Effectiveness Of Embodied Carbon Reduction Methods In UK Construction

Georgina May[1], Atefeh Abbaspour[1*]

[1]Department of Civil Engineering and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK
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Abstract. Over the years, carbon emissions have gained significant importance within the construction industry. Different factors throughout the life cycle of a project can have a direct implication on the total carbon footprint of a construction project. This paper focuses on a steel structure designed in accordance with Eurocode and dives deeper into different parameters and how changing configurations at the design stage have a direct correlation to the overall embodied carbon output. The five parameters considered in this investigation are steel grade, concrete grade, load reduction, bay sizing, and composite deck changes.
For steel grade, a comparison is made between S275, S355, and S460 to determine which is the optimal grade to use. Concrete grades of C25/30, C32/40, and C40/50 are also compared, along with the addition of Ground Granulated Blast Furnace Slag (GGBS) content and how the percentage content impacts the embodied carbon output. The effect of different imposed load cases is also considered to determine how decreased load can lead to reduced steel weight and consequently lower carbon emissions. Additionally, a number of bay sizes have been tested to determine their effect on the structure. The final parameter considered is the composite deck profile used and its gauge thickness to determine the differences in the configuration of the structure.
Ultimately, each of these parameters can be considered at the design stage of any project to find the most effective solution, while reducing the overall carbon footprint. When combining the best configuration from each parameter, including S460 steel grade, concrete grade of C25/30 with 75% GGBS, imposed loading of 2.0 kN/m^2, a 6×6 m bay size, and ComFlor® 60 1.0 mm deck, the overall structure is reanalyzed. In this case, the final model resulted in 604 $kgCO_2e/m^2$ carbon emissions, which represents a reduction of 38.8% from the base model. This outcome provides an overall review of how many small changes, when combined, can have a larger impact leading to a more effective and sustainable design.

Keywords: Embodied carbon; Mitigating carbon emissions, Structure design, Carbon footprint, IStructE

1. Introduction

As the topic of climate change continues to gather greater political, social, and economic impetus, the need for reducing carbon emissions has become an important factor across various industries. One industry, in particular, is the construction industry, with the production of materials, on site activities and material transportation contributing a hugely significant portion of carbon emissions globally. Consequently, there is a large onus on construction projects to identify and actively reduce the carbon output of their physical build and construction processes.

Buildings and construction statistically make up approximately 40% of energy related CO_2 emissions with structural engineering choices contributing around 10% of this figure (Abergel, Dean & Dulac, 2017). In terms of emissions this translates to roughly 4.2 $GtCO_2e$ (carbon dioxide equivalent) per annum. Due to this significant contribution, it is vital to be aware of the impact that current commonly used materials currently have on this figure.

Concrete is currently one of the most widely used materials for construction, with annual production for 2019 reaching 4.1 Gt (Curry, 2020).The main contributor of carbon within concrete is the cement, with 50% of its carbon emissions resulting from the chemical reaction that occurs as a by-product of clinker production (Development, 2009; Cheng et al., 2023). Consequently, the amount of carbon emitted, during the process of manufacturing concrete, varies heavily in correlation with the quantity of Portland cement specified.

Concrete containing only Portland cement has an embodied carbon factor of 0.912 $kgCO_2e/m^2$. Two of the popular replacements for ordinary Portland cement are Ground Granulated Blast Furnace Slag (GGBS) and Pulverised Fuel Ash (PFA) which have similar chemical reaction properties and can improve the strength and durability of concrete. In this case, the embodied carbon factor of cement can be reduced to 0.278 $kgCO_2e/m^2$ when utilising 73% GGBS in place of Portland cement (Grazia et al., 2020). Furthermore, to mitigate the carbon emissions associated with cement production, Costa and Ribeiro, (2020) proposed the repurposing of civil construction waste (CCW) as an alternative raw material in the production of Portland clinker, partially replacing limestone-clay mixtures. This approach resulted in a reduction of up to 8.1% in CO_2 emissions.

Alongside concrete, steel is another vital material utilised in the majority of construction projects. These two materials along with timber are the most highly utilised in construction. In a study by Hawkins *et al.* (2021), these materials' carbon emissions and climatic impacts were assessed and compared within a typical medium-rise building structure. The findings

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indicated that concrete and steel structures exhibited the highest impacts, attributed to emissions generated during material production and construction. In contrast, timber considered as the most favourable option with the lowest impact.

There are two main production methods used to manufacture steel to be used in construction, basic oxygen furnace (BOF) which is powered using fossil fuel plants and electric arc furnaces (EAF) (Kildahl et al., 2023). In terms of usage, BOF plants supply approximately 70% of steel globally and 60% of steel in the UK and EU (World Steel Association, 2019). Given the nature of the production process, the carbon output for producing steel in this way is significant, especially due to its reliance on fossil fuels which are notorious for negatively contributing to carbon emissions.

In 2021, EAF accounted for 30% of steel production globally (World Steel Association, 2021). Whilst the process still relies on consuming a large amount of energy, this energy can be sustainably sourced through alternative and renewable energy methods. The process also allows for the use of recycled materials and can even produce steel with 100% recycled content. If renewable sources are utilized in the EAF, there is the potential of mitigating 1.5 Gt of CO_2 emissions annually (IRENA, 2020). Although EAF appears to be a simple solution to lowering embodied carbon, the availability of EAF plants is limited within the UK (total 4 sites in the UK) which produce approximately 3 milion tonnes of steel annually (Eurofer-The European Steel Association, 2021). This amount is much less than the demnd for the steel in the country. This means that the majority of steel required should be imported. In 2018, the surplus requirement for crude steel was imported from China with 87% of this being produced using BOF (World Steel Association, 2021).

A large proportion of decisions that affect embodied carbon occur during the design stages of construction. The Institution of Structural Engineers (IStructE) has developed a Hierarchy of Net Zero Design, that outlines the most efficient way to reach net zero design which contains three main sections including 'use less stuff', 'specify low impact' and 'offset' (The institution of structural Engineers, 2023).

Within 'use less stuff', the main goal is to eliminate the need for material as a first effort. The main approach is to discover whether construction is genuinely required or whether repurposing existing structures is a viable option. Once the need for construction has been confirmed, the focus then shifts into more efficient ways to design the structure. Furthermore, 'specify low impact' refers to designing structures with minimal environmental impact throughout their lifecycle, including construction, operation, maintenance, and eventual demolition or deconstruction. This involves considering factors such as material selection, waste reduction, carbon footprint, etc. On the other hand, 'offset' refers to compensating for their carbon emissions by funding projects that reduce greenhouse gas emissions elsewhere, such as renewable energy projects or tree planting initiatives (Arnold, 2021).

The main aim of this investigation is to evaluate the effectiveness of embodied carbon reduction methods on construction sites, focusing on material contributions. This investigation will focus on assessing the effects of using lower carbon materials, recycled materials and optimised design on the overall embodied carbon of a structure. This will be achieved by taking a control structural model and calculating comparable carbon values. The carbon output will be calculated using the IStructE carbon calculator and will provide a quantitative value that can then be used to evaluate the differences in output for each method.

