A computational paradigm for the optimisation of steel building structures based on cost and carbon indexes in early design stages

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Abstract. The study explores a practical engineering paradigm that aims to augment the cost and carbon analysis of steel building structures. Cost and carbon functions were developed specifically for this purpose including raw material, fabrication, design, fire protection, and erection components. A customised computational model for the analysis of structural alternatives is investigated. The proposed model is tested in an actual building case where several benchmark designs are computed. The outputs from the model are compared with a small number of actual design alternatives which were developed by engineering practitioners. The proposed method can significantly increase the understanding of the design space's boundaries whilst the computed solutions have exhibited enhanced cost and carbon performance compared to actual designs.

1. Introduction

Although steel framed building structures are designed according to standards, which define minimum safety limits, their material efficiency is rarely being systematically addressed in practice. This inherently creates large inefficiencies in the way building structures are designed and constructed. Moynihan and Allwood investigated 79 steel-framed buildings, and concluded that unused mass of steel framed buildings could reach nearly 46% of the building's total mass due to over-specification of the steel sections (Moynihan & Allwood, 2014). Furthermore, Dunant et al. in their study confirmed that 35-45% of the steel by mass of the steel frame is not required in terms of structural efficiency (Dunant, et al., 2017).

Traditionally, the relationships between the cost of materials and the cost of fabrication in construction is considered to have a significant impact on the final design selection. In the literature, cost optimisation can be found in several instances: welded steel structures (Jarmai & Farkas, 1999), steel frames with semi-rigid connections (Hayalioglu & Degertekin, 2005), design, fabrication, and manufacturing (Sawada, et al., 2006; Heinisuo, et al., 2010; Haapio, 2012) and entire steel structures (BCSA & TATA, 2013). Cost as a single metric is easy to comprehend and quantify, however, its relationship with other environmental impact metrics is more complicated to determine. For example, even though material reductions are important in CO_2 optimisation this does not mean that material reduction will also yield cost optimum solutions.

Although optimisation methods are available to engineering practitioners for more than three decades, their implementation is limited by the different requirements addressed in every project (Prager, 1970). Even though mathematical techniques are well established in structural optimisation, which vary from construction scheduling (Zhou, et al., 2013), construction site layout (Zhou, et al., 2009), construction management (Suliman, et al., 2011), size, shape and topology optimisation (Frans & Arfiadi, 2014), and member optimisation in high rise buildings (Kingman, et al., 2015; Stromberg, et al., 2012; Stromberg, et al., 2012), more practical optimisation models are still needed. Despite the different optimisation studies of steel buildings found in the literature, the relationship between cost and carbon performance in early design stages has not been effectively addressed in the past. Understanding these relationships is a significant challenge and if appropriately addressed could offer structural engineers better ways to evaluate optimised design configurations. The study investigates a practical optimisation paradigm applied and validated in steel framed buildings developed to augment both cost and carbon performance of the structure during the early phases of the design development.

2. Research Approach

The objectives of the study are threefold: 1) To establish a cost and carbon model for the assessment of steel structures, 2) To develop the computational model for the analysis of structural alternatives, and 3) To verify the model in a real building case. In this study the results obtained from the computational model are evaluated against actual design solutions in a comparative study.

The study begins by defining the cost and carbon functions that are processed into a custom cost and carbon analysis model of steel structures. The cost and carbon functions use data factors from literature review and other empirical data sources. The analytical part of the study comprises of two components. In both components, the objectives are cost and embodied carbon minimisation of the steel structure. The functional unit of the study is defined as the floor system of the structure. In the first component of the study, engineering-based alternatives are developed using a manual trial-and-error design procedure. In this component, feasible designs are articulated by engineers and indicated as “actual” solutions. These designs depend on engineers’ perception of optimality and due to time constraints only a small part of the solution space can be developed.

On the other hand, the second component includes theoretical design alternatives that are computed in the parametric structural model. In this component, designs are specified as “benchmark” solutions. Multiple configurations can be analysed rapidly and therefore the design space can be fully explored. At this phase of the study, the outputs from both components are used as inputs in the cost and carbon model in a separate process. However, an integrated cost and carbon model within the parametric structural model is currently under development. The cost and carbon model utilises the cost and carbon functions previously mentioned as well as material quantities, construction properties, etc. from the structural analysis models. The cost and carbon results for the actual and the benchmark solutions are evaluated and plotted in a 2D-graph that assess discrepancies between the two solution sets.

