Journal of Cleaner Production 345 (2022) 131177

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Comparing different strategies of minimising embodied carbon in concrete floors

Amila Jayasinghe [a,*], John Orr [a], Will Hawkins [b], Tim Ibell [b], William P. Boshoff [c]

[a] Department of Engineering, University of Cambridge, UK
[b] Department of Architecture and Civil Engineering, University of Bath, UK
[c] Department of Civil Engineering, University of Pretoria, South Korea

ARTICLE INFO

Handling Editor: Meisam Tabatabaei

Keywords:
Concrete floors
Embodied carbon
Parametric design
Optimisation strategies
Alternative construction forms

ABSTRACT

The present climate emergency demands the construction industry to minimise the carbon footprint of concrete buildings. In this paper, the potential different optimisation strategies to reduce 'cradle-to-gate' embodied carbon of concrete floors which require different levels of modifications to the conventional design and construction practice were compared. The embodied carbon savings possible from parametrically optimising slab depth and grade of concrete, post-tensioning, considering alternative conventional slab types, and adopting novel thin shell floor systems were quantified for a range of spans. Compared to reinforced concrete flat slabs designed for conventional span/depth ratios, minimising slab depths and considering lower grades of concrete can reduce embodied carbon of flat slabs up to 12%, only with changes to the design methods. By adopting other conventional alternatives available in the present market, post-tensioning can save embodied carbon up to 23% but two-way slabs on beams and hollow-core slabs can save up to 36%. Much higher carbon reductions up to 65% are possible with novel construction methods of thin shell floors that transfer loads through membrane action rather than bending. Hence, the construction industry should approach shape optimised floor construction forms in future while adopting parametric design and considering conventional alternatives in the present to minimise carbon emissions.

1. Introduction

The construction industry is responsible for a rising share of carbon emissions. The greenhouse gas emissions from global cement production alone are 6% of the total emissions due to human activities (UNFCCC, 2017). Hence, minimising the carbon footprint of buildings is of utmost importance in the present context. As the quantity of greenhouse gas emitted due to the construction activities, embodied carbon can be used to quantify the environmental impact of building designs. Sansom and Pope (2012) and Foraboschi et al. (2014) showed that up to 75% of the embodied carbon of the superstructure is from floors. Different researchers have demonstrated various strategies to minimise embodied carbon of concrete floors which require some changes to the conventional methods in design, and construction. Eleftheriadis et al. (2018), Trinh et al. (2021) and Ferreiro-Cabello et al. (2016) developed optimisation algorithms to minimise embodied carbon of concrete flat slabs by varying different design parameters, and their findings are applicable without changing the present construction methods of reinforced concrete flat slabs. Kaethner and Burridge (2012), Drewniok (2021) and Goodchild et al. (2009) compared different systems available in the market to identify the floor type with minimum embodied carbon for given design criteria, where implementing the findings need changes in the early stage procurement. Block et al. (2017) and Hawkins et al. (2020) developed novel low carbon floor systems to remove unwanted concrete by transferring loads through compressive membrane actions rather than flexure. Implementing such optimisation techniques may require different levels of effort, based on the local market technology maturity and availability of options. As an example, adopting a novel shape optimised floor system may require more investments and training, compared to a method of optimising the floor designs with available construction practice. Also, different optimisation techniques may result in different levels of carbon savings. Therefore, this study compares and contrasts different strategies to reduce embodied carbon of concrete floors which require different levels of modifications to the

* Corresponding author.
E-mail addresses: jaas2@cam.ac.uk (A. Jayasinghe), jjo33@cam.ac.uk (J. Orr), wh604@bath.ac.uk (W. Hawkins), abstji@bath.ac.uk (T. Ibell), billy.boshoff@up.ac.za (W.P. Boshoff).

https://doi.org/10.1016/j.jclepro.2022.131177
Received 1 November 2021; Received in revised form 22 February 2022; Accepted 27 February 2022
Available online 28 February 2022

conventional design and construction practice.

