07/06/2021

Word count - 6182

# Comparing the embodied carbon and cost of concrete floor solutions


Amila Jayasinghe

*Department of Engineering, University of Cambridge, UK*

*Corresponding Author: jaas2@cam.ac.uk*

John Orr

*Department of Engineering, University of Cambridge, UK*

*jjo33@cam.ac.uk*

Tim Ibell

Department of Architecture & Civil Engineering, University of Bath, UK

*abstji@bath.ac.uk*

William P Boshoff

Department of Civil Engineering, University of Pretoria, South Africa

*billy.boshoff@up.ac.za*

**Abstract**

Multi-objective optimisation of concrete floors for economic and environmental performance is critical in the present context since the building construction sector is responsible for a rising share of the global economy and greenhouse gas emissions. This study explores how the designs with optimum cost and embodied carbon are governed by the selection of a concrete floor system and column spacing. Discrete concrete floor designs were generated parametrically varying the column spacing for eight different construction forms available in practice. Pareto optimal solutions for cost and cradle-to-gate embodied carbon were identified for a range of column spacings. The trends of the sensitivity of the optimum solutions were also investigated due to inherent uncertainty and potential variations in the cost and embodied carbon of different constituents. Column spacings can be increased up to 2 m than the optimum, compromising cost or embodied carbon only up to 10% due to their nonlinear relationship, depending on the slab type. Post-tensioning can reduce embodied carbon of flat slabs for spans longer than 7 m but do not reach Pareto optimality due to available cheaper floor solutions with similar levels of embodied carbon. Flat slabs can be suggested as Pareto optimal for spans within 6 m to 8 m when construction time and storey height is considered, due to reduced cost. However, parallelly Pareto optimal two-way slabs on beams have up to only 8% higher cost but up to 37% lower embodied carbon than flat slabs. While the floor designs are optimum for spans within 5 to 7 m for most of the slab types, two-way slabs on beams and/or hollow-core slabs are the optimum choice for a wide range of spans depending on relevant cost and carbon coefficients.

**Keywords**:

concrete floor systems, column layout, embodied carbon, cost, optimisation

# 1 Introduction

The construction industry plays a significant role in the world performance of both economy and environmental degradation. The global construction industry values about 10 trillion USD per year which is 13% of the world economy, as estimated by McKinsey Global Institute (2017). Global Construction Perspectives and Oxford Economics (2015) predict that the global construction market will reach 17.5 trillion USD by 2030 with an average annual growth rate of 3.9%. International Energy Agency (Global Alliance for Buildings and Construction, 2020) evaluates that 10% of global carbon emissions are from the building construction industry, but Huang et al. (2018) claims that the share can be as high as 23% counting for indirect emissions. Reinforced concrete is widely used in the construction industry. Miller et al. (2016) show that the annual global consumption of concrete is approximately 10 billion $m^3$ being responsible for 8.6% of all anthropogenic carbon emissions. Therefore, multi-objective optimisation in concrete building design is of vital importance in the present context.

If a building is to be designed for a specified function, several feasible designs can be developed varying the layout and the type of slab. Exploring such a design space can potentially identify the design with minimum possible cost and embodied carbon. However, proceeding with such a design may be hindered due to functional requirements, architectural demands, and availability. Therefore, understanding how each design aspect relates to the cost and embodied carbon is of crucial importance for engineers in the conceptual design stage for efficient bargaining.

Several different concrete floor solutions are available in the industry along with the design guidelines in the present context. Following BS EN 1992-1-1 (BSI, 2015) for the design of concrete structures, The Concrete Centre (Brooker, 2009; Bond *et al.*, 2019) has published design guidelines for several types of slabs mentioning relative pros and cons regarding the speed of construction, economy, ease of service distribution, storey height, and potential off-site construction. Supporting optimisation of slabs, they have developed the program Concept V4: Cost and Carbon (The Concrete Centre, 2020) which can rank the floor type in terms of either cost or embodied carbon when the column grid is input. Flat slabs, two-way spanning slabs, post-tensioned flat slabs, one-way slabs, one-way slabs on wide beams, ribbed slabs, troughed slabs, and hollow-core slabs are designed in the program, following Economic Concrete Frame Elements to Eurocode 2 (Goodchild, Webster and Elliott, 2009). In this study, the above program is used to explore the relative performance of each floor construction form considering differences in design column layout, slab depth, amount of concrete and steel, usage of formwork, construction time, and total floor height.

## 2 Literature Review

Quantifying the environmental impact of structures is essential for optimisation. Estimating the resulting greenhouse gas emissions from construction activities and subsequent operations has been widely illustrated in the literature for life cycle assessment of buildings (Ortiz, Castells and Sonnemann, 2009; Cabeza *et al.*, 2014; Chau, Leung and Ng, 2015; Means and Guggemos, 2015). Life Cycle Assessment can be approached in a Process-based, an Input-Output or a Hybrid method. As reviewed by Bahramian and Yetilmezsoy (2020), Rashid and Yusoff (2015), and Singh et al. (2011), Process-based methods are more time consuming and complex, while Input-Output methods may result in less accurate approximations. The databases such as Inventory of Carbon and Energy by Circular Ecology (2020) contains carbon coefficients of construction materials based on the available literature, to facilitate estimation of carbon emissions of building designs based on their material consumption. Gibbons and Orr (2020), Hammond and Jones (2008), and RICS (2017) guide how to calculate embodied carbon, as the carbon emissions associated with material extraction and manufacturing, transportation, maintenance and end of life activities. Being interested in optimising structural design of buildings in the conceptual design phase, minimising embodied carbon is a well-suited objective function in this scope. Still, the previous studies which focused on optimising the energy consumption related to construction activities (embodied energy) are also considered in the review, due to the similarity of the objective.

Several researchers have discussed the differences in the environmental and economic performance of available floor systems. The Concrete Centre (Goodchild, Webster and Elliott, 2009) suggests that flat slabs are generally economical up to 8 or 9 m span and post-tensioned flat slabs are economical up to 12 or 13 m. Still, they specify ranges of spans which different floor systems are economical but do not specify which system is the most economical for a given span. Drewniok et al. (2020) compared embodied carbon of several slab types for a range of spans and observed that waffle slabs were optimum for all viable spans, and hollow-core slabs had the second-lowest embodied carbon for spans longer than 7 m. They noticed that flat slabs, two-way slabs, and post-tensioned flat slabs had similar embodied carbon for 4 m to 7 m spans. Kaethner and Burridge (2012) compared several floor solutions including flat slabs, post-tensioned flat slabs, and composite slabs for three different scenarios and concluded no structural scheme gave the lowest embodied carbon consistently. Miller et al. (2015) compared one-way spanning slabs, flat slabs with and without drop panels for active and passive reinforcement for a fixed column grid and found that all three slab types resulted in reduced embodied energy up to 49% with post-tensioning. They observed that the reinforced flat slab design had 7% less embodied energy compared to the other two reinforced solutions which had almost the same embodied energy. With a case study, Paik and Na (2020) showed that voided slabs can reduce embodied carbon from an equivalent solid concrete floor solution. However, Foraboschi et al. (2014) analysed several floor options and highlighted that the lightweight products in the voided slab can increase total embodied energy compared to flat slabs. These studies suggest that different floor solutions may have different costs and carbon performances which depend on the design layout.

Several studies have noted the importance of column layout in optimising floors. Eleftheriadis et al. (2018a) used a BIM-based genetic algorithm to optimise embodied carbon of flat slabs and observed that the program attempts to approach designs with thinner slabs on denser column grids. Furthermore, Ferreiro-Cabello et al. (2016) and Miller et al. (2015) found optimums in designs with the shortest column spans they considered. However, Sahab et al. (2005) optimised flat slabs and observed that the relationship between span and cost is nonlinear with a minimum, but they have considered shorter spans than in other studies. Therefore, it is important to investigate the difference in optimum column spacings for various floor types.