2. Methodology

2.1 Life cycle modules

Carbon output is measured in sections for a structure. These are referred to as modules and run throughout the whole life cycle of a building. According to BS EN 15978 (British Standards Institution, 2011), modules A1-A3 refer to the raw material supply, transport (importation) and manufacturing of the materials used. A4-A5 refers to the construction processes, whilst B1-B5, C1-C4, and D refer to use, end of life and beyond the life cycle, respectively.

This investigation will focus on lifecycle modules A1-A3, and investigating the impact of using lower carbon and recycled materials on the overall embodied carbon. This study will rely on material parameter changes in order to assess the output of a design scheme. In order to achieve this, a control model has been adopted. This will then be adapted to incorporate material and design optimisations, such as altering the concrete grade and load reduction. The results will then be compared against the control model using the carbon emission value calculated using the IStructE carbon calculation toolkit.

2.2 Design principle

A steel frame superstructure will be the main focus of this investigation, incorporating a composite deck. This allows both steel and concrete parameters to be evaluated, but also keeps the structure simple and relatively straight forward to design in larger quantities. For simplification, emission values will be calculated and collated into groups based on the parameter being investigated. The outputs will be evaluated within the parameter groups to identify the most optimal adaptation.

Following this, the most effective output will be assessed against other parameters. The alterations are going to be split into parameters to isolate one variable change at a time. By doing this it becomes possible to assess the impact of 'smaller' design changes in real construction scenarios. The models will each be designed in MasterSeries design software and will be structurally sound. MasterSeries is a powerful and user-friendly tool which offers a wide range of analysis and design modules, covering everything from simple beam calculations to complex building structures. It can be integrated with other modelling software, including Revit, AutoCAD, etc (MasterSeries, 2024). Although correct design protocol and standards have been utilised in this

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process, detailing has been excluded (such as connections).

2.3 Control model

A simple model has been designed to act as a control variable throughout the investigation. Whilst the aim of the investigation is to change the parameters of the design, the following design data has been kept consistent throughout each model (excluding the independent variable), to avoid errors in design as well as inaccurate results.

The model incorporates the superstructure only and has been designed in accordance with Eurocodes 1, 2, and 3. MasterSeries design software automatically applies these codes within the design and autogenerates load cases using the design load factors from the code. The premise behind the structure is that of an office building, 36×36 m on plan and 12 m in height, 3 storeys. For ease of design, the full internal area of the building has been designed for office loading, although in reality the footprint would contain varying loads to account for different usages of the areas.

The general principle of this structure is a standard steel frame using UK standard sections in steel grade S355 and consists of a composite deck that will assist in the lateral restraint of the building, as well as transferring the vertical loads onto secondary beams. These will then transfer the loads onto the primary beams before transferring down the columns into the substructure. The substructure is excluded from this investigation.

For the control model, it has been assumed that the structure consists of a 130 mm deep composite slab. The metal deck profile implemented in the structure is ComFlor® 51+ with a gauge of 1.0 mm and A393 mesh reinforcement throughout. The concrete grade is C32/40 and contains 25% GGBS. To keep the design simple, the roof structure has been kept as the same profile and makeup as the accessible floors, although in reality a different metal sheeting could be utilised.

The loading for the structure has been taken from Eurocode guide for office loading which suggests vertical imposed area loading for office use is 2.0-3.0 kN/m^2. The control model adopts 3.0 kN/m^2 in imposed loading as this theoretically allows for any level of office use. Eurocode also suggests an additional imposed load of 1.0 kN/m^2 for partitions which has been implemented. To account for ceilings, services, screed and potential raised floor systems, a super-imposed dead load of 1.0 kN/m^2 has been applied to all accessible floors.

For the roof, it has been assumed that the roof will be inaccessible with the exception of maintenance, thus an imposed load of 0.6 kN/m^2 has been adopted, combined with a super imposed dead load of 2.0 kN/m^2 to encompass possibilities such as solar panels, finishes and plant situated on the roof. Snow loading is typically calculated to be less than the 0.6 kN/m^2 that has already been adopted for imposed loading and has therefore been omitted from the analysis.

The aforementioned loads have been applied to the model using panel loading in MasterSeries, with the loads spanning between the secondary beams.

Horizontal forces are accounted for in applied wind loading and notional horizontal loading. Notional horizontal loading is automatically applied through MasterSeries load combinations. As the model is essentially a simulation, a random location has been selected to derive the wind load from. The values for this calculation have been extracted from Eurocode and calculated within MasterSeries Wind Analysis. For this structure, the maximum peak wind pressure has been calculated to be 0.558 kN/m^2 at 12 m above ground level.

Directional wind pressure has also been included in the analysis to allow for a realistic design. Wind loading has been applied to the model as wind panels and incorporated into load cases, this generates varying pressures as a result of differing heights and directions. As with many designs, this design has been taken as a fully pinned frame. This is a conservative assumption as connections do allow for some level of fixity. To reflect this in the analytical model, all horizontal members have been inputted with member end releases, whilst the vertical members have pinned static supports on the ends.

The model includes vertical bracing, in the form of cross bracing, in designated bays on each face of the building. These have been applied as tension only members with released ends. Members have been sectioned into groups (shown in Fig. 1). Each of these groups have the same section size to replicate buildability and rationalisation. Furthermore, Fig. 2 illustrates the structural model (control model) along with the magnitude and application of the panel loads.