2. Literature review

Embodied carbon has been widely used as a performance indicator in optimising the environmental impacts of buildings. Carbon emissions associated with extraction and manufacturing of building materials and products, transportation, maintenance, and disposal can be identified as embodied carbon (Hammond and Jones, 2008; RICS, 2017; Gibbons and Orr, 2020). BS EN 15978 (BSI, 2011) standardises the assessment of buildings by defining different stages of the lifecycle. The stages A1 to A3 represent the emissions related to raw material extraction, transportation, and manufacturing in the 'Product' stage, defined as 'cradle-to-gate'. The case studies by Monahan and Powell (2011), Nadoushani and Akbarnezhad (2015), Meneghelli (2018), Li et al. (2013), Moncaster et al. (2018) illustrated that 'cradle-to-gate' phase is responsible for around 70%–90% of total life cycle embodied carbon. The databases such as Inventory of Carbon and Energy (Circular Ecology, 2021) presents 'cradle-to-gate' embodied carbon coefficients for various building materials. Total embodied carbon of buildings can be estimated based on such databases as the performance indicator for structural optimisation.

Despite the present climate emergency, the construction industry is resistant to novel low carbon techniques. Giesekam et al. (2016) surveyed the barriers to the uptake of low carbon building materials and identified a range of issues in terms of institutional, habitual, economic, technical, knowledge, and perception. Orr et al. (2019) also implemented a survey and highlighted that ease of construction is valued more than material efficiency and emphasised aligning incentives to minimise carbon emissions. Kershaw and Simm (2014) surveyed the drivers and obstacles to low carbon design of school buildings and revealed the complexity of building systems and perceived extra cost as common barriers. Pan and Pan (2021) also surveyed the industry partners and identified that the challenges to implementing low carbon methods can be economical, legislative, cultural, knowledge and even geographical. Hence, understanding the potential savings of embodied carbon by different optimisation strategies against the required modifications to the conventional design and construction practice is useful in decision making.

Flat slab solutions are popular in the construction industry due to presumed speed and ease of construction, minimum overall depth, flat soffit, absence of beams, and flexibility in the plan layout (British Cement Association, 2001; The Concrete Society, 2007). The conventional design process of flat slabs may begin with a predetermined span/depth ratio on a determined column grid, following guidelines such as by IStructE (IStructE, 2017) or The Concrete Centre (Bond et al., 2019). Different researchers have approached the optimisation of flat slabs in different scopes and methods. Trinh et al. (2021) parametrically optimised flat slab designs and illustrated that the lowest carbon designs were associated with shorter spans, thinner slab depths, and lower grades of concrete. They also demonstrated that carbon reductions up to 33% were possible by post-tensioning. Miller et al. (2015) further supported their claims by designing flat slabs for a range of spans and reducing embodied impacts up to 40% by post-tensioning. Ferreiro-Cabello et al. (2016) designed a range of flat slabs for three different column grids and highlighted the importance of minimising column spacing while demonstrating the nonlinear behaviour between slab thickness and embodied carbon. Nevertheless, they obtained minimum embodied carbon with designs closer to minimum allowable slab thickness but showed a possibility of having optimum in a marginally deeper slab for more than 6 m spans. Eleftheriadis et al. (2018) also optimised flat slabs with a BIM-based genetic algorithm varying column layout, member sizes and reinforcing details, and claimed that the layout has the largest impact on embodied carbon. They also discussed the possibility of minimising embodied carbon by increasing slab thickness, but such examples had carbon savings around 1%. Therefore, embodied carbon of flat slabs can be reduced by optimising the column layout, slab thickness, reinforcing details, grade of concrete, and by post-tensioning, where the required design modifications are applicable within the available construction practice.

