimisation scenarios to be tested. For example, if clients wish to explore the impact of various loading scenarios or construction types the entire optimisation procedure could be repeated without significant time loss.

4.3 Future Recommendations

Design and decision-making applications could be significantly improved by efficient computational analysis and deep domain knowledge obtained from the structural engineering practitioners in real design projects (Tamošaitienė & Gaudutis, 2013). The current study suggested that for the effective implementation of automated optimisation models, enhanced workflows that augment human-computer interactions would be required in the future. The main benefits from such workflows could be summarised in the efficient way to address the complexities associated with the sustainable design and optimisation of steel building structures.

Furthermore, it is expected that the proposed parametric model would become relevant in the context of the emerging BIM domain. Early BIM studies that investigate the sustainability and lifecycle performance integration in steel structures were presented in Eleftheriadis *et al*. (2015) and Oti & Tizani (2015). However, future efforts could build upon the current study to further improve the structural engineering and sustainability analyses with the cost or energy notions at building level following similar approaches presented in Basbagill *et al.* (2013) and Ilhan & Yaman (2016). For instance, the quantity take-off functionalities of BIM would allow the proposed model to utilise material quantities directly from other building components to support a robust whole building cost and carbon analyses. Additionally, the cost and carbon inventories that are necessary for the deployment of the model could be embedded within typical BIM schedules or shared material repositories. In that way, project stakeholders could review and update the relevant EPD data based on project-specific information. Finally, the design and fabrication optimisation characteristics of the proposed model could be amplified within BIM ensuring efficient workflows between structural engineers and fabricators.

5. Conclusions

A novel optimisation approach for the development of cost and carbon efficient steel structures was established and tested in this paper. The novelty of the study lied in its capability to integrate cost and embodied carbon numerical models with engineering compliance analysis for the optimisation of typical steel construction configurations. A computational model that synthesises these analyses was developed and tested in an actual building scenario. To validate the proposed computational model a comparative optimisation assessment was performed. The comparative analyses utilised optimised configurations which were developed by structural engineering practitioners and configurations computed by the parametric analysis model. Results demonstrated the efficiency of the automated model in optimising a typical building for its cost and embodied carbon performance in a fraction of the time when compared to the time needed by the engineering practitioners to deploy a discrete set of optimised designs. Overall, it was suggested that the optimisation quality as well as the optimisation efficiency could be facilitated and enhanced from the implementation of the proposed design analysis.

Acknowledgments

The research described in this paper was financially supported by Innovate UK through the 'Innovative engineering approach for material, carbon and cost efficiency of steel buildings' project with reference number 102477.

References

AECOM. (2016). *Spon's Architect's and Builders' Price Book 2017.* Taylor and Francis.

Basdagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment , 60*, 81-92.

BCSA & TATA Steel. (2015). *Steel Construction - Cost.* BCSA.

BCSA. (2017). *Annual Review.* London: BCSA.

Beghini, A., & Sarkisian, M. (2014). Geometry optimization in structural design. *83rd Annual SEAOC Convention.* Indian Wells, CA.

Department for Business, Energy & Industrial Strategy. (2016). *Building Energy Efficiency Survey.* London, UK: Department for Business, Energy & Industrial Strategy.

Department for Communities and Logal Government . (2017). *English Housing Survey .* London: Department for Communities and Logal Government .

Dimoudi, A., & Tompa, C. (2008). Energy and environmental indicators related to construction of office buildings. *Resources, Conservation and Recycling, 53*(1-2), 86-95.

Dunant, C., Drewniok, M., Cullen, J., Eleftheriadis, S., & Allwood, J. (2018). Regularity and optimisation practice in steel structural frames in real design cases. *Resources, Construction & Recylcing*.

Eleftheriadis, S., Duffour, P., Greening, P., James, J., Stephenson, B., & Mumovic, D. (2018). Investigating relationships between cost and CO2 emissions in reinforced concrete structures using a BIM-based design optimisation approach. *Energy and Buildings*.

Eleftheriadis, S., Dunant, C., Drewniok, M., & Rogers-Tizard, W. (2017). A computational paradigm for the optimisation of steel building structures based on cost and carbon indexes in early design stages. *In Proceedings: 24th International Workshop on Intelligent Computing in Engineering (EG-ICE 2017) .* Nottingham, UK: Curran Associates.

Eleftheriadis, S., Mumovic, D., & Greening, P. (2017). Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renewable and Sustainable Energy Reviews*, 811–825 .