Design loads and member thicknesses are important to study regarding minimising embodied carbon of concrete floors. Several feasible designs can be generated for the same design load and the span, varying the member thickness and the provided amount of reinforcement. Eleftheriadis et al. (2018b), Jayasinghe et al. (2021) and Oh et al. (2019) emphasised the importance of selecting the right design depth in minimising embodied carbon by considering a range of viable member thicknesses. Goodchild et al. (2009) developed the design guidelines titled ‘Economic Concrete Frame Elements to Eurocode 2’ by designing a series of slabs with different thicknesses and identifying the design with minimum cost for each column spacing and slab type. Since Concept V4 is based on the above design guidelines, further investigations on optimising slab thickness were not considered in this scope. Even though design loads can be treated as an independent variable in concrete slab design, Peters (2018) reviewed experimental data of real loading on office buildings and found an average of 0.6 $kN/m^2$ with a standard deviation of 0.34 $kN/m^2$. Also, Drewniok and Orr (2019) experimentally illustrated the conservativeness of conventional design loads by measuring the applied load on a crowded room. Furthermore, Drewniok et al. (2020) and Hawkins et al. (2021) demonstrated the importance of minimising the design loads in minimising embodied carbon of concrete slabs. UK NA to BS EN 1991-1-1 (BSI, 2019) recommends values for imposed loads to be used in the design depending on the intended use of the building, suggests 2.5 $kN/m^2$ for office buildings. Therefore, the imposed load in this study was set to be 2.5 $kN/m^2$ without exploring the results for other level of loads. Slab designs with different purposes and load intensities may result in different observations. Hence, the conclusions derived in this study may be limited to floor designs in office buildings.

BS EN 15978 (BSI, 2011) defines a method to assess the lifecycle environmental performance of construction works. The standard specifies modules A1 to A3 as the cradle-to-gate processes of the materials, A4 as transportation, A5 as the construction process, [B] as use phase and [C] as the end of life phase. Sansom and Pope (2012) analysed alternative structural options for several types of buildings and concluded that the structural frame has an insignificant impact on carbon emissions due to operational activities in the use phase. Also, they noted that the share of transportation from total embodied carbon can be within 4% to 15%, and that of construction activities within 1% to 15% respectively, depending on the type of building. Gan et al. (2017) estimated cradle-to-site (A1 to A4) embodied carbon of different procurement options for high-rise buildings and noted that the contribution from transportation can be within 1% to 3% unless imported. Wen et al. (2015) studied two slab types and found that the transportation and construction phases were responsible for around 15% of total embodied energy up to practical completion. Considering the end-of-life stage, Wang et al. (2018) compared the life cycle impacts of different types of slab panels and explained that the effect on the total carbon emissions was within 1% to 16%. Rohden and Garcez (2018) also analysed the life cycle emissions of alternative designs for a 30-storey building and demonstrated that the end-of-life demolitions and disposals were responsible for around 15% on average. Furthermore, Malmqvist et al. (2018) explained variations expected in the end-of-life referring to the inherent uncertainty of the waste and recycling practice. This study focuses on the concrete floor systems where all the designs are reasonably expected to have a common path at the end-of-life, having an insignificant relative difference. Therefore, cradle-to-gate (A1-A3) embodied carbon is reasonably sufficient to compare different structural solutions, acknowledging minor contribution and uncertainty of other modules.

Multi-objective optimisation of structural designs has been approached in different ways by different researchers. Kwan et al. (2019) and Martí et al. (2016) optimised cost and embodied carbon separately and then quantify any discrepancy between the two objectives. Fernandez-Ceniceros et al. (2013) segmented the design space based on design criteria to minimise embodied carbon and then optimised the cost of each segment. Mora et al. (2018), Ferreiro-Cabello et al. (2016) and Rempling et al. (2019) plotted embodied carbon (or energy) of all the design solutions against the cost of those solutions and discussed the conflicts without particularly selecting one or more solutions as multi-criteria optimum. Ferreiro-cabello et al. (2018) and Eleftheriadis et al. (2018b) used Pareto Optimal solutions in their studies to optimise cost and carbon simultaneously. Furthermore, Evins (2013) and Gan et al. (2020) reviewed the trends in optimisation and highlighted that Pareto Optimality is well suited to represent optimum trade-off in the design space. A solution can be identified as Pareto Optimal if there is no other point in the set that reduces at least one objective function without increasing another one (Arora, 2012; Ma, 2021). Alternatively, the concept of carbon pricing can be used to convert embodied carbon into a cost for evaluation purposes. Also, carbon pricing can be introduced into the evaluation process as another cost item to provide insight as to how carbon pricing might change the optimum. However, the objective of this study is to illustrate the variation of the embodied carbon and the cost of concrete floors within the viable design space. Adopting carbon pricing in this scope will add a new variable regarding the monetary value on environmental performance while possibly obscuring the variations of the construction costs. Therefore, such an approach will hinder quantitative comparisons of cost and carbon separately for their potential inconsistencies. Hence, Pareto Optimal solutions of a considered design space will indicate the solutions worth focussing on to reduce cost and embodied carbon simultaneously.

Optimisation algorithms need values for the embodied carbon and cost of each constituent of the structural solutions to quantify objective functions. While there are numerous sources for cost and embodied carbon values, uncertainties are inevitable. Hammond and Jones (2008) recommend that embodied carbon coefficients should be generally considered tentative. Omar et al. (2014) and Dixit et al. (2010) observe that embodied carbon values can be geographically and temporally inconsistent. The Inventory of Carbon and Energy by Circular Ecology (2021) states the value of embodied carbon of C 28/35 concrete as 0.126 $kgCO_2e/kg$, 0.136 $kgCO_2e/kg$ and 0.099 $kgCO_2e/kg$ for average, with only CEM I and with 40% fly ash respectively. Also, the cost of construction materials and labour are subjected to variations globally due to differences in economies. Adjusted Net National Income (NNI) per capita of different countries published by The World Bank (2021) reveals the significance of economic inequality. For example, the NNI per capita of the United Kingdom is 35,825 USD whereas that of India is 1,735 USD, which imply the potential differences in labour prices. Therefore, the optimum structural solution may depend on the individual project, based on relevant cost and embodied carbon coefficients. Sensitivity analysis of the coefficients to optimum solutions can capture such potential variability.

Several cutting-edge floor solutions to minimise embodied carbon have been developed by several researchers. Block et al. (2017) presented how rib-stiffened thin vaulted concrete floors with funicular geometry can successfully reduce embodied carbon. Liew et al. (2017) facilitated the above concept with a fabricated mould, and Rippmann et al. (2018) 3D printed the design. Jipa et al. (2018), and Meibodi et al. (2018) introduced 3D printed formwork for topology optimised floors. Huijben (2016) satisfied a similar purpose with a vacuumatic formwork. Hawkins et al. (2020) developed a thin shell floor system with prestressed steel ties. These construction techniques essentially remove unwanted concrete from the slab, thus consumes less concrete compared with a conventional prismatic floor system. Despite the attractive potential of minimising embodied carbon, such solutions are yet to be economical and available in the market while the construction industry continues to expand. Therefore, it is important to examine the possibility to optimise cost and embodied carbon of floor systems within present construction practices by only deviating from the conventional design approach.

## 3 Methodology

A set of discrete concrete floor designs were generated for eight different slab types and different column spacings, depicting the conditions of office buildings. Concept V4 developed by The Concrete Centre (2020) was used in this study to design the slabs and estimate their cost and embodied carbon. The spreadsheet-based program uses the design charts in ‘Economic Concrete Frame Elements to Eurocode 2’. The design charts contain overall depths, estimated amounts of flexural and shear reinforcement, column sizes, and loads on supporting beams or columns for a range of spans, imposed loads and slab types. The charts have been designed to identify economic slab design in each case, based on parametric design to minimise cost. The slabs have been designed considering square panels, moment redistribution up to 15% maximum, fire resistance for 1 hour, and exposure class of XC1 (concrete inside buildings with low air humidity). The program interpolates within the design charts to reach the necessary parameters wherever necessary. Flat slabs, two-way slabs on beams, post-tensioned flat slabs, one-way slabs, one-way slabs on wide beams, ribbed slabs, troughed slabs, and hollow-core slabs were the eight slab types considered in this study. The cost and embodied carbon per unit area of floor area were used for comparisons, and Pareto frontiers were identified to study the multicriteria optimality. All the slabs and columns were designed with C 30/37 (characteristic cylinder strength of 30 MPa and cube strength of 37 MPa at 28 days) except for post-tensioned slabs which used C 32/40. All the designs are assumed to have similar design life, considering similar durability aspects of concrete buildings in general. A superimposed dead load of 0.85 kN/m$^2$ and an imposed load of 2.5 kN/m$^2$ were assumed. Two scenarios were analysed as described below.