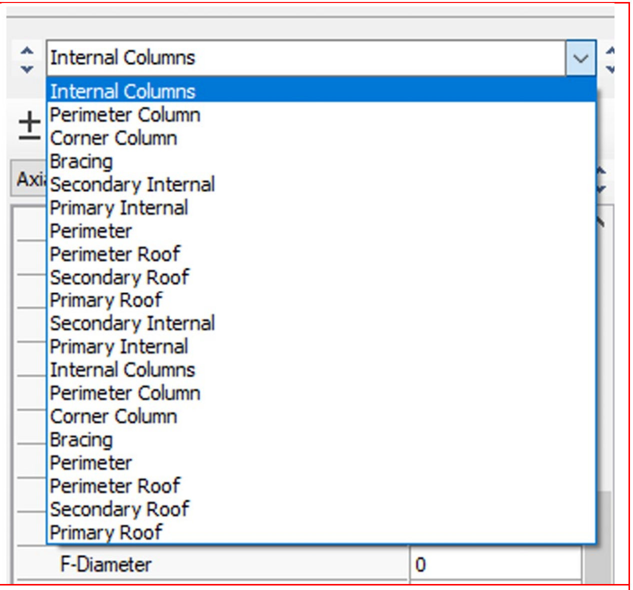

Fig. 1 Member Design Groups for Structural Model

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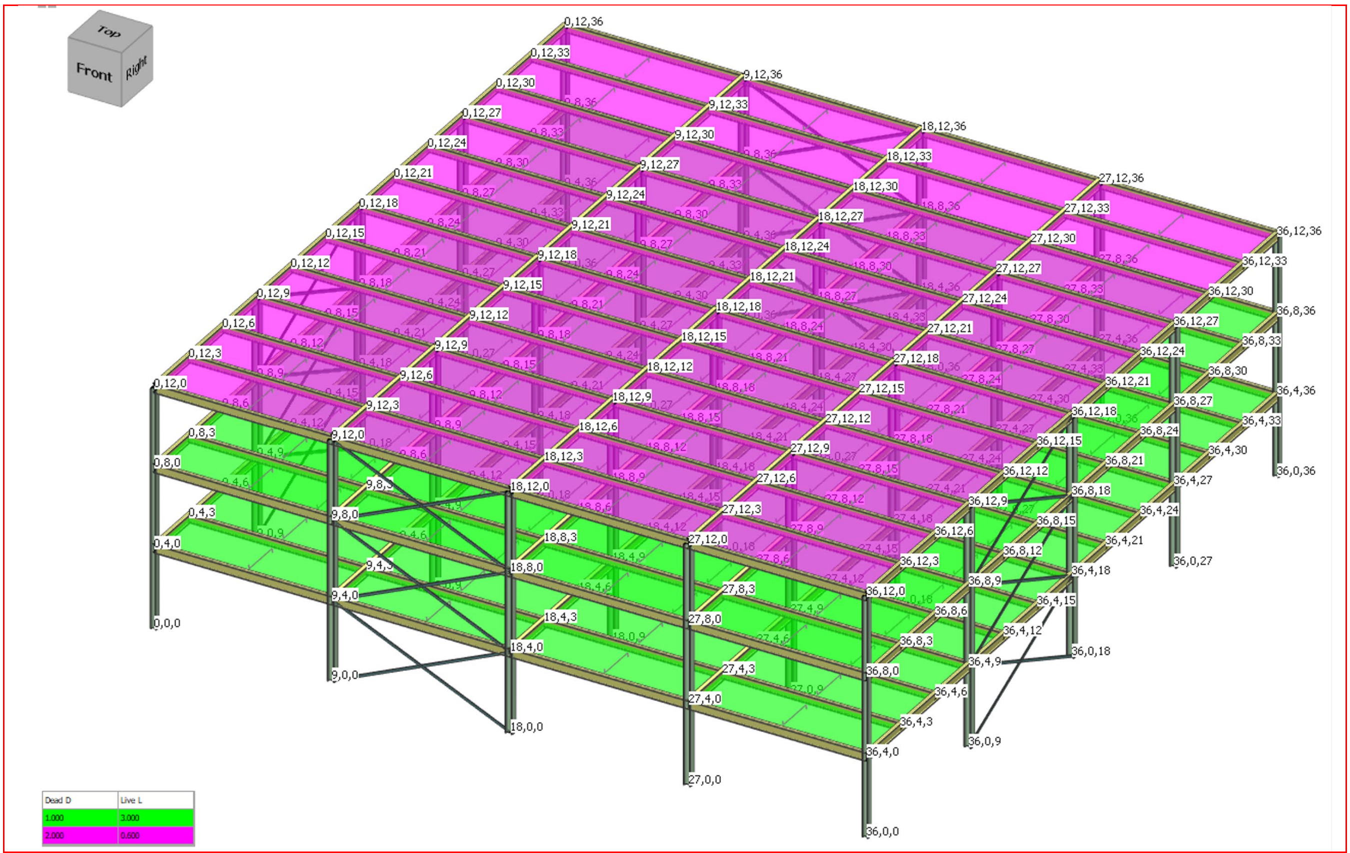

Fig. 2 Control Model with Vertical Loading Panels

The data that has been inputted into the carbon tool have been extracted from the MasterSeries model which an example is summarised in Table 1. Also, Fig. 3 shows a snapshot of the frame data from MasterSeries that lists the weight of the steel sections. Furthermore, an example of Carbon Calculation Tool's input and output for the control model is illustrated in Fig. 4.

Table 1 Inputted data for control model extracted from MasterSeries

Concrete Volume (ComFlor® 51+1 mm)	0.12 m^3/m^2
Area per floor	1296 m^2
No of floors (including roof)	3
Volume of concrete (slabs)	311.04 m^3
Volume of concrete (roof)	155.52 m^3
Weight of deck profile per area (ComFlor® 51+ 1 mm)	14.3 kg/m^2
Weight of concrete (slabs)	37065.6 kg
Weight of concrete (roof)	18532.8 kg

3. Results and discussion

The main value of focus for this investigation is the total value for module A. As can be seen in Fig. 4, the carbon equivalent value for this structure is 895 $kgCO_2e/m^2$. All other models will be evaluated using these units. In this regard, the impact of different structures on reducing the embodied carbon of the control model are investigated in different scenarios by changing the construction materials and sizes of the model. The scenarios include implementing various steel grades, concrete grades, reducing the load, changing the bay sizes, and changing the decks.

Upon completion of the calculations, each carbon reduction method can be evaluated and reviewed in relation to the total embodied carbon output of each scheme. Using the outputs produced by the IStructE carbon tool, the carbon outputs can be tabulated and presented graphically and plotted visually against the result from the control model. By analysing the parameters individually, it allows for the analysis of effect of the isolated changes and highlights the impact that small changes in design can make.

3.1 Steel grades

The effects of steel grade on carbon emissions are not necessarily clear in terms of direct output due to the production process, however the use of higher steel grades is increasing in industry and is a valid option for reducing embodied carbon.