2.1 Cost and Carbon Functions

A database of embodied carbon and cost inventories is established and associated with the relevant material and structural type (beams, concrete, rebar). The review of the materials’ type helps source the embodied carbon inventories: data input from Environmental Product Declarations (EPD) related data or other Life Cycle Inventories (LCI) are utilised. In addition, carbon data from GaBi and econinvent databases were utilised on several occasions. The cost assessment model has been developed based on a feature based cost methodology. Cost factors were used based on Spon’s Architect’s and Builder’s Price Book 2017. In feature-based models, the manufacturing process of steel frames is divided into single processes. Each process is executed at separate cost centres. The comprehensive cost components include raw material, fabrication, design, fire protection, erection. The cost and carbon functions are developed using Microsoft Excel making allowances for manual data input for bill of materials from the structural analysis. The automatic query of cost and carbon functions is currently under development and it will be examined a later stage of the project. The cost functions are strongly related to the structural analysis as beam-level information is used to derive total lengths, total weights, number of elements and total surface area for painting and floor area. The function utilises cost factors for rolled steel sections, precast units, connections, fire protection, transportation, erection. The total cost of the structural system is adjusted in £/m^2. The embodied carbon component utilises concepts from the Life Cycle Assessment (LCA) theory and particularly on environmental standards developed under 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 carbon functions use material quantities from the structural analysis to compute the embodied carbon of the structural steel, coating, precast concrete units, rebar and screed. The output from the carbon model is given in kgCO_2e/m^2.

2.2 Computational Model

To help guide early stage structural steel designs, the computational model explored in this study's principal role is to categorise technologies given the constraints which are often known. For example, for a given load and combination of spans, what type of flooring is preferable? If the ceiling height is restricted, is this different? In general, any number of restrictions in the possible spans, loads, etc. can be applicable. At the same time, the design space is very large: the number of commercially available options is considerable, and the grid, though it is frequently fixed, generally allows for some flexibility. The difficulty is thus to explore as completely as possible the complete solution space of possible floor solutions given a set of constraints.

An exhaustive search is not possible, therefore, the proposed computational model functions as a Monte-Carlo method, generating a large number of putative designs, rejecting those which do not match the constraints and selecting the best so that they can be used as hints for the design work of the structural engineers. The metric used to rank the solutions are predicted cost and carbon footprint, both calculated on the basis of a detailed bill of materials generated by the model. To generate putative designs, the model randomly generates bays from a user- provided length probability distribution which was built in a custom C++ algorithm. Each bay, composed of primary, secondary and tie beams is then calculated according to the prescribed loads. The load on each beam is computed according to the area of the bay, the average area of its neighbours, and its position as a corner, an edge or in the bulk of the floor. For each bay, all possible combinations of technologies are investigated.

The design process envisaged would be this: the engineer uses the model according to the specified spans and loads to choose the floor plate technology most appropriate for the project. In a second step, the engineer would create a preliminary design and evaluate it. The engineer would then use the design space described by the model to help them converge towards an optimal solution: knowing the design space boundary should help deciding whether cheaper or lighter designs are possible, particularly when the design of typical bays is suggested. The definition of the bays (Figure 1) can take three form:

1. Free: a statistical distribution of the possible spans is given. This is appropriate for general guidance where a general idea of the bay size is known, but is not fixed.
2. Semi-defined: the grid is defined in a single direction. This is typically the case for corridors which follow the main grid but which length can be variable.
3. Fixed: the dimension of the bay is fixed along both direction

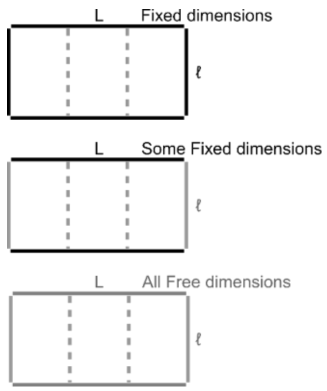


Figure 1: Bay type definition

The computational model (Figure 2) can compute both composite and precast floor designs. The study focuses on the analysis of precast systems only. A database of standard rolled sections has been built in the algorithm but fabricated sections can also be identified. For the purposes of this research the algorithm is searching for the optimum solution within the list of universal sections available on the list. The method for selecting the beams in the precast design is the following:

1. Universal sections are ranked according to their linear density
2. Each section, starting from the lightest is tested in turn for:
   2.1 Frequency
   2.2 Deflection
   2.3 Bending moment
   2.4 Shear strength
3. When a test is failed, the next section is tried
4. When no test fails, the section is selected.
5. Along the longest dimension of a bay, the opportunity to add secondary beams is tried
   5.1 The possible spans are selected
   5.2 The primary and secondary beams are selected as above, taking into account the additional stiffness.