### 3.1 Scenario 1: Considering only the materials and formwork for the structural frame

Concept V4 was used to design one storey frame of 4 by 4 square-shaped bays varying the column spacing from 4 m to 12 m with increments of 0.5 m. This approach could generate closely spaced data points to compare the variation of embodied carbon and cost per unit floor area with span. The cost and carbon calculations of Concept V4 include overall assessment including superstructure, substructure, and common site allowances. The program was adjusted in this scope to isolate the effect of column grid and slab type, excluding the common allowances, as described below.

The program was adjusted to isolate the effect on selecting the column grid and the floor construction form, exclude the common allowances, as described below.

- Cost: Only considered the cost of slabs, beams, and columns for their consumption of concrete, reinforcing steel, tendons, hollow-core panels, and cost of formwork. (excluded foundation, ground floor slabs, preliminary and external works, mechanical and electrical, cladding and allowance for stairs/ shear walls and cost of time difference).
- Embodied Carbon: Only considered the embodied carbon of slabs, beams, and columns for their consumption of concrete, hollow-core panels and reinforcing steel and tendons (excluded ground floor slabs) for cradle-to-gate. The formwork was not included since it is outside the system boundaries considered.

The cost and embodied carbon coefficients recommended by The Concrete Centre based on survey information from industry in June 2020 in the UK context were used as in Table 1. The density of concrete and steel was taken as 2400 kg/m$^3$ and 7850 kg/m$^3$ respectively. Embodied carbon of formwork was not considered since the scope is focussed on A1-A3 life cycle stages. The costs of formwork were estimated based on average values of cost per unit area of the slab, instead of a detailed design of the formwork in this scope. Due to absence of the direct data in the program, the amount of concrete in hollow-core slabs was estimated as the sum of the topping and the volume of concrete in hollow-core panels assuming a void percentage of 49.9% (Concrete Issues, 2021).

**Table 1. Cost and Embodied Carbon Coefficients of Materials**

| Element | Cost | Embodied Carbon |
|---|---|---|
| Concrete C30/37 | 145 £/m$^3$ | 230 kg$CO_2$e/m$^3$ |
| Concrete C32/40 | 145 £/m$^3$ | 240 kg$CO_2$e/m$^3$ |
| Reinforcing steel (rebar) | 980 £/t | 650 kg$CO_2$e/t |
| Tendons | 4000 £/t | 1000 kg$CO_2$e/t |
| Hollow-core panels, 150 mm | 58 £/m$^2$ | 50 kg$CO_2$e/m$^2$ |
| Hollow-core panels, 200 mm | 63 £/m$^2$ | 57 kg$CO_2$e/m$^2$ |
| Hollow-core panels, 250 mm | 78 £/m$^2$ | 65 kg$CO_2$e/m$^2$ |
| Hollow-core panels, 300 mm | 85 £/m$^2$ | 75 kg$CO_2$e/m$^2$ |
| Horizontal formwork- Plain | 36 £/m$^2$ | not considered |
| Horizontal formwork- Ribbed | 66 £/m$^2$ | not considered |
| Vertical formwork | 45 £/m$^2$ | not considered |

### 3.2 Scenario 2: Including the difference in storey height and construction time

Scenario 1 could not capture the effect of the difference in storey height and construction time since the designs had different total areas and perimeters. Since such differences can affect the optimum, another single-story building with a 24 m × 24 m area was analysed for three different column arrangements with 4 m, 6 m, and 8 m spacings. The effect of differences in storey height was estimated as the difference in cost and carbon due to the cladding of the perimeter. The following values were assumed, following the recommendations by The Concrete Centre.

- Cost of cladding: 330 £/m$^2$
- Embodied carbon of cladding for A1-A3 lifecycle stages: 29.8 kg$CO_2$e/m$^2$ for Glass façade from EPD SP 00934 (Saint-Gobian, 2016)
- Cost of time difference: 1.37 £/m$^2$/day assuming a site rental of 450 £/m$^2$/year
    - Flat slabs as the basis (0 delays)

- Post-tensioned slabs faster by 1 day
- Two-way slabs on beams delay by 3 days
- One-way slabs (with or without wide beams) delay by 2 days
- Ribbed slabs and Toughened slabs delay by 4 days
- Hollow-core slabs delay by 1 day

The sensitivity of the optimum designs was investigated by repeating Scenario 1 for four cases: cost of formwork increased by 50% and decreased by 50%, embodied carbon of concrete is increased by 30% and decrease by 30%. The percentage changes were chosen not to represent specific situations but to generally explore the potential deviations.

## 4 Results

Figure 1 illustrates the Pareto optimal solutions for selected column spacings considering cost and embodied carbon per unit floor area according to Scenario 1. Further explaining the meaning of Pareto optimality, no solution performs better than two-way slabs in either cost or embodied carbon in the case of a 7 m × 7 m column grid. In the case of column spacing of 10 m, two-way slabs have minimum embodied carbon, but the cost could be further reduced by selecting hollow-core slabs at the expense of embodied carbon. Still, no other solution performs better than those two solutions for column spacing of 10 m.

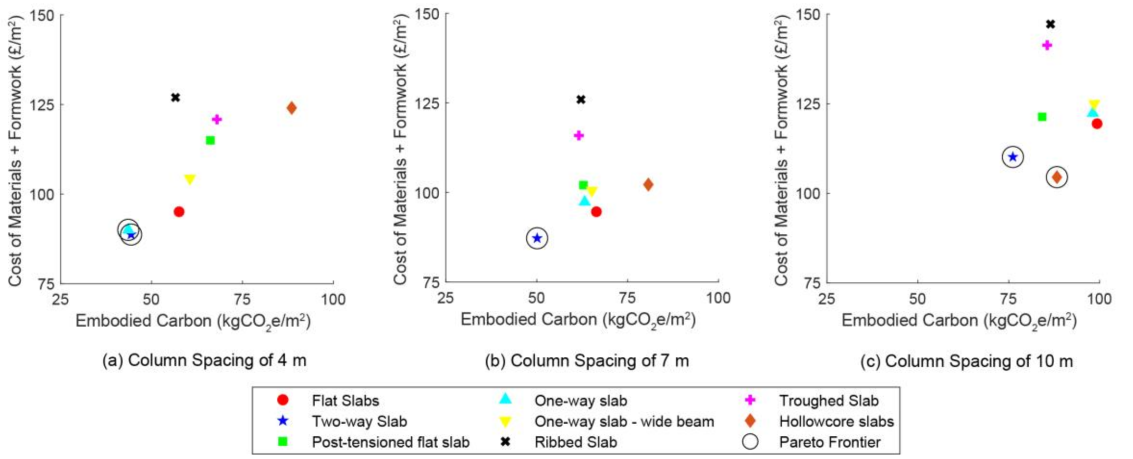



**Figure 1. Pareto optimal floor solutions for different column spacings**

Figure 2 shows how the Pareto optimal solutions for cost and embodied carbon vary with the column spacing as in Scenario 1, in a 3D representation. The column spacing in 4 bay x 4 bay floor plans was varied from 4 m to 12 m in 0.5 m steps, and cost and embodied carbon per unit area are plotted in the figures. 2D views of the same graph are presented for better visibility. The only Pareto optimal solution up to column spacing of 8.5 m is two-way slabs. Hollow-core slabs become Pareto optimal for column spacings greater than 9 m, sometimes being the only Pareto optimal solution. There are single points where one-way slabs and troughed slabs were identified as Pareto optimal.