Several studies have investigated the difference in embodied carbon of conventional floor systems. Kaethner and Burridge (2012) compared flat slabs, post-tensioned flat slabs, and several types of precast and composite slabs for three building designs, and concluded no structural scheme gave the lowest embodied carbon consistently. Goodchild et al. (2009) developed design guidelines based on parametric analysis for economic frames with one-way slabs, one-way slabs with wide beams, ribbed slabs, troughed slabs, two-way slabs on beams, flat slabs, waffle slabs, post-tensioned flat slabs, and hollow-core slabs. They recommended which slab type would be economical for which spans but haven't compared the cost or embodied carbon despite recommending several slab types for some spans. Referring to their design charts, Drewniok (2021) compared the variation of the embodied carbon of flat slabs, post-tensioned flat slabs, two-way spanning slabs on beams, waffle slabs, hollow-core slabs, and composite hollow-core slabs with column spacing. They observed that waffle slabs had minimum embodied carbon for all the spans considered. From the other slab forms, the lowest embodied carbon was with composite hollow-core slabs for spans longer than 7 m and flat slabs or two-way spanning slabs on beams for shorter spans. Based on Goodchild et al. (2009)'s work, The Concrete Centre (2020) developed the programme 'Concept V4' to compare cost and embodied carbon of different slab types for an input column grid. Therefore, considering alternative slab types available in the construction market at the preliminary design stage is proven to be important in minimising embodied carbon in buildings.

Concrete floor systems in which the load transferring mechanism is based on flexure essentially keep concrete mass under the neutral axis in tension, ignore in design and not fully utilising the capacity. Hence, concrete floors with flexural load paths are often wasteful, despite their popularity. Several research groups are exploring the possibility of reducing the amount of concrete required for floors by switching the dominant structural behaviour from bending to membrane action. Block et al. (2017) described how vaulted concrete shells stiffened with ribs can reduce embodied carbon in floors. Liew et al. (2017) and Rippmann et al. (2018) proceeded to develop necessary prototypes using tailored formwork and additive manufacturing respectively. Hawkins et al. (2019, 2020) also illustrated how embodied carbon can be reduced in concrete floors with textile reinforced thin concrete shells and prestressed steel ties. Such novel construction forms are still being further researched and would require further investments for the uptake in the industry irrespective of possible attractive carbon reductions. However, it is important to consider such cutting-edge floor types as a viable strategy to minimise embodied carbon in concrete floors by adopting novel construction techniques.

3. Methodology

This study compares the effectiveness of different carbon reduction strategies for concrete floors depending on the effort required to adopt them (Fig. 1). Starting from the conventional design of reinforced concrete flat slab, stepwise changes to traditional design and construction practice are introduced to minimise embodied carbon, as follows.

1. Optimise flat slabs by only changing the design approach (requires no change in the present construction practice of flat slabs)
    a. Parametric design to optimise slab depth
    b. Parametric design to optimise slab depth and grade of concrete
2. Consider alternative floor systems in practice (requires selecting other conventional slab types available in the market)
    a. Post-tensioned flat slabs
    b. Other conventional alternatives such as two-way slabs on beams, hollow-core slabs, and ribbed slabs

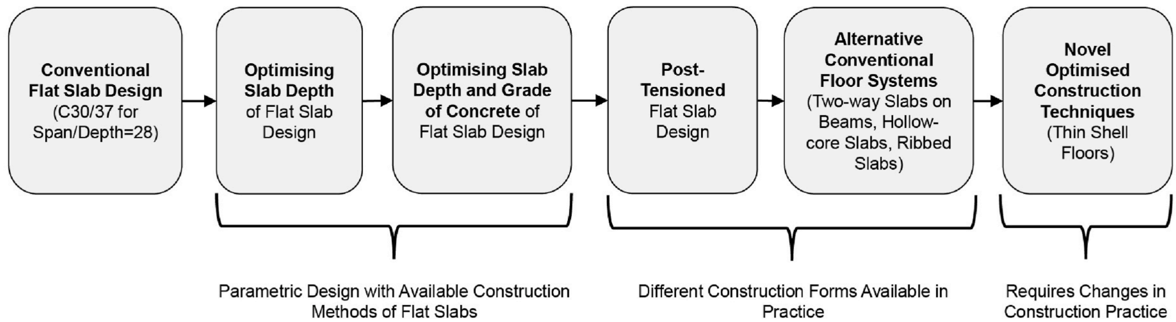


Fig. 1. The strategies to minimise embodied carbon in concrete floors in the order of effort required to implement them.