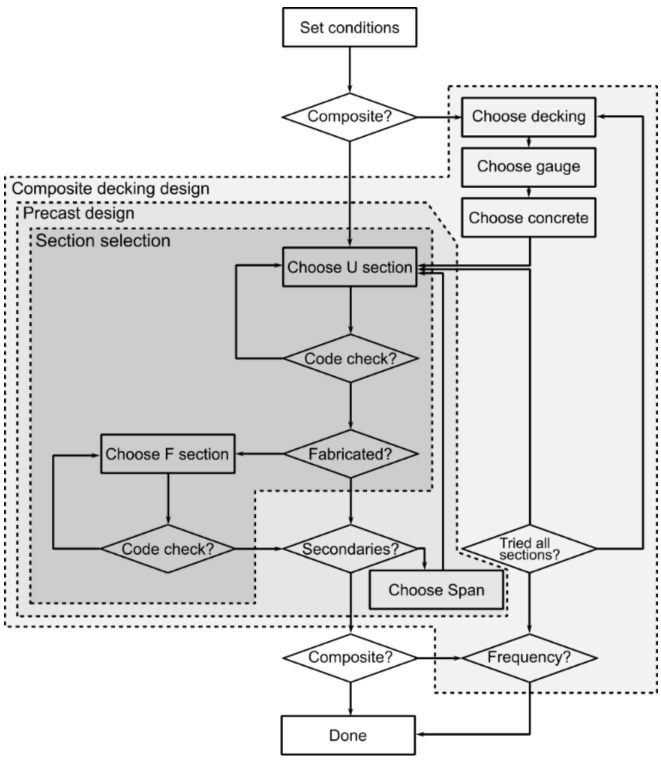


Figure 2: Representation of the computational model

3. Optimisation Scope

The optimisation options were separated into global and local levels. Components at global level refer to those elements that affect the project at high level, generally at the earlier stages of the design/concept, and were more heavily influenced by Architecture. Typically these factors could include: column grid, primary/secondary beam spacing, floor type depth, loadings, structural zone, and fire strategy. Local optimisation methods were those that could be decided upon at a later stage of design. These were factors that only really affected the beams independently, with little impact on the surrounding members, and were generally governed by the Engineer. Examples of these factors could be: member/section type, steel grade, connection type, cell/opening type, fire protection. The optimisation model in this study has focused on components from the global level analysis with aim to identify methods to augment early stage efficient design solutions.

4. Case Study

An in-depth investigation into the optimisation of a simplified steel frame was carried out. The frame selected was an actual design project. The building was part of a new 2 storey school block, with a single line of seven uniform classrooms with corridor down one side and circulation cores at either end (Figure 3).

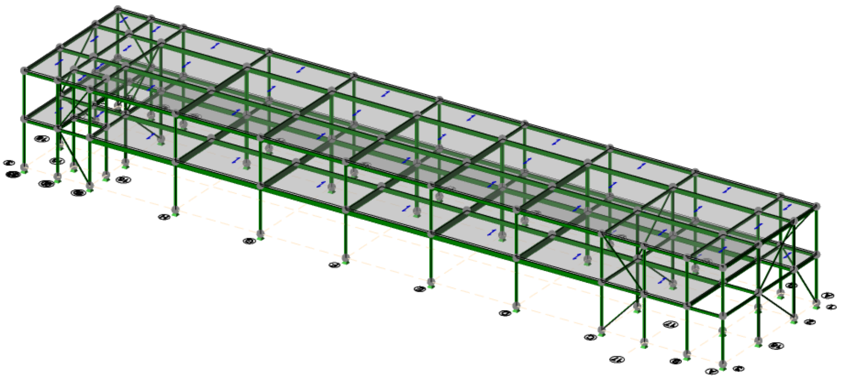


Figure 3: Typical layout of beams at first floor (the roof used an identical layout)