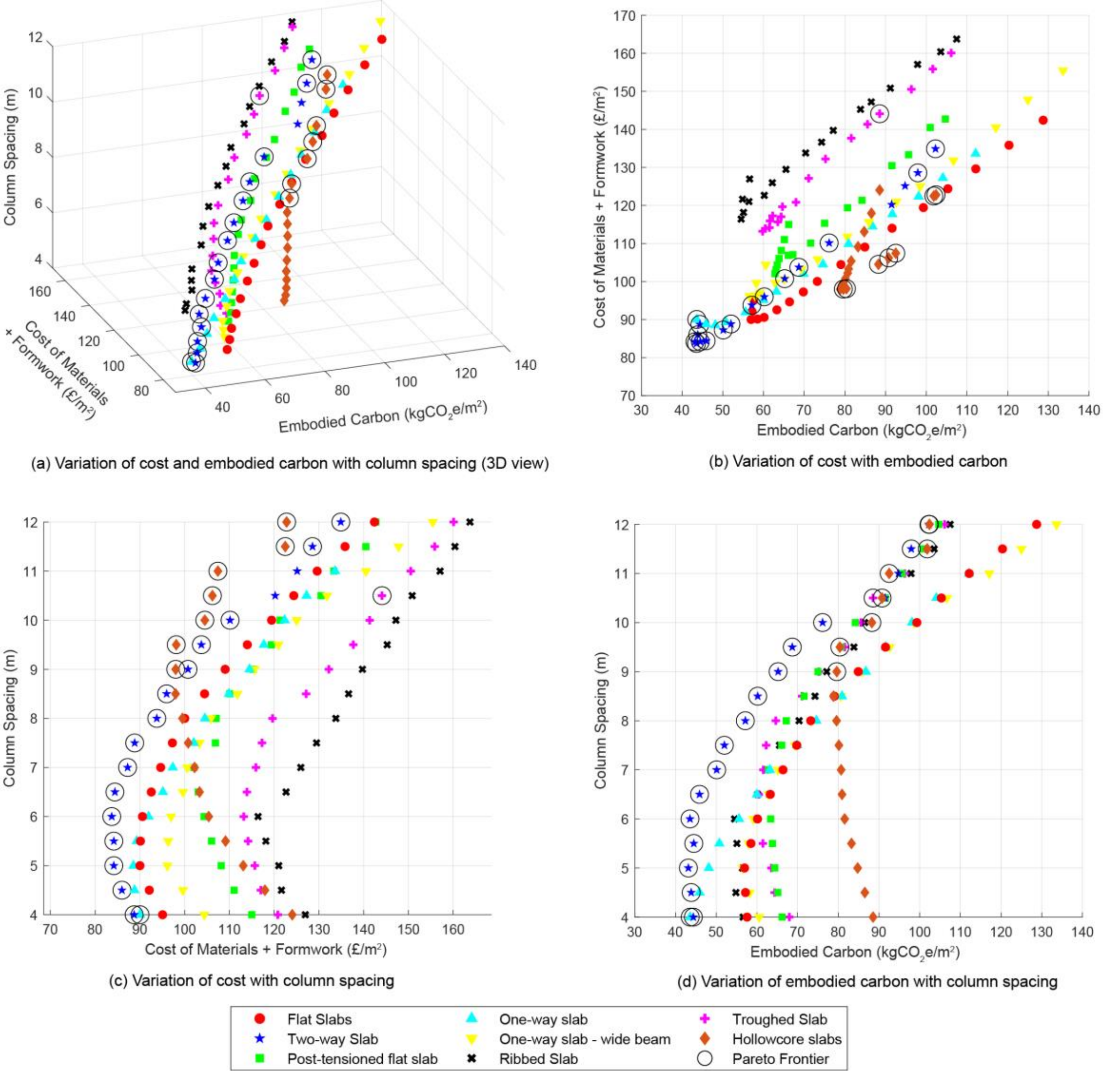



**Figure 2. Variation of Pareto optimal solutions with column spacing**

It was noted that the relationships between cost or embodied carbon and column spacing are nonlinear, and different floor construction forms have optimum designs at different column spacings. Figure 3 shows the variation of percentage difference in cost and embodied carbon with column spacing compared to the minimum possible value for several floor solutions. The optimum column spacing for flat slabs for cost and carbon is 5 m. Still, the variations of the cost up to 7.5 m spacing and embodied carbon up to 6.5 m spacing is below 10% compared with the minimum. Hollow-core slabs have the optimum cost and embodied carbon when the column spacing is 8.5 m while the variations are stepwise due to the discrete fixed depths of the panels. The variations in embodied carbon for all the slab types were higher than that of cost.

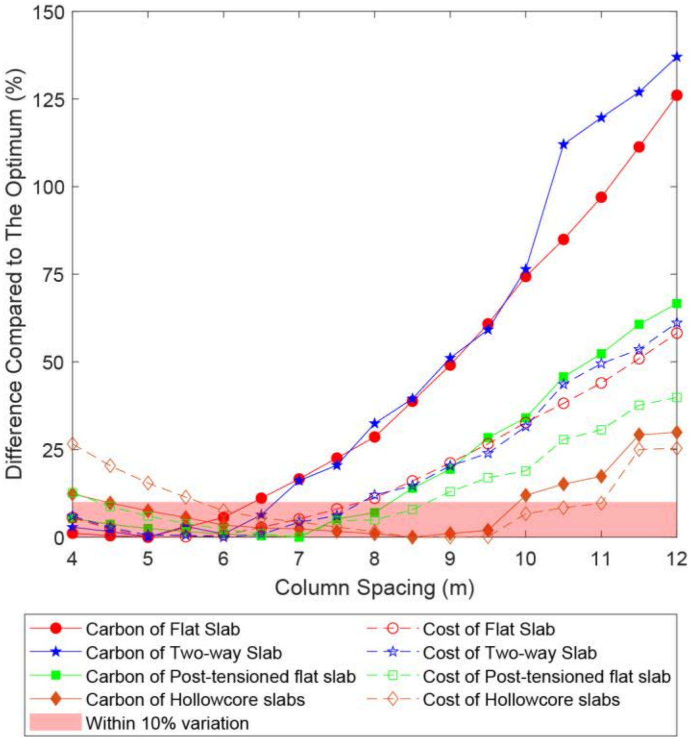



**Figure 3. Variation of cost and embodied carbon with column spacings compared to the minimum possible**

Figure 4 presents the sensitivity of the optimum solutions for cost and carbon coefficients in Scenario 1. Reducing the cost of formwork has extended the range of column spacing where two-way slabs are the only Pareto optimal while increasing the cost has a reversed effect. The program calculated the cost of formwork by separating the vertical and horizontal components of the formwork and assigning them separate cost coefficients. The coefficients for both vertical and horizontal components of formwork have been varied by the same percentage for the sensitivity analysis. The method suggested that changing the formwork cost will not switch the Pareto optimal solutions among the systems which need different types of formwork. As an example, the optimum solutions have not been switching between two-way slabs and flat slabs. Reducing the embodied carbon coefficients of concrete suggested two-way slabs are Pareto optimal for an extended range of column spacings while increasing the coefficients had the reversed effect. Higher column spacings had hollow-core slabs as the only Pareto optimal solution when embodied carbon of concrete was considered higher.