3. Adopt novel construction methods based on shell floors (requires changes in the present construction practice)

Discrete floor designs were generated to represent the above five approaches considering a layout of 3 bay x 3 bay square column grids. The column spacing was parametrically varied from 4 m to 12 m in 1 m intervals to generate sufficient data points to observe its impact on each carbon optimisation strategy. The design of floors in office buildings was idealised in this study with a superimposed dead load of 1.5 kN/m^2, an imposed load of 2.5 kN/m^2, and a perimeter load of 10 kN/m for cladding. Only the structural frame of one storey floor was considered in this scope for embodied carbon calculations. The quantity of construction materials required for slabs, beams, columns, and shells for each design was estimated to calculate the embodied carbon per unit floor area.

3.1. *Parametric optimisation of flat slabs*

The flat slab design with minimum embodied carbon for a given column grid was identified by developing a series of designs parametrically varying the slab depth, and grade of concrete, as explained in Fig. 2. The flat slabs were designed based on BS EN 1992-1-1 (BSI, 2015), and the relevant supporting guidelines (The Concrete Society, 2007; The Concrete Centre, 2009; Bond et al., 2019). A MATLAB program was developed to design the flat slabs and estimate the embodied carbon due to their repetitive nature. The design moments were calculated considering slab strips as beams spanning between column and middle strips. The amount of reinforcement was treated as a continuous variable. When the column spacing, slab depth, and the grade of concrete is input, the developed MATLAB programme calculated the required amount of flexural and shear reinforcement. The flexural reinforcement was calculated for top and bottom layers for both directions considering moments at column points and spans in the column strips and middle strips. The reinforcement along the grid lines on the edges of the plan area and in the middle were also separately designed. A moment redistribution of 15% was adopted. The detailing requirements at columns and simplified curtailing rules were also considered referring to the guides by The Concrete Centre (The Concrete Society, 2007; Bond et al., 2019). The punching shear links were designed considering square-shaped columns at the corner, side, and internal points. Since the column spacing has a direct impact on optimisation, columns were also designed with C30/37 at the corner, side, and internal positions. The column size was taken as 6% of the span to keep the design stress less than 17 N/mm^2, referring to preliminary design tables in IStructE (2017) guidelines. To achieve realistic results, the design load for columns were based on the load of three storeys, and the column height was taken as 3.5 m. The amount of reinforcement in the columns was calculated referring to the design charts by The Concrete Centre (Bond et al., 2019). Thereafter, the programme quantified the amount of concrete and steel per unit area for each design considering both slabs and columns to estimate embodied carbon per unit area. The extent of the design space of flat slabs was limited by the following factors.

- Need of compression reinforcement
- Maximum area of flexural reinforcement (4%)
- Shear failure at column perimeter
- Deflection-based on adjusted span/depth ratio according to BS EN 1992-1-1

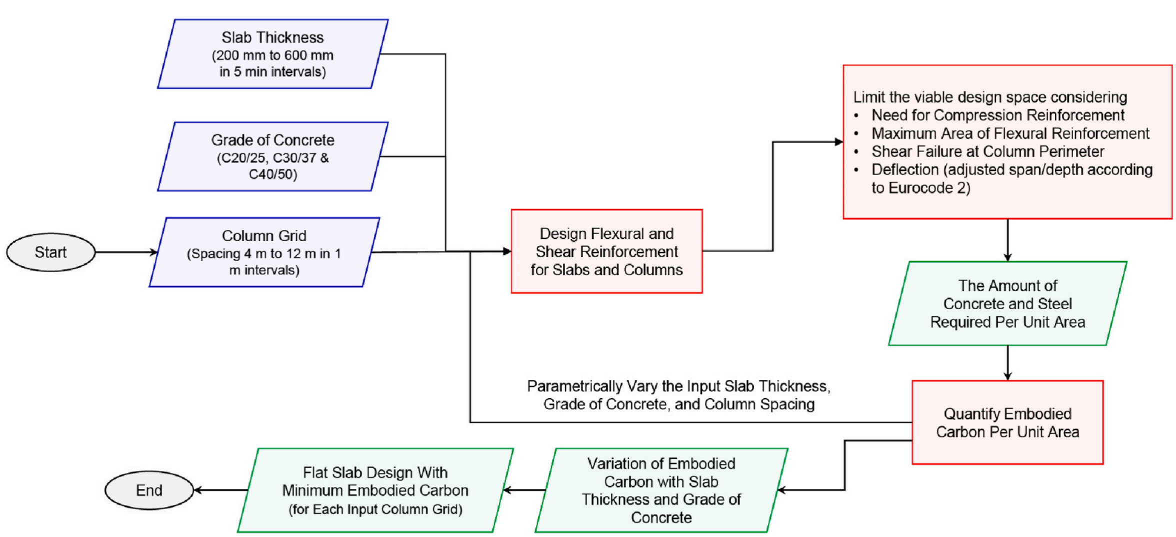


Fig. 2. Method of parametric optimisation of flat slabs.