5. Engineering-Based Designs

Due to time constraints, only limited variations were looked at, with the other potential variables restricted. Fixed variables were:

- Column grid – this was fixed in this instance. Partly as it vastly reduced the potential number of options, but also because as a classroom block (room sizes fixed with non-negotiable clear spans) there was limited potential to alter this anyway.
- 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.
- Circulation cores – as the location of these was not altered, the general arrangement of beams within them also remained unchanged. This meant that the vertical bracing that provided the lateral stability system also remained unchanged. Wind loads were applied using a modeller tool built into the software, and this was also unchanged between each option.

- Cladding loads were ignored in all cases, as were the effect of any permanent partitions (e.g. around lift cores and stairwells).
- For all cases, the overall structural depth was left unrestricted. Whilst this may have provided some interesting results, it would have resulted in too many variables, and given that the primary load bearing members in all cases run along the perimeters of rooms it also was unlikely to be a restrictive issue in practice.

Table 1: The areas that were varied in the study were

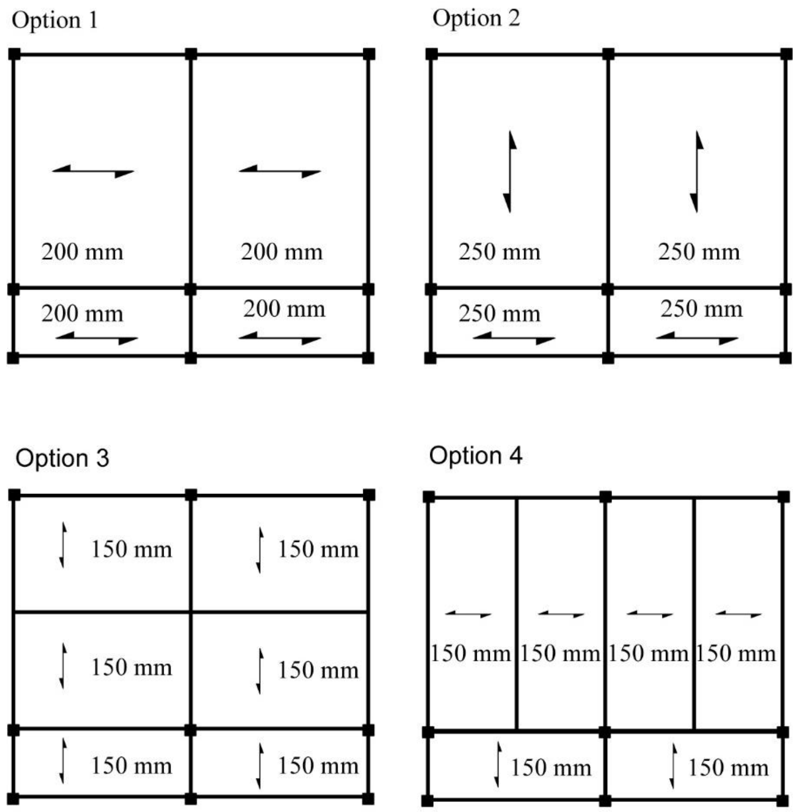
Floor Type	Floor Depths	Floor Finishes	Beam Spacing
Precast planks	For precast this involved simply varying the depth of the planks in standard 50 mm increments (and allowing for secondary beams were necessary).	For the precast options, typically a 75 mm topping screed was added (as is usually necessary to provide an acceptable finish), however this was removed for comparison in two of the options.	Several variations of floor beam arrangement were considered, representing what were believed to be the various realistic patterns

5.1 Design Assumptions

Design was carried out on Tekla Structural Designer software in full accordance with Eurocode 3 (Steel). In each option, members were 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. In principle, due to the relatively small variance between options only a small selection of member sizes were used across all options. Columns as well as beams were altered where necessary. Bracing was maintained as the same sections throughout.