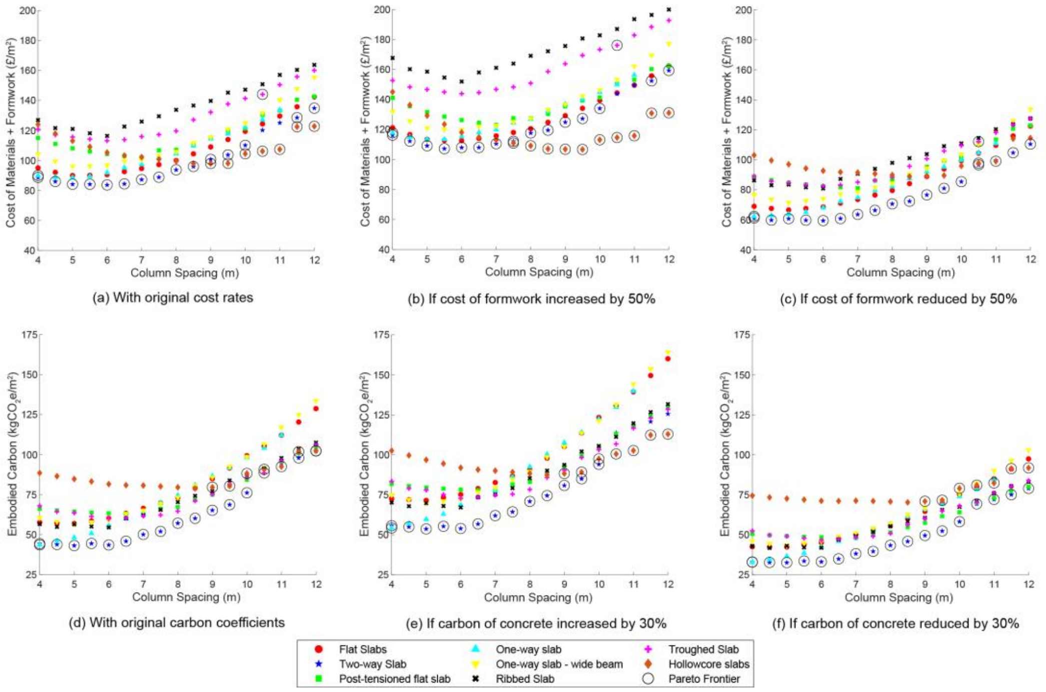



**Figure 4. The sensitivity of Pareto optimal solutions**

The amounts of concrete and formwork required for different floor designs were further investigated to understand why the sensitivity of Pareto optimal solutions was majorly limited to two-way slabs and hollow-core slabs. Figure 5(a) informs the contribution to the amount of concrete in the design from columns, beams and slabs for the column spacing of 7 m for several slab choices. Varying the embodied carbon coefficient of concrete would not suggest another solution as the optimum since two-way slabs have already the minimum quantity of concrete compared to the other solutions. Furthermore, Figure 5(b) shows the breakdown of the amount of formwork for the same case. The increase in the quantity of formwork by 8.6% due to additional beams in two-way slabs compared to flat slabs could not switch the Pareto optimality with a 50% variation of formwork cost.

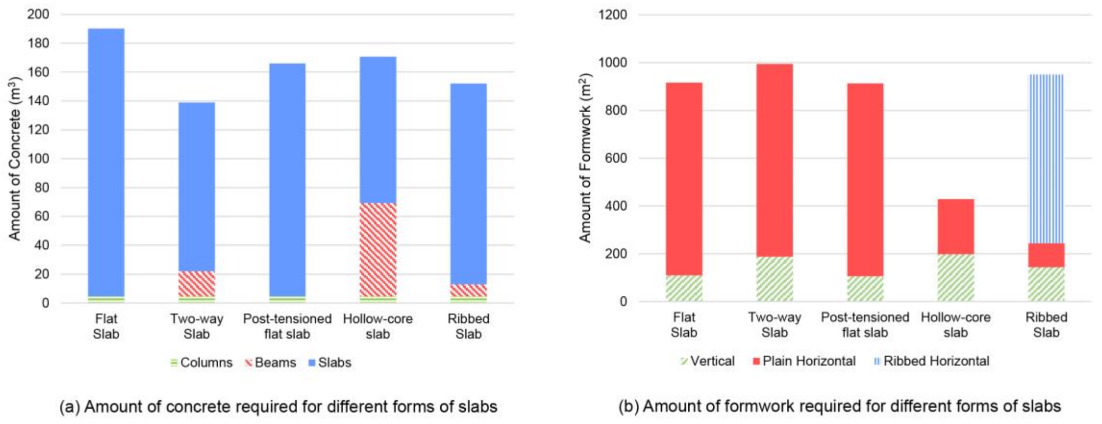



**Figure 5. Amount of concrete and formwork required for different forms of slabs for 7 m column spacing**

Even if prestressing is expected to reduce slab thickness and hence minimise embodied carbon, Figure 1 shows that the relative performance of reinforced and post-tensioned flat slabs is inconsistent throughout the design column spacing. Figure 6 describes why post-tensioning did not effectively reduced embodied carbon for shorter spans. Despite the reduction in slab thickness, post-tensioning requires a higher grade of concrete and tendons, both of which have higher carbon coefficients than the constituents in reinforced design. Therefore, percentage reductions in the slab depth due to post-tensioning do not directly represent the percentage reduction in embodied carbon. Post-tensioning flat slabs with shorter spans in which the depth cannot be reduced further due to recommendations for fire safety or shear performance is pointless. The shortest span of post-tensioned flat slabs designable by Concept V4 is 6 m, and that same design is output for a 4 m span. Post-tensioned flat slabs have less embodied carbon than reinforced flat slabs for spans longer than 6.5 m.

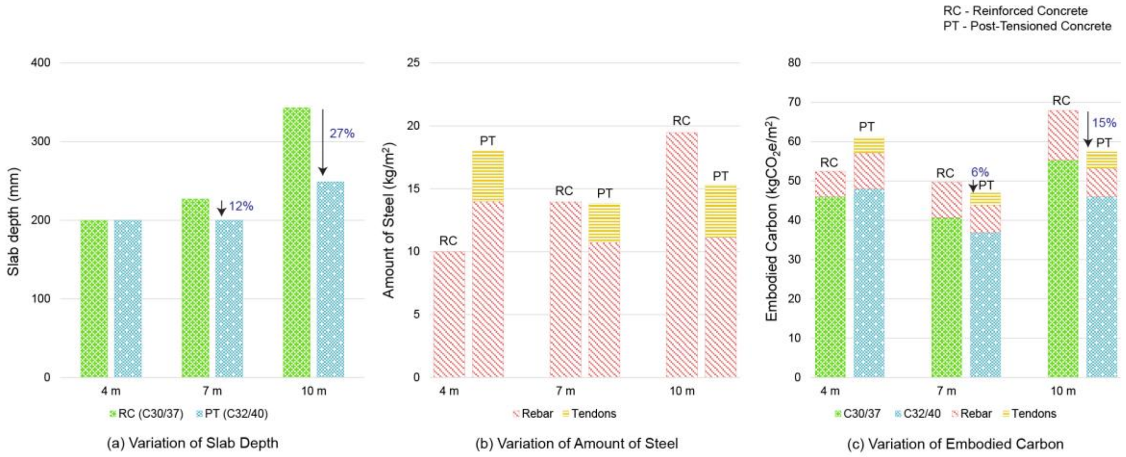
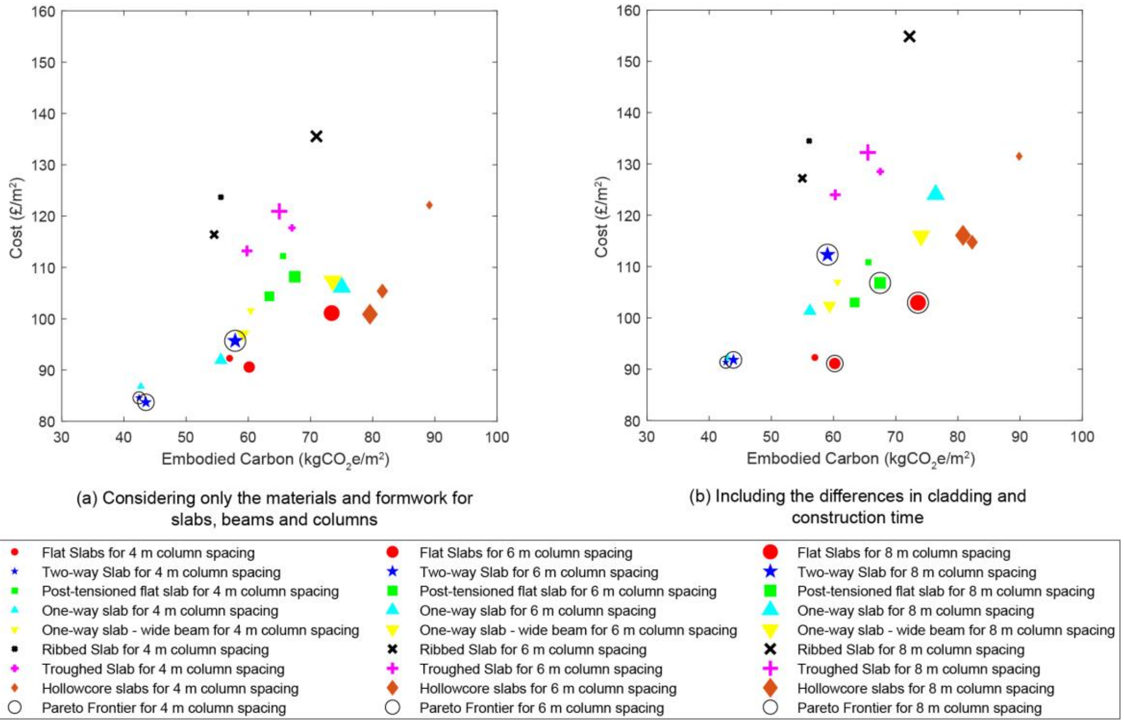