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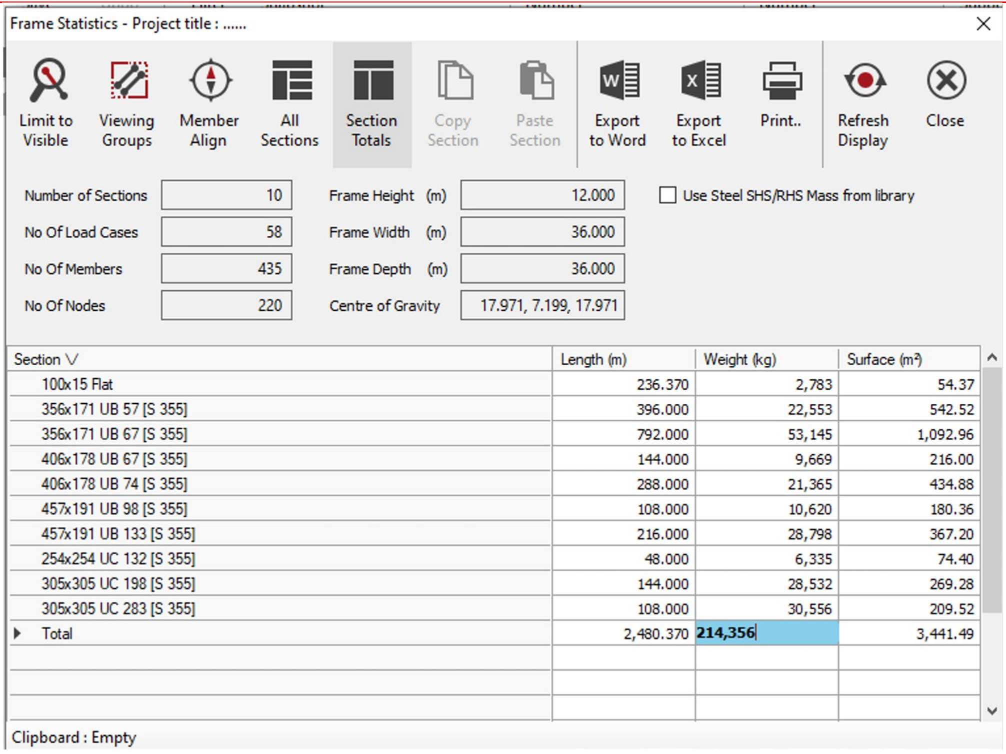
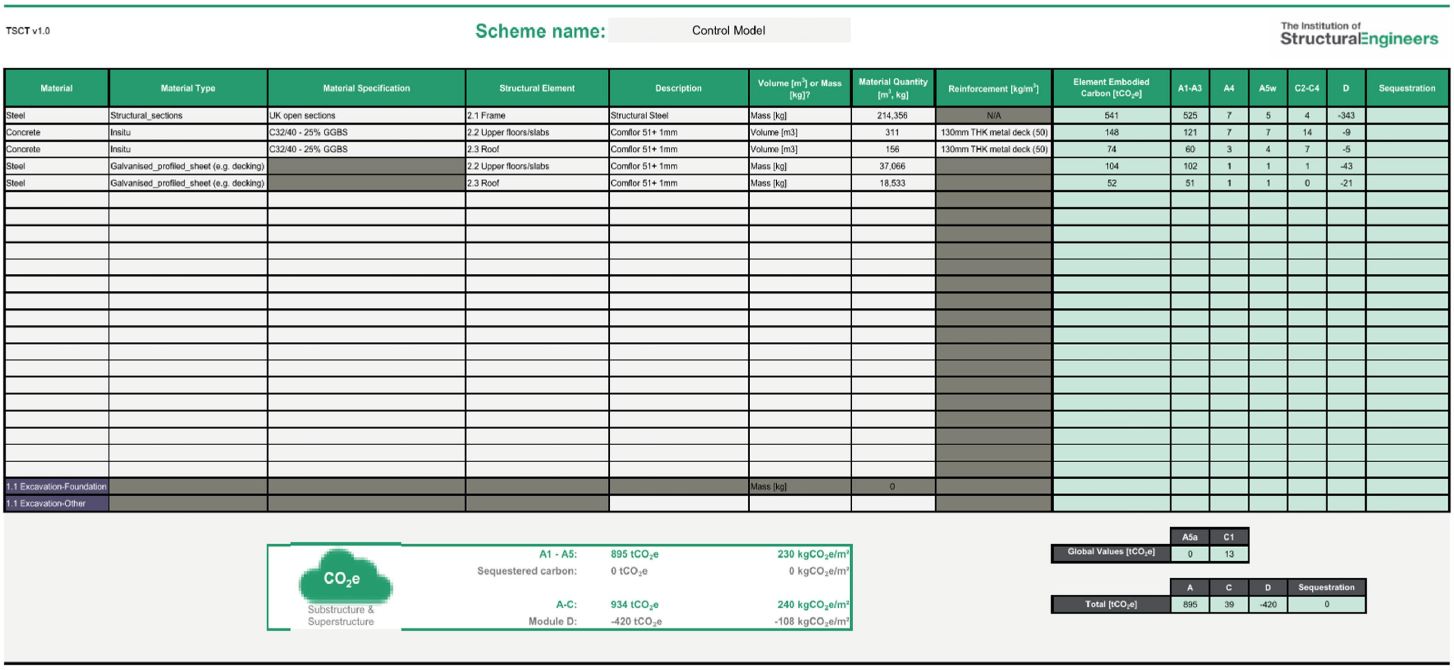


Section	Length (m)	Weight (kg)	Surface (m²)
100x15 Flat	236.370	2,783	54.37
356x171 UB 57 [S 355]	396.000	22,553	542.52
356x171 UB 67 [S 355]	792.000	53,145	1,092.96
406x178 UB 67 [S 355]	144.000	9,669	216.00
406x178 UB 74 [S 355]	288.000	21,365	434.88
457x191 UB 98 [S 355]	108.000	10,620	180.36
457x191 UB 133 [S 355]	216.000	28,798	367.20
254x254 UC 132 [S 355]	48.000	6,335	74.40
305x305 UC 198 [S 355]	144.000	28,532	269.28
305x305 UC 283 [S 355]	108.000	30,556	209.52
Total	2,480.370	214,356	3,441.49

Fig. 3 Inputted data from MasterSeries showing the weight of the steel sections



Material	Material Type	Material Specification	Structural Element	Description	Volume [m³] or Mass [kg]?	Material Quantity [m³, kg]	Reinforcement [kg/m³]	Element Embodied Carbon [tCO$_2$e]	A1-A3	A4	A5w	C2-C4	D	Sequestration
Steel	Structural_sections	UK open sections	2.1 Frame	Structural Steel	Mass [kg]	214,356	N/A	541	525	7	5	4	-343	
Concrete	Insitu	C32/40 - 25% GGBS	2.2 Upper floors/slabs	Comflor 51+ 1mm	Volume [m3]	311	130mm THK metal deck (50)	148	121	7	7	14	-9	
Concrete	Insitu	C32/40 - 25% GGBS	2.3 Roof	Comflor 51+ 1mm	Volume [m3]	156	130mm THK metal deck (50)	74	60	3	4	7	-5	
Steel	Galvanised_profiled_sheet (e.g. decking)		2.2 Upper floors/slabs	Comflor 51+ 1mm	Mass [kg]	37,066		104	102	1	1	1	-43	
Steel	Galvanised_profiled_sheet (e.g. decking)		2.3 Roof	Comflor 51+ 1mm	Mass [kg]	18,533		52	51	1	1	0	-21	
1.1 Excavation-Foundation					Mass [kg]	0								
1.1 Excavation-Other														

	A5a	C1
Global Values [tCO$_2$e]	0	13

	A	C	D	Sequestration
Total [tCO$_2$e]	895	39	-420	0

Fig. 4 An example of IStructE's input and output for the control model

In older construction, steel grades S275 and lower can be seen in site. This is uncommon in modern design, with the current standard steel grade being S355 for structural steels (with the exception of bracing members and plates). To investigate the effects of steel grade, three models have been produced. The measurable output for this parameter will be the reduction in steel weight based on the increased strength of the steel. The control model is designed using standard S355 grade steel sections. An additional two models have been developed using S275 and S460 grade steel respectively.

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The relevant data has been extracted from these models to generate the carbon calculation tool. The concrete and deck weight do not deviate from the control model; thus, the steel section weight is the only updated value. The carbon values have been calculated. The resulting carbon equivalent values in each scenario are shown in Fig. 5.

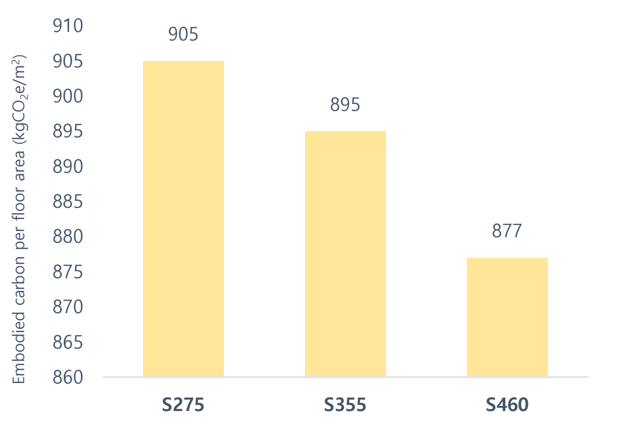

Fig. 5 Carbon output for steel grade scenarios

According to Fig. 5, utilising a stronger grade of steel reduces the overall weight of steel required in the structure. The higher strength of the steel allows for lighter weight and smaller sized sections, due to the increased capacity of the members, thus reducing the overall tonnage.