5.2 Actual Solutions

In total, 11 precast options were identified. The layout and design options tested are shown in Figure 4. The material outputs were used to calculate the equivalent embodied CO_2 and cost for each option using the cost and carbon models previously described. This figure was then used for comparison between the options to determine which had the lowest value. Figure 5 shows the cost and carbon results for the entire structure of the 11 actual solutions analysed. Designs 1-4 were sized based on the optimum beam size, and plates were added to achieve the minimum 175 mm thickness needed for the bearing distance of 2 precast planks. Designs 4-8 were restricted, so that only beams with a minimum width of 175 mm were allowed, this meant that additional plates were not needed. All of designs 1-8 were designed assuming a propped construction. Designs 9-10 were designed as un-propped, and required torsion design for the temporary case where planks would be present on one side of the beam only. The final two cases are as per designs 1 and 2, but with no screed required. Designs 11 and 12 proved to be the most cost and carbon efficient solutions. The reduced screed lowered the volume of concrete and therefore the weight of the structure, subsequently reducing the steel weight. Designs 4 and 8 were both variations of beam layout 4, which required a larger number of steels with smaller spanning planks. This layout was not cost effective, and produced the largest cost and carbon solutions. There did seem to be a clear distinction between beams that had a limited minimum width of 175 mm, and in each case, the addition of flat plates to a smaller beam appeared to provide a most cost and carbon efficient solution. The results from Design 3 are interesting as it appears to have 5% less carbon and 5% more cost compared to Design 1. This can be attributed due to the larger number of total steel members used in Design 3 which increases erection, fabrication and fire protection costs. On the other hand, the total weight of steel is approximately the same with Design 1 but the use of 150 mm planks significantly reduces the carbon emissions in the floor construction. Design 9, which was equivalent to Design 1 with additional design contingency for torsion applied to the beam was more carbon intensive and costly than its counterpart (Design 1). However, this difference was smaller than many of the other factors. It should be noted that Design 10 encountered difficulties during the design stage and has been omitted from this results comparison.



Type	Design No.	Beam Layout	Beam Restrain	Beam Type	Comments	Precast Type	Plank Depth (mm)	Screed Depth (mm)	Floor Areas (m^2)
Precast	1	Option 1	Pinned	Universal	N/A	Hollowcore	200	75	1259
Precast	2	Option 2	Pinned	Universal	N/A	Hollowcore	250	75	1259
Precast	3	Option 3	Pinned	Universal	N/A	Hollowcore	150	75	1259
Precast	4	Option 4	Pinned	Universal	N/A	Hollowcore	150	75	1259
Precast	5	Option 1	Pinned	Universal	No steel plate	Hollowcore	200	75	1259
Precast	6	Option 2	Pinned	Universal	No steel plate	Hollowcore	250	75	1259
Precast	7	Option 3	Pinned	Universal	No steel plate	Hollowcore	150	75	1259
Precast	8	Option 4	Pinned	Universal	No steel plate	Hollowcore	150	75	1259
Precast	9	Option 1	Pinned	Universal	Torsion	Hollowcore	200	75	1259
Precast	10	Option 4	Pinned	Universal	Torsion	Hollowcore	150	75	1259
Precast	11	Option 1	Pinned	Universal	No screed	Hollowcore	200	-	1259
Precast	12	Option 2	Pinned	Universal	No screed	Hollowcore	250	-	1259