**Figure 6. Variation of slab depth, amount of steel and embodied carbon of reinforced (RC) and post-tensioned (PT) flat slabs for 4 m, 7 m, and 10 m spans**

Figure 7 shows how the inclusion of differences in construction time and storey height affected the Pareto optimal solutions, the outcome of Scenario 2. The floors were designed with column grids of 4m, 6m and 8m for an area of 24 m x 24 m to have a common floor area and perimeter, and cost and embodied carbon per unit floor area are plotted. Without such considerations, two-way slabs are the only Pareto optimal solution for all three considered column spacings, as in Figure 7(a). Introducing the effects promotes some of the flat slabs and post-tensioned flat slabs as Pareto optimum since they have lower total floor depths and are believed to be faster in construction, as in Figure 7(b).




(a) Considering only the materials and formwork for slabs, beams and columns

(b) Including the differences in cladding and construction time

**Figure 7. Effect of construction time and storey height on Pareto optimal solutions**

## 5 Discussion

At the end of the study, eight different concrete floor types have been designed for 17 different column grids. Pareto optimal solutions reflect the options which are to be focussed on for the optimum trade-off between cost and carbon. When the construction time and cladding are not included, the Pareto optimal solutions are mainly limited to two-way slabs and hollow-core slabs. The one exception is the one-way slabs are Pareto optimal together with two-way slabs for 4 m spans because both had the same slab depth, at the minimum possible. Other than the first point, two-way slabs on beams are the only Pareto optimal solution for the spans up to 8.5 m, which means no other floor solutions had lower carbon or cost compared to two-way slabs on beams. Slabs spanning more than 9 m have hollow-core slabs as Pareto optimal, together with two-way slabs on beams. The sharp ended Pareto fronts which allow limited trade-offs suggests that the cost and the embodied carbon are well correlated. If the entire design space is considered, two-way slabs spanning from 5 m to 6 m is the choice with the least cost and embodied carbon for material consumption.

The sensitivity of the above observations is studied by varying the cost of formwork and the embodied carbon of concrete by 50% and 30% respectively. These percentage variations were aimed at illustrating potential trends in the responses of the optimum solutions, rather than to depict specific situations. Still, the Pareto optimal solutions switch only between two-way slabs and hollow-core slabs. Embodied carbon coefficient of concrete can influence the importance of minimising the amount of concrete used on the floor. Two-way slab designs have the minimum volume of concrete for the shorter spans considered whereas hollow-core slabs have lesser for longer spans. Other floor types are not selected as carbon optimum for any carbon coefficient for concrete since they always have higher volumes of concrete than two-way slabs and hollow-core slabs. Varying the cost of formwork is aimed to illustrate how the complexity of formwork affects Pareto optimal solutions. Increasing the cost of formwork extended the range in which hollow-core slabs are Pareto optimal. Also, ribbed slabs and troughed slabs that need complex formwork are pushed away from being optimal. Still, a 50% increase in the cost of formwork is not sufficient to promote flat slabs to Pareto optimal, though the flat slabs move towards the optimum. Even in a case where a higher cost of formwork results in flat slabs being cheaper than two-way slabs, both solutions will be Pareto optimal while low carbon solutions are still the two-way slabs.

All the slab types have optimum carbon and cost for spans between 5 m and 7 m, except hollow-core slabs. This nonlinear relationship between cost (or carbon) and column spacing is an important aspect to investigate in the conceptual design stage. As an example, the embodied carbon of flat slabs is minimum when the span is 5 m. Still, the variation of cost and compared to the minimum is within 10% for design spans smaller than 7.5 m and 6.5 m respectively. Longer spans may not be sensible comparing the percentage increase in embodied carbon against the percentage increase in span. Practical construction projects have architectural and functional requirements to consider in addition to cost and carbon. Parametric analysis of this nature reveals the common agreements among different aspects and can help to achieve a design with balanced objectives, rather than specifying one design with minimum embodied carbon or cost.

Hollow-core slabs show a stepwise variation of carbon and cost with column spacing after 8.5 m. Up to a span of 8.5 m, the carbon and cost gradually decrease. This shows how wasteful the design of hollow-core slabs can be in case the span of the predesigned hollow-core panels is not fully utilised. Post-tensioning may not reduce the embodied carbon of flat slabs for shorter spans due to usage of a higher grade of concrete and tendons, but the benefit increases as the design span increases. Post-tensioned slabs have a similar level of embodied carbon as ribbed slabs, troughed slabs, and hollow-core slabs for 9 m to 12 m spans. Out of those four-floor types, hollow-core slabs are mainly highlighted as the Pareto optimal, being the cheapest option. Since hollow-core slabs are the only precast option considered in this study, the designs have significant differences in construction methods compared to other slab types considered. Nevertheless, hollow-core slabs are spotlighted as Pareto optimal solutions for longer spans, emphasising the importance of considering optimised precast solutions in minimising embodied carbon.

Considering the differences in construction time and the storey height can promote flat slab options as Pareto optimal. In contrast, two-way slabs are the only Pareto optimal system for all three column spacings analysed, when such effects are not considered. However, Pareto optimal solutions are to be critically evaluated in decision making. As an example, both two-way slabs and flat slabs are noted as Pareto optimal when the column spacing is 6 m. While two-way slabs have minimum embodied carbon, the cost can be reduced by 0.8% with flat slabs but embodied carbon is increased by 37%. In the case of 8 m span slabs, flat slabs can reduce cost by 8.3% than two-way slabs but compromise embodied carbon by 25%. In the two spans considered above, the percentage savings of cost are 2% and 33% of the resulting percentage increase in embodied carbon respectively. Therefore, Pareto optimal solutions can narrow down the focus, but they cannot be treated equally in engineering decision making.

This study compares cost and embodied carbon values per unit area, after designing the slabs with different floor areas. This approach is needed to generate solutions for a wide range of column spacings with an adequate number of closely spaced data points, although the reality in the practical design is not entirely reflected. However, the presented concept is still applicable in real-world design projects to compare several feasible column layouts and construction forms.

## 6 Conclusion

Different construction forms of concrete floors have different costs and embodied carbon performances which vary with the design span. Thus, parametric design of available floor solutions for allowable column layouts can identify the solution with optimum cost and embodied carbon. Pareto optimal solutions can be effectively used to sieve the design space to optimise embodied carbon and cost in parallel. Still, the optimums are to be critically compared in decision making by quantifying the relative gain of one objective and loss of the other.