Looking at the results obtained, the results for each steel grade (S275, S355 and S460), can be compared by calculating the percentage difference between their corresponding embodied carbon outputs. The steel grade with the highest carbon output is S275. This results in an overall steel weight of 218,387 kg. Consequently, the total carbon output for this model is 905 $kgCO_2e/m^2$ (inclusive of the composite deck). The steel weight in isolation accounts for 551 $kgCO_2e/m^2$, which makes up 60.8% of the overall figure.

The second highest embodied carbon emission is produced by the model utilising S350 steel grade. For this model the steel section weight amounts to 214,265 kg. The steel sections alone produce 541 $kgCO_2e/m^2$, which is 60.4% of the overall figure of 895 $kgCO_2e/m^2$.

The most efficient steel grade in the analysis is S460. The resultant steel section weight is 207,389 kg. The embodied carbon for this model calculates to 877 $kgCO_2e/m^2$. In terms of contribution to this figure, the isolated steel sections embodied carbon is 524 $kgCO_2e/m^2$, 59.7% of the overall output. When looking at these results in conjunction with each other, it can be seen that changing the steel grade does have an effect on the carbon output of a superstructure.

The control model aligns with the S355 model, which resulted in being the median output. By utilising the lower grade of steel, the carbon output increased by 1.11%. When a higher grade of steel is utilised the carbon output decreases by 2.03%. This means that by selecting a higher grade of steel, with respect to this model, at the design stage of a project, a minimum decrease in carbon output of 1.11% can be achieved.

3.1.1. Advantages and disadvantages

The main advantage of using an optimal steel grade relates to the carbon output. The results above show that the embodied carbon of the material required is lower due to the reduction in quantity/weight needed. The other effect that the reduction in steel weight has, is that using less steel, there is less carbon output associated with transportation and processing on site. This means that fewer transportation resources are needed to move the lighter steel materials, thereby reducing emissions from transportation activities. Similarly, less energy and resources are required for processing and handling lighter steel components on-site, further minimizing carbon emissions throughout the construction process. With the usage of higher steel grades increasing, the availability is also forecast to increase, making it potentially more readily available in the future than the lower steel grade of S275.

The main disadvantages of S460 grade steel are the cost and current availability. Whilst the specification of this steel grade is increasing, the current usage is low meaning that the cost to specify this steel can be costly. The most readily available grade for structural steel is S355 making it the most cost effective. The production of S460 steel is also not as commonplace as S355 meaning that the suppliers, at present may be further afield resulting in larger carbon outputs for transportation to site.

3.2. Concrete grade

Concrete grade has a significant effect on the amount of carbon it produces. The strength of the concrete, defining its grade, largely correlates to the quantity and quality of cement used in the mix. Where the concrete strength is higher, the quantity of cement used increases and consequently increases its carbon emission.

There are a lot of factors that dictate the grade of concrete utilised within a design such as fire resistance and exposure types. Within this investigation, these factors have been omitted for ease, however it has been appreciated that these may cause variations in slab depth and could have marginal effects on the spanning capabilities of the metal deck profile.

The control model uses a concrete grade of C32/40. The minimum allowable concrete strength for ComFlor® decking is C25/30 whilst the highest strength being C40/50. For this reason, three models have been produced to replicate the aforementioned grades.

Additional to the grades, the GGBS content for these models have been changed. The GGBS content does not reduce the strength of the concrete, however, it does cure at different rates for varying percentages of replacement. Therefore, this

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amendment does not require reanalysis of the structural models, consequently this has been encapsulated within the carbon calculation only. The strength of the concrete itself will affect the weight of steel required to support the deck, as well as having a different carbon value per grade.

Based on the results of changing the concrete grade which is depicted in Fig. 6, there are minimal effects on the weight of steel sections, however, the emissions based on concrete grade alone change with the concrete grade.

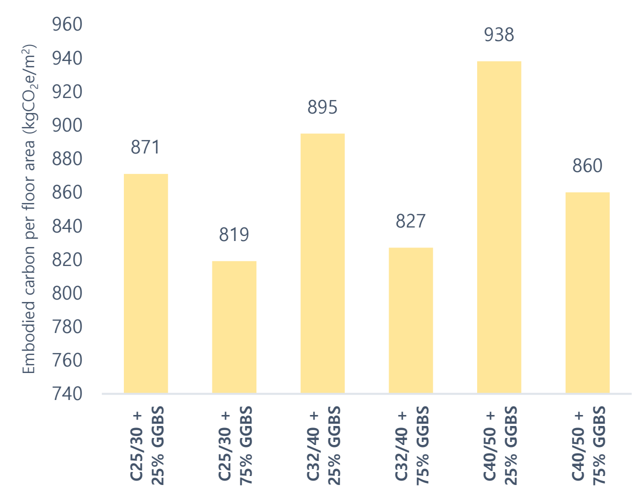

Fig. 6 Carbon output for concrete grade scenarios

Looking at the results obtained, the results for each concrete grade (C25/30, C32/40 and C40/50), can be compared by calculating the percentage difference between their corresponding embodied carbon outputs. Within each grade, two quantities of GGBS replacement (25% and 75%), have also been investigated.

The highest carbon output is produced by the model utilising C40/50 grade concrete. When incorporating 25% GGBS replacement, the carbon value is 938 $kgCO_2e/m^2$, whilst the value for specifying 75% GGBS replacement is 860 $kgCO_2e/m^2$. The carbon saving by using less ordinary Portland cement is an 8.7% reduction.

By utilising C40/50 concrete, the structural steel weight is 223,198 kg. The concrete grade that produces the second highest carbon is C32/40. At 25% GGBS replacement, the total carbon produced by the model is 895 $kgCO_2e/m^2$. For the slabs containing 75% GGBS, the carbon produced is 827 $kgCO_2e/m^2$.

Similarly, to the C25/30 model, the weight of structural steel used is 214,265 kg for both models, thus the concrete grade does not have a major impact in the structural steel weight. The percentage of carbon saving achieved by selecting 75% GGBS replacement in this instance is 7.9%.

The concrete grade that produces the lowest emissions, at 25% GGBS replacement, is grade C25/30. This grade is the lowest grade specifiable for use with ComFlor® composite deck and produces an overall emission of 871 $kgCO_2e/m^2$ for this structure. C25/30 also produces the least carbon emissions for 75% GGBS replacement, generating 819 $kgCO_2e/m^2$. For this model, the steel weight is 214,265 kg for both GGBS replacement values.

By specifying 75% GGBS replacement instead of 25%, a reduction of 6.2% carbon output can be achieved. Looking at the results collectively, it can be seen that the concrete grade does have an impact on the embodied carbon within a structure. Comparing the values for 25% GGBS replacement in each grade, by specifying C32/40 as opposed to C40/50, a carbon reduction of 4.7% can be achieved. By specifying C25/30 a further reduction of 2.7% can be achieved. If the concrete grade can be reduced from C40/50 at 25% GGBS replacement to C25/30 with 75% GGBS replacement, the carbon can be reduced by 13.5%.