Figure 4: Grid layout and design options for engineering-based designs

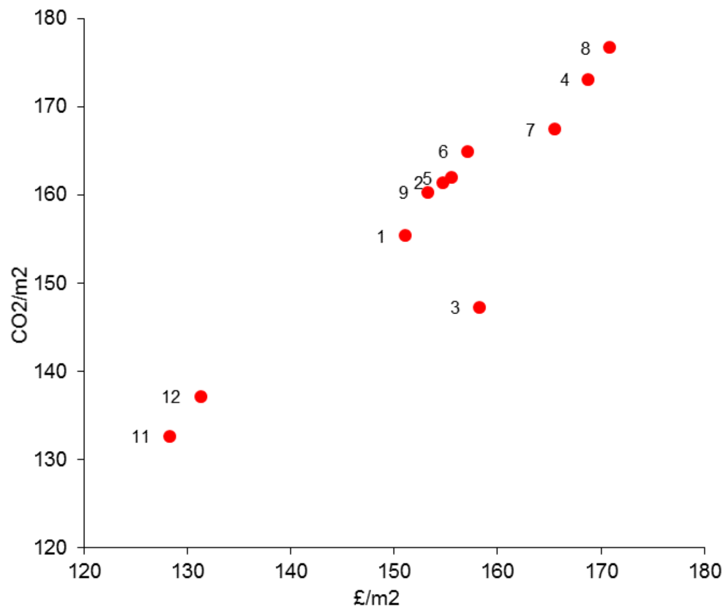


Figure 5: Results for Engineering-Based Designs for the whole structure

6. Computational-Based Designs

The design conditions and constraints used to populate the actual solutions were also implemented as input data in the computational-based designs. Based on the defined data input possible design configurations were computed to satisfy Eurocode 3 and the structural requirements set by the engineering practitioners. The resulting 20,000 designs were computed in less than 5 min. The material listings for these solutions were then compiled, using direct output from the structural analysis. In total the data collected included:

- Total steel weight by member type
- Total steel surface area – this is to calculate the area of paint needed.
- Total volume of precast planks
- Total volume of in-situ concrete. This included the infill concrete around and between planks for the precast options
- Total weight of reinforcing steel. For precast options it allowed a basic weight for the pre-stress tendons, as well as allowance for tying bars around the perimeter and between planks.
- Total weight of additional steel. This is to allow for plates and/or angles required where beams are selected that don't meet the required minimum bearing areas. No allowance has been made for connections for any of the options.

Figure 6 shows the representation of the design space as populated by the model for the steel beams of the structure. The swarm with the black nodes includes all the computational-based solutions and is combined with engineering-based designs which are represented by the red nodes. The comparative analysis with the actual designs only includes the first nine designs excluding the ones without screed (designs 11 and 12) in order to understand the impacts of the steel members on the cost and carbon results. It is evident that all the design solutions populated from the computational model are more economical than the cheapest actual solution by 12-18%. The carbon performance of the computational-based solutions lies on the lower boundary of the actual designs. Almost 50% of the swarm has similar carbon performance compared to the most carbon efficient actual solution. Furthermore, the design space showed that additional

6-8% carbon reductions could be achieved from the design of steel beams by optimising mainly the spans' distribution and the classification of more efficient beam sizes.