Considering the cost and cradle-to-gate embodied carbon of building materials and formwork for structural frame with spans between 4 m and 12 m, the Pareto optimality converged to two-way slabs on beams and hollow-core slabs. Hollow-core slabs can become Pareto optimal for spans longer than around 8 m while two-way slabs can be the optimum for the full range of spans considered. Whether the optimum for a given span is either both aforementioned options or one of them depends on the adopted cost rates and carbon coefficients. The optimum column spacings for all the considered in-situ slab types are within 5 m to 7 m. Two-way slabs on beam with 5 m to 6 m spans have the least cost and embodied carbon of all the possibilities considered. However, the relationships between the performance criteria and column spacing are nonlinear. Increasing spans by up to 2 m more than the optimum can still result in designs with embodied carbon or cost within 10% variations from the minimum.

Post-tensioning reduces concrete consumption of flat slabs for column spacings longer than 7 m, reaching similar levels of embodied carbon as hollow-core slabs. Still, post-tensioned flat slabs are not identified as Pareto optimal since the cost is higher than hollow-core slabs. Considering the differences in construction time and storey height of different floor systems can advance flat slabs as Pareto optimal, mainly due to reduced cost. However, the percentage savings of cost by selecting flat slabs instead of two-way slabs on beams can only be up to 8.3% while the resulting increase in embodied carbon is up to 37%.

Therefore, adopting two-way slabs on beams and hollow-core slabs while optimising the column spacings can simultaneously reduce the cost and carbon emissions of concrete floors within the available construction practice.

## 7 Acknowledgement

The authors would like to acknowledge the Churchill Jafar Studentship for PhD study at the University of Cambridge.

## 8 References

Arora, J. S. (2012) *Introduction to Optimum Design*. 3rd edn. Elsevier. doi: 10.1016/C2009-0-61700-1.

Bahramian, M. and Yetilmezsoy, K. (2020) 'Life cycle assessment of the building industry: An overview of two decades of research (1995–2018)', *Energy and Buildings*. Elsevier B.V., 219, p. 109917. doi: 10.1016/j.enbuild.2020.109917.

Block, P., Rippmann, M. and Van Mele, T. (2017) 'Compressive Assemblies: Bottom-Up Performance for a New Form of Construction', 87(4), pp. 104–109. doi: 10.1002/ad.2202.

Bond, A. J. *et al.* (2019) *How to Design Concrete Structures using Eurocode 2*. 2nd edn. London: The Concrete Centre.

Brooker, O. (2009) *Concrete Buildings Scheme Design Manual*. Surrey: The Concrete Centre.

BSI (2011) *BS EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings Calculation method*. London: BSI.

BSI (2015) *BS EN 1992-1-1:2004+A1:2014: Eurocode 2 - Design of concrete structures: Part 1-1: General rules and rules for buildings*. London: BSI.

BSI (2019) *NA to BS EN 1991-1-1:2002- UK National Annex to Eurocode 1: Actions on structures*. London: BSI.

Cabeza, L. F. *et al.* (2014) 'Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review', *Renewable and Sustainable Energy Reviews*. Elsevier, 29, pp. 394–416. doi: 10.1016/j.rser.2013.08.037.

Chau, C. K., Leung, T. M. and Ng, W. Y. (2015) 'A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings', *Applied Energy*, 143(1), pp. 395–413. doi: 10.1016/j.apenergy.2015.01.023.

Circular Ecology (2021) *Embodied Carbon - The ICE Database*, *Circular Ecology*. Available at: https://circularecology.com/embodied-carbon-footprint-database.html (Accessed: 8 October 2020).

Concrete Issues (2021) *Less is more with hollow- core slabs*. Available at: https://www.concreteissues.com/en/stories/1-16/less-is-more-with-hollow-core-slabs/ (Accessed: 21 February 2021).

Dixit, M. K. *et al.* (2010) 'Identification of parameters for embodied energy measurement: A literature review', *Energy and Buildings*, 42(8), pp. 1238–1247. doi: 10.1016/j.enbuild.2010.02.016.

Drewniok, M., Orr, J. and Astle, P. (2020) *Relationships between building structural parameters and embodied carbon Part 1 – Reinforced concrete floors solutions*. Available at: https://www.researchgate.net/publication/354343197_Relationships_between_building_structural_parameters_and_embodied_carbon_Part_1_-_Reinforced_concrete_floors_solutions?fbclid=IwAR2LrBgpQFih0qq4hdx5CIi-MbFsjcABy_tuBDvXq6DBtTewBdxdr1eqKLg.

Drewniok, M. and Orr, J. J. (2019) *Office floor loading*, *Minimising Energy in Construction*. Available at: https://www.meicon.net/floor-loading (Accessed: 10 March 2021).

Eleftheriadis, S. *et al.* (2018) 'Investigating relationships between cost and CO2 emissions in reinforced concrete structures using a BIM-based design optimisation approach', *Energy and Buildings*. Elsevier B.V., 166, pp. 330–346. doi: 10.1016/j.enbuild.2018.01.059.

Eleftheriadis, S., Duffour, P. and Mumovic, D. (2018) 'BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives', *Energy and Buildings*. Elsevier B.V., 173, pp. 587–600. doi: 10.1016/j.enbuild.2018.05.042.

Evins, R. (2013) 'A review of computational optimisation methods applied to sustainable building design', *Renewable and Sustainable Energy Reviews*. Elsevier, 22, pp. 230–245. doi: 10.1016/j.rser.2013.02.004.

Fernandez-Ceniceros, J. *et al.* (2013) 'Decision support model for one-way floor slab design: A sustainable approach', *Automation in Construction*. Elsevier B.V., 35, pp. 460–470. doi: 10.1016/j.autcon.2013.06.002.

Ferreiro-cabello, J. *et al.* (2018) 'Metamodel-based design optimization of structural one-way slabs based on deep learning neural networks to reduce environmental impact', *Engineering Structures*. Elsevier, 155(November 2017), pp. 91–101. doi: 10.1016/j.engstruct.2017.11.005.

Ferreiro-Cabello, J. *et al.* (2016) 'Minimizing greenhouse gas emissions and costs for structures with flat slabs', *Journal of Cleaner Production*. Elsevier Ltd, 137, pp. 922–930. doi: 10.1016/j.jclepro.2016.07.153.

Foraboschi, P., Mercanzin, M. and Trabucco, D. (2014) 'Sustainable structural design of tall buildings based on embodied energy', *Energy and Buildings*. Elsevier B.V., 68, pp. 254–269. doi: 10.1016/j.enbuild.2013.09.003.

Gan, V. J. L. *et al.* (2017) 'Developing a CO2-e accounting method for quantification and analysis of embodied carbon in high-rise buildings', *Journal of Cleaner Production*. Elsevier Ltd, 141, pp. 825–836. doi: 10.1016/j.jclepro.2016.09.126.

Gan, V. J. L. *et al.* (2020) 'Simulation optimisation towards energy efficient green buildings: Current status and future trends', *Journal of Cleaner Production*. Elsevier Ltd, p. 120012. doi: 10.1016/j.jclepro.2020.120012.

Gibbons, O. P. and Orr, J. J. (2020) *How to calculate Embodied Carbon*. London: IStructE. Available at: https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/.

Global Alliance for Buildings and Construction (2020) *2020 Global Status Report for Buildings and Construction*. United Nations Environment Programme. Available at: https://globalabc.org/news/launched-2020-global-status-report-buildings-and-construction.

Global Construction Perspectives and Oxford Economics (2015) *Global Construction*

*2030: A global forecast of the construction industry to 2030*. London: Global Construction Perspectives Limited and Oxford Economics. Available at: https://www.ciob.org/industry/policy-research/resources/global-construction-CIOB-executive-summary.

Goodchild, C. H., Webster, R. M. and Elliott, K. S. (2009) *Economic Concrete Frame Elements to Eurocode 2*. Surrey: The Concrete Centre.

Hammond, G. P. and Jones, C. I. (2008) 'Embodied energy and carbon in construction materials', *Proceedings of the Institution of Civil Engineers - Energy*, 161(2), pp. 87–98. doi: 10.1680/ener.2008.161.2.87.

Hawkins, W. *et al.* (2020) 'A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors', *Engineering Structures*. Elsevier, 207(September 2019), p. 110195. doi: 10.1016/j.engstruct.2020.110195.