The change in steel weight within all of the models for concrete grade are minimal, however, it does increase in the C40/50 grade model. This means that by selecting a lower grade of concrete, only, at the design stage of a project, with respect to this model, a minimum decrease in carbon output of 2.7% can be achieved. By specifying a higher replacement of GGBS, a minimum decrease of 6.2% can also be achieved.

3.2.1. Advantages and disadvantages

The main advantages of specifying lower grade of concrete are the carbon output and the cost. Cost of concrete tends to increase with the concrete strength, as does the embodied carbon in the material. This is due to the ordinary Portland cement content. The reduction in carbon output is amplified when coupled with a higher percentage of GGBS replacement, making it a viable option for reducing carbon footprint.

The grade of concrete depends on many factors including building loads and fire rating. This means that it is not always a suitable change to make when focusing on carbon reduction. Whilst the cost of lower grade concrete reduces, increasing the GGBS content of concrete does increase the cost of the material. Additionally, the GGBS content of concrete can affect the cure time of the concrete. This has both an impact on time, effecting the programme, which adds to the financial implications.

3.3. Load reduction

While imposed load reduction can only be applied to specific circumstances, the scenario in the control model looks at office loading. Code recommendations suggest that the imposed loading should be between 2.0 kN/m^2 and 3.0 kN/m^2 for office areas. In reality, offices have varying requirements for end use, such as spread-out open plan working areas versus individual cubicles back-to-back.

In order to simulate design optimisation, the impact of reducing the imposed load has been investigated. For this parameter, imposed loadings of 3.0 kN/m^2, 2.5 kN/m^2, and

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2.0 kN/m^2 have been applied respectively to three separate models. Loadings for partitions and super-imposed dead load have been kept consistent throughout at 1.0 kN/m^2 each. The measurable output, in this instance, is the weight of steel in the completed design.

As can be seen from the calculations, reducing the imposed loading on a structure does have an effect on the material required structurally and consequently effects the embodied carbon emitted through the materials. By looking at the results from the three scenarios with differing imposed loads (3.0 kN/m^2, 2.5 kN/m^2, 2.0 kN/m^2) which is shown in Fig. 7, the magnitude of the carbon reduction can be calculated by comparing the percentage difference in carbon outputs.

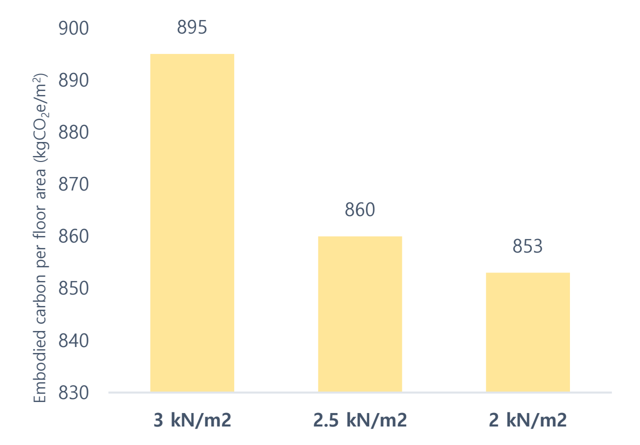

Fig. 7 Carbon output for load reduction scenarios

The highest embodied carbon is produced by the model containing an imposed load of 3.0 kN/m^2. The weight of structural steel required to support the loading is 214,356 kg. This accounts for 541 kgCO_2e/m^2 or 60.4% of the total value of 895 kgCO_2e/m^2.

The second highest embodied carbon is produced by the model containing an imposed load of 2.5 kN/m^2. This model contains 200,366 kg of structural steel sections. This value makes up 506 kgCO_2e/m^2 or 58.8% of the total carbon output of 860 kgCO_2e/m^2.

The most efficient scenario for this section is the model utilising 2.0 kN/m^2. The steel weight is 197,562 kg. This accounts for 499 kgCO_2e/m^2 which calculates to be 58.5% of the total figure of 853 kgCO_2e/m^2. When looking at these results in unison with each other, it can be seen that when the imposed loading is reduced the carbon output is also reduced. The carbon reduction is achieved as a result of reducing the quantity of structural steel.

The control model utilises the maximum imposed load recommendation from Eurocode for office loading, 3.0 kN/m^2. If this value is reduced to 2.5 kN/m^2 the carbon reduction can be reduced by 3.9%. If the load is reduced further to 2.0 kN/m^2, the carbon output can be reduced by a further 0.8%. This means that by reducing the imposed load by 0.5 kN/m^2, at the design stage of a project, with respect to this model, a minimum decrease in carbon output of 0.8% can be achieved.

3.3.1. Advantages and disadvantages

The advantage to reducing imposed loading on a structure is the saving in material quantities. Not only does this lead to less production/ manufacturing cost, it also reduces the carbon produced through the embodied carbon of the materials.

A disadvantage of this carbon reduction method is that it is not always a viable option. Where building could have potential for multipurpose use or the use is unknown, the imposed load applied may need to be conservative for safety reasons. Additionally, whilst the proposed use by the client may allow for load reduction at the initial design stage, it does not account for the future use of the building. This instance may result in a redesign that emits more carbon than is saved during the first design.

3.4. Bay sizes

A general assumption in design is that the larger the span of beams, the more optimal the design. Where clients request as much column free, open space as possible, this solution is typical. However, it is often possible to reduce the bay spacing in a superstructure, especially at the perimeter of the building. It is good practice in design to try and keep member spacing even, regular and symmetrical within the structure. This allows for members to be rationalised and ensures that the loading can spread equally around the frame.

As this investigation looks at a frame only, the spacing of the columns and primary beams can be regular. For this parameter the building has been modelled utilising 9×9 m, 6×6 m, and 4×4 m bay spacing. The secondary beams remain at 3 m spacing throughout the three models; thus, the metal deck is still within acceptable utilisation.

Based on the calculations for the change in bay sizes, the resulting steel section weight varies and consequently has an impact on the embodied carbon output. The results for the three bay size combinations are illustrated in Fig. 8.

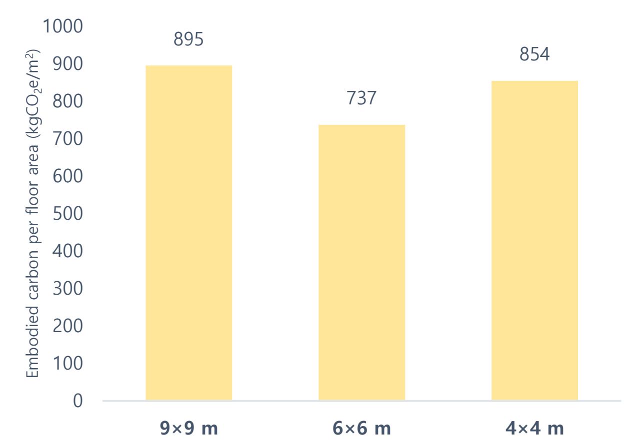

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Fig. 8 Carbon output for bay size changing scenarios

The scenario that produced the highest carbon output is the model with 9×9 m bay sizes. The weight of the structural steel required in this model is 214,356 kg. This generates an embodied carbon value of 541 $kgCO_2e/m^2$, accounting for 60.4% of the overall model value of 895 $kgCO_2e/m^2$.

The second highest carbon output occurs in the model utilising a 4×4 m grid. In this model the weight of the structural steel sections comes to 197,996 kg. This generates an embodied carbon value of 500 $kgCO_2e/m^2$, accounting for 58.8% of the overall model value of 854 $kgCO_2e/m^2$.