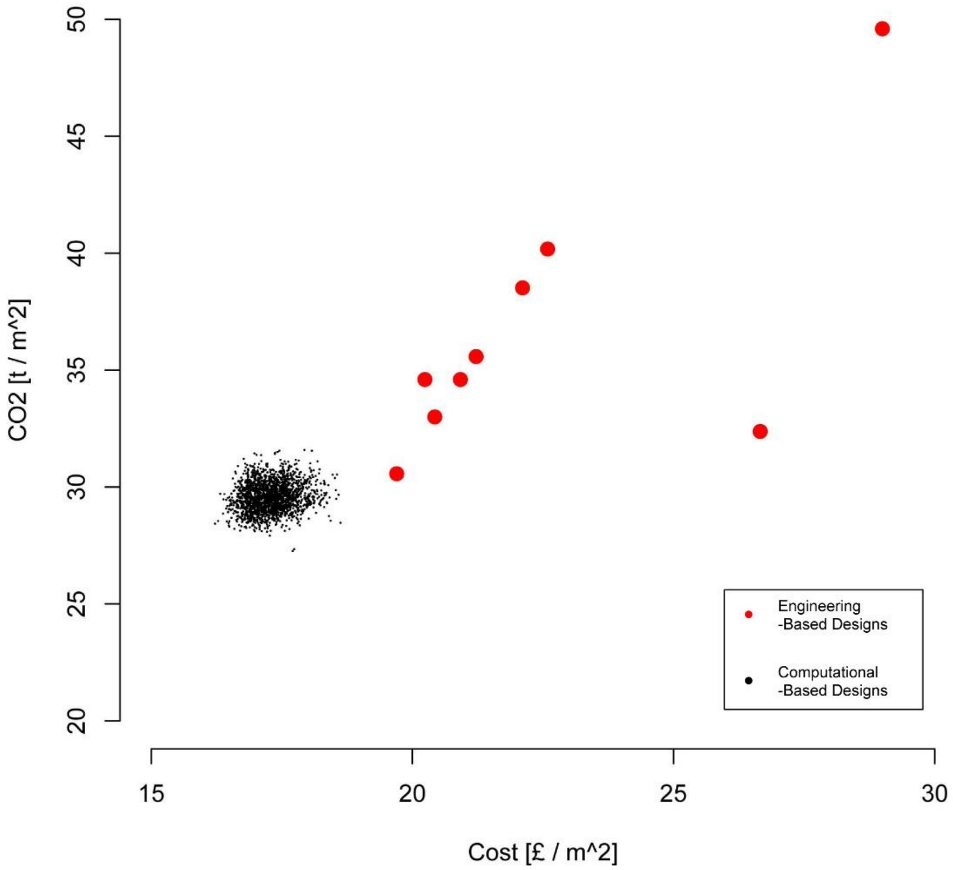


Figure 6: Design space and cost and carbon relationships

7. Conclusions

The study has focused on the development of a practical computational model for the optimisation of steel structures based on their cost and carbon performance. The research offers a new paradigm to structural engineers for the analysis of design alternatives during the early design stages where time restrictions often limit the exploration of the entire design space. The proposed computational model provides rapid analysis of the solution space which can increase the understanding of available designs and overall could enhance decision-making. Comprehensive cost and carbon functions were established using relevant material, manufacturing, fabrication, and construction factors which were then computed using the bill of materials generated by the computational model. An actual building was used to verify the proposed methodology. The engineering efficiency of the solutions was validated utilising an engineering-based approach. The results obtained from the completed computations on the tested building has showed that both cost and carbon performance could be enhanced when compared to the actual designs solutions by 12-18% and 6-8% respectively. The reasons for the enhanced efficiencies were mainly due to more appropriate use of spans and beam sections. This is part of a larger study and therefore additional investigations in multiple building scenarios are required in order to fully verify the efficiency of the computational model. Nevertheless, the initial findings are encouraging and could be used in the refinement of a new engineering paradigm for cost and carbon optimisation in steel building structures.

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References

BCSA & TATA, S., 2013. Steel Construction – Cost. Technical report, s.l.: s.n.

Dunant, C. et al., 2017. Roles of regularity and optimisation practice in steel structural frames: A comparative study of real design cases. Construction & Building Material, p. Submitted.

Frans, R. & Arfiadi, Y., 2014. Sizing, Shape, and Topology Optimizations of Roof Trusses Using Hybrid Genetic Algorithms. Procedia Engineering, Volume 95, pp. 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 and Structures, 83(21), pp. 1849-1863.

Heinisuo, M., Laasonen, M. & Haapio, J., 2010. BIM based manufacturing cost estimation of building products. Cork, Ireland, ECPPM.

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

Kingman, J., Tsavdaridis, K. & Toropov, V., 2015. Applications of topology optimization in structural engineering: High-rise buildings and steel components. Jordan Journal of Civil Engineering, 9(3), pp. 335 - 357.

Moynihan, M. & Allwood, J., 2014. Utilization of structural steel in buildings. Proc. R. Soc. A, Volume 470, p. 20140170.

Prager, W., 1970. Optimization of structural design. Journal of optimization theory and applications, 6(1), pp. 1-21.

Sawada, K. et al., 2006. A simple estimation of fabrication cost and minimum cost design for steel frames. s.l., Proceedings of the Fourth China-Japan-Korea Joint symposium on Optimization of Structural and Mechanical Systems.

Stromberg, L., Beghini, A., Baker, W. & Paulino, G., 2012. Design of structural braced frames using group optimization. Chicago, Illinois, United States, 20th Analysis and Computation Specialty Conference.

Stromberg, L., Beghini, A., Baker, W. & Paulino, G., 2012. Topology optimization for braced frames: combining continuum and beam/column elements. Engineering Structures, Volume 37, pp. 106-124.

Suliman, M. O., Kumar, V. S. & Abdulal, W., 2011. Optimisation of uncertain construction time-cost trade off problem using simulated annealing algorithm. Mumbai, India, Information and Communication Technologies (WICT), 2011 World Congress.

Zhou, F., AbouRizk, S. & Al-Battaineh, H., 2009. Optimisation of construction site layout using a hybrid simulation-based system. Simulation Modelling Practice and Theory, 17(2), pp. 348-363.

Zhou, J. et al., 2013. A review of methods and algorithms for optimizing construction scheduling. Journal of the Operational Research Society, 64(8), pp. 1091-1105.