Hawkins, W., Peters, A. E. and Mander, T. (2021) 'A weight of your mind: Floor loadings and the climate emergency', *The Structural Engineer*, 99(5), pp. 18–20.

Huang, L. *et al.* (2018) 'Carbon emission of global construction sector', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 81(June 2016), pp. 1906–1916. doi: 10.1016/j.rser.2017.06.001.

Huijben, F. (2016) 'Vacuumatic formwork: a novel granular manufacturing technique for producing topology-optimised structures in concrete', *Granular Matter*. Springer Berlin Heidelberg, 18(2), pp. 1–8. doi: 10.1007/s10035-015-0602-0.

Jayasinghe, A. *et al.* (2021) 'Minimising embodied carbon in reinforced concrete beams', *Engineering Structures*. Elsevier Ltd, 242(September 2020), p. 112590. doi: 10.1016/j.engstruct.2021.112590.

Jipa, A. *et al.* (2018) ‘3D-Printed Formwork for Prefabricated Concrete Slabs’, *First International Conference on 3D Construction Printing in conjunction with the 6th International Conference on Innovative Production and Construction*, 2018(November). doi: 10.13140/RG.2.2.26722.89280.

Kaethner, S. C. and Burridge, J. A. (2012) ‘Embodied CO2of structural frames’, *Structural Engineer*, 90(5), pp. 33–40. Available at: https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-5/embodied-co2-of-structural-frames/.

Liew, A. *et al.* (2017) ‘Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor’, *Engineering Structures*. Elsevier Ltd, 137, pp. 323–335. doi: 10.1016/j.engstruct.2017.01.075.

Ma, S. (2021) ‘find_pareto_frontier’. MATLAB Central File Exchange. Available at: https://uk.mathworks.com/matlabcentral/fileexchange/45885-find_pareto_frontier.

Malmqvist, T. *et al.* (2018) ‘Design and construction strategies for reducing embodied impacts from buildings – Case study analysis’, *Energy and Buildings*. Elsevier B.V., 166, pp. 35–47. doi: 10.1016/j.enbuild.2018.01.033.

Martí, J. V., García-Segura, T. and Yepes, V. (2016) ‘Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy’, *Journal of Cleaner Production*, 120, pp. 231–240. doi: 10.1016/j.jclepro.2016.02.024.

McKinsey Global Institute (2017) *Reinventing Construction: A Route To Higher Productivity*. McKinsey & Company. Available at: https://www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution.

Means, P. and Guggemos, A. (2015) 'Framework for Life Cycle Assessment (LCA) Based Environmental Decision Making during the Conceptual Design Phase for Commercial Buildings', *Procedia Engineering*, 118, pp. 802–812. doi: 10.1016/j.proeng.2015.08.517.

Meibodi, M. A. *et al.* (2018) 'Smart slab: Computational design and digital fabrication of a lightweight concrete slab', in *Recalibration on Imprecision and Infidelity - Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture, ACADIA 2018*, pp. 434–443.

Miller, D., Doh, J. H. and Mulvey, M. (2015) 'Concrete slab comparison and embodied energy optimisation for alternate design and construction techniques', *Construction and Building Materials*. Elsevier Ltd, 80, pp. 329–338. doi: 10.1016/j.conbuildmat.2015.01.071.

Miller, S. A., Horvath, A. and Monteiro, P. J. M. (2016) 'Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%', *Environmental Research Letters*. IOP Publishing, 11(7). doi: 10.1088/1748-9326/11/7/074029.

Mora, T. D. *et al.* (2018) 'Tools and procedures to support decision making for cost-effective energy and carbon emissions optimization in building renovation', *Energy and Buildings*. Elsevier B.V., 167, pp. 200–215. doi: 10.1016/j.enbuild.2018.02.030.

Oh, B. K. *et al.* (2019) 'Comprehensive investigation of embodied carbon emissions , costs , design parameters , and serviceability in optimum green construction of two-way slabs in buildings', *Journal of Cleaner Production*. Elsevier Ltd, 222, pp. 111–128. doi: 10.1016/j.jclepro.2019.03.003.

Omar, W. M. S. W., Doh, J. H. and Panuwatwanich, K. (2014) 'Variations in embodied energy and carbon emission intensities of construction materials', *Environmental Impact Assessment Review*. Elsevier Inc., 49, pp. 31–48. doi: 10.1016/j.eiar.2014.06.003.

Ortiz, O., Castells, F. and Sonnemann, G. (2009) 'Sustainability in the construction industry : A review of recent developments based on LCA', *Construction and Building Materials*. Elsevier Ltd, 23(1), pp. 28–39. doi: 10.1016/j.conbuildmat.2007.11.012.

Paik, I. and Na, S. (2020) 'Comparison of environmental impact of three different slab systems for life cycle assessment of a commercial building in South Korea', *Applied Sciences*, 10(20), pp. 1–16. doi: 10.3390/app10207278.

Peters, A. E. (2018) *Real Floor Loading*, *Minimising Energy in Construction*. Available at: https://www.meicon.net/real-floor-loading (Accessed: 25 April 2021).

Rashid, A. F. A. and Yusoff, S. (2015) 'A review of life cycle assessment method for building industry', *Renewable and Sustainable Energy Reviews*. Elsevier, 45, pp. 244–248. doi: 10.1016/j.rser.2015.01.043.

Rempling, R. *et al.* (2019) 'Automatic structural design by a set-based parametric design method', *Automation in Construction*. Elsevier, 108(October), p. 102936. doi: 10.1016/j.autcon.2019.102936.

RICS (2017) *Whole life carbon assessment for the built environment Whole life carbon assessment for the built environment*. London: Royal Institution of Chartered Surveyors. Available at: https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/.

Rippmann, M. *et al.* (2018) 'Design, fabrication and testing of discrete 3D sand-printed floor prototypes', *Materials Today Communications*. Elsevier, 15(June 2017), pp. 254–259. doi: 10.1016/j.mtcomm.2018.03.005.

Rohden, A. B. and Garcez, M. R. (2018) 'Increasing the sustainability potential of a reinforced concrete building through design strategies: Case study', *Case Studies in Construction Materials*. Elsevier Ltd., 9, p. e00174. doi: 10.1016/j.cscm.2018.e00174.

Sahab, M. G., Ashour, A. F. and Toropov, V. V (2005) 'Cost optimisation of reinforced concrete flat slab buildings', *Engineering Structures*, 27, pp. 313–322. doi: 10.1016/j.engstruct.2004.10.002.

Saint-Gobian (2016) *CLIMALIT- Environmental Product Declaration- S-P-00934*. Stockholm: The International EPD System. Available at: https://www.environdec.com/library/_?Epd=11994.

Sansom, M. and Pope, R. J. (2012) 'A comparative embodied carbon assessment of commercial buildings', *Structural Engineer*, 90(10), pp. 38–49. Available at: https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-10/research-a-comparative-embodied-carbon-assessment/.

Singh, A. *et al.* (2011) 'Review of Life-Cycle Assessment Applications in Building Construction', *Journal of Architectural Engineering*, 17(1), pp. 15–23. doi: 10.1061/(asce)ae.1943-5568.0000026.

The Concrete Centre (2020) 'Cost and Carbon: Concept V4'. London: The Concrete Centre. Available at: https://www.concretecentre.com/Publications-Software/Design-tools-and-software/Concept-V4-Cost-and-Carbon.aspx.

The World Bank (2021) *Adjusted net national income per capita (current US $)*. Available at:

https://data.worldbank.org/indicator/NY.ADJ.NNTY.PC.CD?end=2018&start=2018&view=map (Accessed: 5 March 2021).

Wang, J. J. *et al.* (2018) 'Life cycle impact comparison of different concrete floor slabs considering uncertainty and sensitivity analysis', *Journal of Cleaner Production*, 189, pp. 374–385. doi: 10.1016/j.jclepro.2018.04.094.

Wen, T. J., Siong, H. C. and Noor, Z. Z. (2015) 'Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia', *Energy and Buildings*. Elsevier B.V., 93(2015), pp. 295–302. doi: 10.1016/j.enbuild.2014.12.002.