The most efficient bay spacing is the 6×6 m grid. The structural steel section weight in this model is 151,333 kg. This generates an embodied carbon value of 382 $kgCO_2e/m^2$, accounting for 51.8% of the overall value of 737 $kgCO_2e/m^2$.

When comparing the above results, it can be seen that the bay size used in the control model produces the highest embodied carbon value. By reducing this to the second highest, 4×4 m spacing, the carbon can be reduced by 4.7%. The carbon can also be reduced by 14.7% if a 6×6 m bay sized is implemented. The above results mean that by deciding on an optimal bay spacing, only, at the start of the design process, with respect to this model, can result in a carbon reduction of 14.7%.

3.4.1. Advantages and disadvantages

The main advantage of optimising bay sizes is the carbon and material saving. By implementing a bay spacing that reduces the quantity of steel required, the cost of the material will be lower as well as the carbon emitted during the manufacturing and transportation processes. Additionally, from the results above, smaller bay sizes do not automatically equate to the most optimal solution. In some cases, the bay spacing could be increased and allow for more utilisable space during the use of the building.

The main disadvantage to this method is the feasibility. This investigation assumes an equal bay spacing throughout the structure and does not account for column free areas required inside the structure. In reality this is not always the case, column locations and bay spacing may be dictated by the clients brief and be unachievable.

3.5. Deck changes

The control model utilises a ComFlor® 51+1mm deck. Utilising a deck with a larger gauge or deeper profile allows the deck to make larger spans resulting in larger secondary beam spacings. Using ComFlor® software, the allowable span of each deck has been calculated which has then been utilised to decide the secondary beam spacings in the model. Four models have been produced to incorporate different decking profiles.

The decks that have been used in the design are ComFlor® 51+ and ComFlor® 60. For each of these decks, gauges of 1.0 mm and 1.2 mm have been assessed. Limitations in the ComFlor® software mean that the concrete grade of C32/40 cannot be implemented, however a grade of C30/37 has been included instead. The intention of this is to be conservative but as close to the required grade as possible.

Table 2 presents the data collated from ComFlor® designer. The spans in this table have been transferred to the MasterSeries model to be used in the design. In terms of carbon output, the difference in embodied carbon for each deck has been taken as negligible for the purposes of this investigation. The resulting weight of steel sections has been taken as the measurable variable.

Table 2 Deck Spans for ComFlor®

Scenario	Profile	Gauge (mm)	Allowable span (m)	Span used (m)	Max unity	Slab depth (mm)	Concrete grade
A	ComFlor® 51+	1	3.25	3	0.94	130	C30/37
B	ComFlor® 51+	1.2	3.75	3.75	1	130	C30/37
C	ComFlor® 60	1	4	4	0.94	130	C30/37
D	ComFlor® 60	1.2	4.25	4.25	0.98	130	C30/37

As the metal deck profile changes in this section, the volume of concrete and the weight for the deck have been calculated below in Table 3. These values have been used in the carbon calculation.

Table 3 Deck data in for ComFlor®

Scenario	Concrete volume (m^3)		Weight per deck area (kg/m^2)	Weight of deck (kg)	
	Slab	Roof		Slab	Roof
A	311.04	155.52	14.3	37065.6	18532.8
B	311.04	155.52	17.3	44841.6	22420.8
C	254.02	127.01	11.2	29030.4	14515.2
D	254.02	127.01	14.3	37065.6	18532.8

From the above calculation, the impact of changing the composite deck profile can be assessed. It can be seen that the change in deck leads to varying secondary beam spans and has an effect on volume of concrete as well as structural

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steel section weight. The results of the scenarios investigated in this section are shown in Fig. 9.

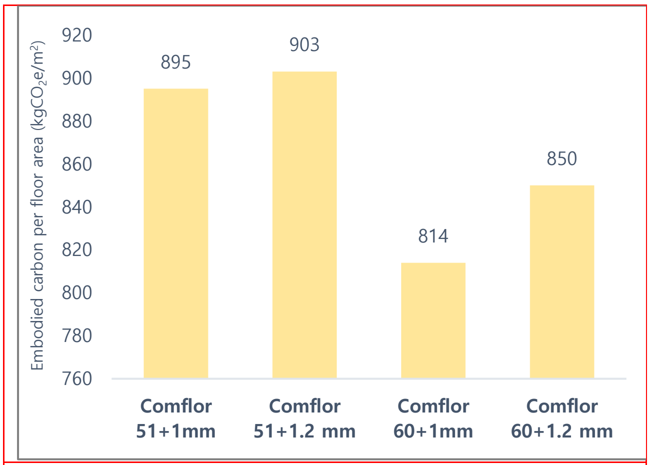

Fig. 9 Carbon output for deck changing scenarios

According to Fig. 9, the least effective deck utilised is ComFlor® 51+ 1.2 mm. This decking utilises secondary beam spacing of 3.75 m, and also has highest self-weight of the four decks. The carbon emitted through using this deck is 903 $kgCO_2e/m^2$.

The model producing the second highest carbon output is the ComFlor® 51+ 1.0 mm. This deck utilises secondary beam spacing of 3 m. The self-weight of this deck is the second highest and produces a carbon output of 895 $kgCO_2e/m^2$. The second most efficient model incorporates a ComFlor® 60 1.2 mm deck. This deck has the same self-weight as the ComFlor® 51+ 1.0 mm deck however it utilises larger secondary beam spacing of 4 m. The carbon output for this model is 850 $kgCO_2e/m^2$.

The most efficient model contains the ComFlor® 60 1.0 mm deck. It is the lightest weight of the four decks and incorporates the largest secondary beam spacing of 4.25 m. The carbon output for this model is 814 $kgCO_2e/m^2$. When comparing the outputs against each other, it can be seen that the least optimal deck is ComFlor® 51+ 1.2 mm. By specifying the deck with the second highest emissions (ComFlor® 51+ 1.2 mm), the carbon can be reduced by 0.9%. This value can be further reduced by 5.2% by specifying the ComFlor® 60 1.2 mm.

By using the most optimal solution a further 4.3% reduction can be achieved. The above results mean that by changing the composite deck profile during the design process, with respect to this model, can result in a carbon reduction of at least 0.9%.

3.5.1. Advantages and disadvantages

The main advantage to using the deeper profile of decking is that the deck can span further. This allows for larger secondary beam spacing and can reduce the weight of steel required. Consequently, this reduces both carbon and cost associated with the structural steel sections. In this case the decking is also lighter weight and has a lower emission value itself.

The main disadvantage in this case is cost, larger depth decks can cost more. The other downside is regarding to parameters of the design. A larger span often means that the deck achieves lower in terms of fire rating and can result in a thicker slab being required. This can result, in some cases, in increased cost from concrete as well as higher emissions.

3.6. Combined model

The combined model has been designed to incorporate the most effective changes implemented in the previous models. By doing this, the result is essentially an optimal model. When comparing this to the control model, the variable parameters can be assessed as a whole, and their effectiveness reviewed. Table 4 shows the parameter from each category that generated the lowest carbon model for its group. These are the parameters that have been taken forward into the combined model.