Eleftheriadis, S., Mumovic, D., Greening, P., & Chronis, A. (2015). BIM Enabled Optimisation Optimisation Framework for Environmentally Responsible and Structurally Efficient Design Systems. *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining: Connected to the Future.* Oulu, Finland.

Foraboschi, P., Mercanzin, M., & Trabucco, D. (2014). Sustainable structural design of tall buildings based on embodied energy. *Energy and Buildings, 68*, 254-269.

Frans, R., & Arfiadi, Y. (2014). Sizing, Shape, and Topology Optimizations of Roof Trusses Using Hybrid Genetic Algorithms. *Procedia Engineering, 95*, 185-195.

Haapio, J. (2012). *Feature-based costing method for skeletal steel structures based on the process approach.* Tampere, Finland: Julkaisu-Tampere University of Technology.

Hayalioglu, M., & Degertekin, S. (2005). Minimum cost design of steel frames with semi-rigid connections and column bases via genetic optimization. *Computers & Structures, 83*(21), 1849-1863.

Heinisuo, M., Laasonen, M., & Haapio, J. (2010). BIM based manufacturing cost estimation of building products. In *eWork and eBusiness in Architecture, Engineering and Construction:ECPPM 2010* (pp. 53-59). London, UK: Taylor & Francis Group.

Ilhan, B., & Yaman, H. (2016). Green building assessment tool (GBAT) for integrated BIM-based design decisions. *Automation in Construction, 70*, 26-37.

Jarmai, K., & Farkas, J. (1999). Cost calculation and optimisation of welded steel structures. *Journal of Constructional Steel Research, 50*(2), 115-135.

Luo, Z., Yang, L., & Liu, J. (2016). Embodied carbon emissions of office buildings: a case study of China's 78 office buildings. *Building and Environment, 95*, 365-371.

Moncaster, A., & Symons, K. (2013). A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy and Buildings*, 514-523.

Moussavi Nadoushani, Z., & Akbarnezhad, A. (2015). Effects of structural system on the life cycle carbon footprint of buildings. *Energy and Buildings, 102*, 337-346.
Moynihan, M., & Allwood, J. (2014). Utilization of structural steel in buildings. *Proc. R. Soc. A, 470*, 20140170.
Oti, A. H., & Tizani, W. (2015). BIM extension for the sustainability appraisal of conceptual steel design. *Advanced Engineering Informatics, 29*, 28-46.
Pomponi, F., & Moncaster, A. (2017). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews, 81*(2), 2431-2442.
Prager, W. (1970). Optimization of structural design. *Journal of Optimization Theory and Applications, 6*(1), 1-21.
RIBA. (2013). *Outline Plan of Work.* London, UK: RIBA.
Sawada, K., Shimizu, H., Matsuo, A., Sasaki, T., Yasui, T., & Namba, A. (2006). A simple estimation of fabrication cost and minimum cost design for steel frames. *4th China-Japan-Korea Joint Symposium on Optimization of Structural and Mechanical System*, (pp. 89-94). Kunming, China.
SCI. (2011). *Composite Design of Steel Framed Buidings.* Ascot, UK: SCI.
SCI. (2016). *Steel Construction - Floor Vibration.* Ascot, UK: SCI.
SteelConstruction.info. (2017). End of life LCA and embodied carbon data for common framing materials. London, UK. Retrieved December 2017, from https://www.steelconstruction.info/End_of_life_LCA_and_embodied_carbon_data_for_common_framing_materials
Stromberg, L., Beghini, A., Baker, W., & Paulino, G. (2012). Design of structural braced frames using group optimization. *20th Analysis and Computation Specialty Conference* (pp. 267-277). Chicago, Illinois, United States: ASCE.
Stromberg, L., Beghini, A., Baker, W., & Paulino, G. (2012). Topology optimization for braced frames: combining continuum and beam/column elements. *Engineering Structures, 37*, 106-124.
Tamošaitienė, J., & Gaudutis, E. (2013). Complex assessment of structural systems used for high-rise buildings. *Journal of Civil Engineering and Management, 19*(2), 305-317.
Tsavdaridis, K., Kingman, J., & Toropov, V. (2015). Applications of topology optimization in structural engineering: High-rise buildings and steel components. *Jordan Journal of Civil Engineering, 9*(3), 335 - 357.
United Nations, Framework Convention on Climate Change. (2016). *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015, Part Two: Action taken by the Conference of the Parties at its twenty-first session.* Paris, France: United Nations.
Vukotic, L., Fenner, R. A., & Symons, K. (2010). Assessing embodied energy of building structural elements. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 163*(3), 147-158.