Table 4 Optimal parameters of all scenarios

Group	Effective parameter
Steel grade	S460
Concrete grade	C25/30 75% GGBS
Load reduction	2.0 kN/m^2
Bay size	6×6 m
Deck changes	ComFlor® 60 1.0 mm

The values from the model in Fig. 10 have been used to calculate the carbon output of the combined model. From this model, the structural steel self-weight is 151,281 kg. This results in an overall carbon output of 604 $kgCO_2e/m^2$. When comparing the above result with the control model, the embodied carbon emission reduced from 895 $kgCO_2e/m^2$ to 604 $kgCO_2e/m^2$. This is an overall reduction of 38.8%.

4. Conclusions

The main focus of this investigation was to investigate the effectiveness of embodied carbon reduction methods. Upon analysing five different parameters that have direct implication on the carbon output of a design, the following conclusions can be made.

When considering steel grade, currently the only way to measure its embodied carbon impact is to analyse the overall weight of the structure based on increased strength, rather than directly linking the embodied carbon based on manufacture of higher steel grade. The implications of using a higher steel grade have a direct correlation to the overall weight of steel in the structure and consequently the carbon output.

Concrete grade and GGBS replacement percentages also directly impact the embodied carbon in the material. The lower the concrete grade, the less carbon is emitted during production. By replacing ordinary Portland cement with

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GGBS the carbon output is also reduced.

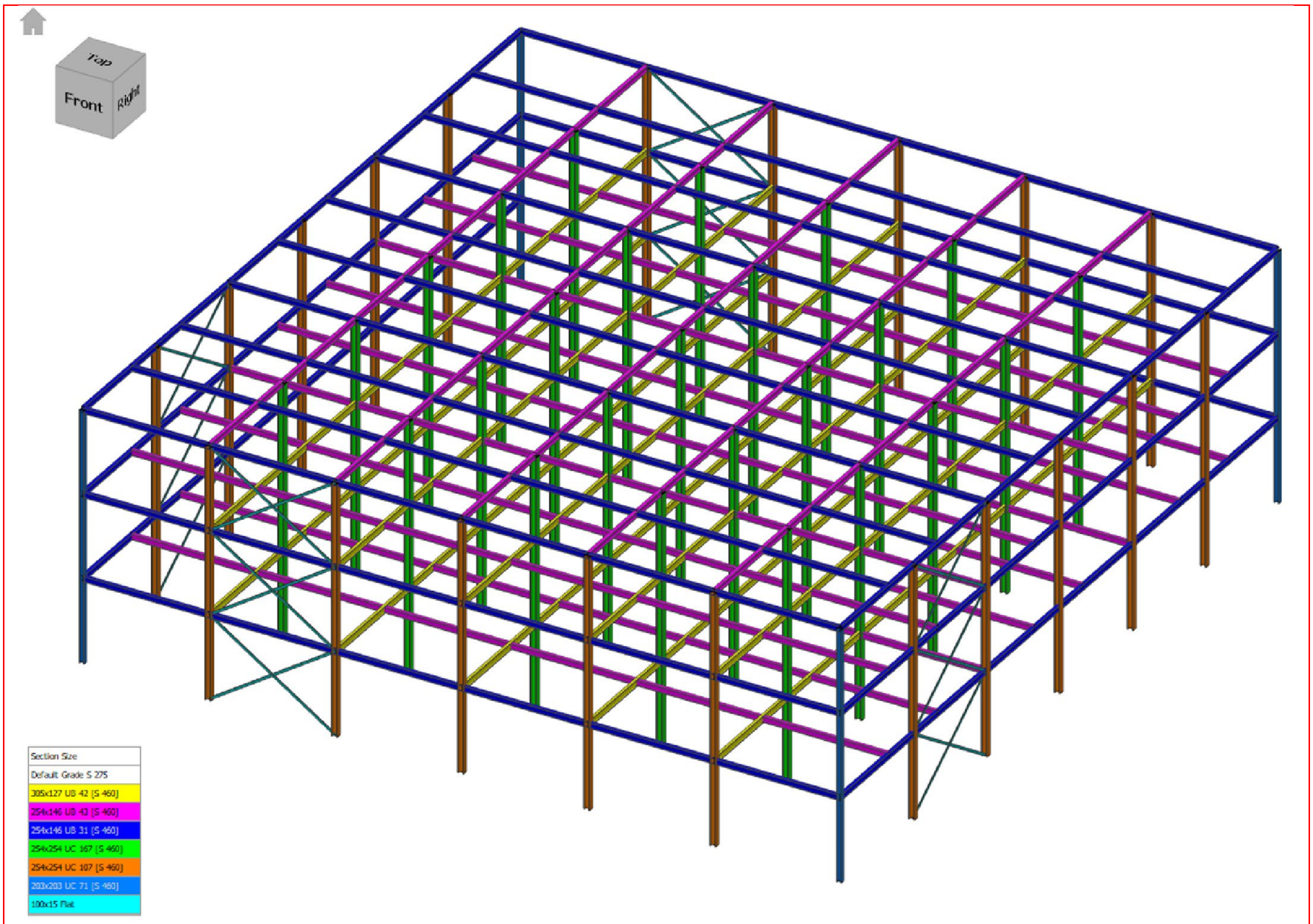

Fig. 10 Structural Model for Combined Model

The greater the percentage of GGBS replacement, the greater the reduction in carbon output. Even though the addition of GGBS helps reduce carbon, the overall cost is greater and therefore would need to be considered.

Considering the different imposed loading scenarios tested, the total weight of the structure reduces as the imposed loading reduces. Whilst this can reduce the embodied carbon output, the viability of reducing loads needs to be considered based on end use of the building and the client's requirements.

By comparing the impact of varying bay sizes within a structure, it can be concluded that there is no direct link between smaller bay sizes and carbon reduction. When the bay sizes are reduced, there is a larger quantity of members, resulting in potential for more steel tonnage. When a larger bay size is considered, quantity of steel is less, whereas the weight of the overall structure may be significantly higher due to larger section sizes. Ultimately, an optimised bay size would be decided using a trial-and-error approach, whilst meeting architectural requirements and keeping cost to a minimum.

When considering composite deck profiles, the main factor that affects carbon output is the weight of the deck as well as the volume of concrete within the composite slab. The deck that utilises the lowest volume of concrete, as well as having the lowest self-weight, produced the least embodied carbon. Although the deck can help achieve a lower carbon output, other factors, such as fire resistance, may dictate the minimum deck profile required for a design, even though it may not be the most effective in terms of carbon emissions.

By taking the most effective parameter from each of the above, it becomes possible to see the overall impact that combining each parameter can have on the carbon footprint of a structure. Whilst analysing each parameter in isolation, some may have a greater affect than others, however, when combining each factor, the cumulative impact is significantly greater. It can also help in reducing cost, the number of elements required and help improve sustainability.

Further research into alternative carbon reduction methods can be carried out to assist in structural design optimisation. In this thesis, a steel structure was considered, whereas within the construction industry, structures can be of reinforced concrete or timber. The use of these materials would have a direct effect on the embodied carbon output of an overall structure. To gain a broader understanding of the

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embodied carbon in construction, it would be prudent to investigate a structure of similar properties whilst utilising the aforementioned materials. This further research would help determine the most effective construction material and structural frame type which would benefit the overall carbon footprint for a new construction.

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