The minimum slab thickness was limited to 200 mm considering a fire rating of R90. The nominal cover to reinforcement was taken as 25 mm considering 15 mm minimum for concrete inside buildings with low air humidity, and an additional 10 mm for deviations. The effective depths were calculated assuming a reinforcement bar diameter of 20 mm. Vibration performance was not considered in this scope since the concrete floors generally meet vibration criteria due to inherent mass (Brooker, 2009). Durability concerns require the use of C30/37 or higher grades use in office buildings for both indoor and outdoor environments according to BS EN 1992-1-1, but C20/25 was also considered in this study to explore the potential of reducing embodied carbon.

For a given column spacing, flat slabs were designed for thicknesses varying from 200 mm to 600 mm in 5 mm intervals, using C20/25, C30/37, and C40/50. Comparing the embodied carbon of each design could identify the flat slab design with minimum possible embodied carbon for the selected column spacing. Likewise, optimum floor designs with reinforced concrete flat slabs for spans varying from 4 m to 12 m were identified.

3.2. Alternative Concrete Slab systems

The program 'Concept V4' (The Concrete Centre, 2020) developed by the concrete centre was used in this study to generate floor designs for eight alternative slab systems, as described in Fig. 3. The programme is based on the guide 'Economic Concrete Frames to Eurocode 2' (Goodchild et al., 2009) by The Concrete Centre. The guide contains design charts to select the slab thickness for several conventional slab types for a range of column spacing and imposed loads. The estimated reinforcement densities are also parallelly listed. The design charts have been developed based on a series of parametric designs to minimise the cost. 'Concept V4' uses those design charts to estimate the required material quantities and then the embodied carbon per unit area for each design. The above guide has charts for optimised beam designs as well, and 'Concept V4' uses them to design the beams wherever necessary (e.g.: for two-way spanning slabs on beam and hollow-core slabs). The embodied carbon estimations of floor designs with flat slabs, two-way slabs on beams, post-tensioned flat slabs, one-way slabs, one-way slabs on wide beams, ribbed slabs, ribbed slabs with wide beams, and hollow-core slabs were obtained for each column spacing. The floors were designed with C30/37 except for post-tensioned flat slabs which used C32/40. The embodied carbon coefficients in the program were amended based on the literature review in this study, as explained in Section 3.4. The program was refined to quantify the embodied carbon of the structural frame of one storey only, excluding the common allowances such as ground floor slabs.

'Concept V4' is capable of comparing both the embodied carbon and the cost of different floor solutions for an input column grid. In the scope of this paper, only the embodied carbon is discussed, whereas the authors (Jayasinghe et al., 2021) have comprehensively discussed the cost vs embodied carbon of conventional slab types in a separate article.

3.3. Novel optimised construction techniques

The floor system proposed by Hawkins et al. (Hawkins, 2019, 2020; Hawkins et al., 2019, 2020) based on thin textile-reinforced concrete shells and prestressed ties were considered (Fig. 4) as an example of a less conventional but also less carbon-intensive alternative floor system. The uniform thickness shells were supposed to be cast with fine-grained concrete and reinforced with two layers of glass fibre textile. The shells were designed as groin vaults to primarily act in compression, while steel ties were designed to act in tension. The top surfaces of the floors were filled with a recycled aggregate fill to create a flat surface. Since the design tables did not contain the data for column design, the relevant shares of embodied carbon from columns were extracted from the flat slab analysis. The design charts (Hawkins, 2020) referred to in this study provide shell thickness, steel tie diameter, overall height, column width, fibre reinforcement ratio, and grade of concrete for the design with minimum embodied carbon for a given span.

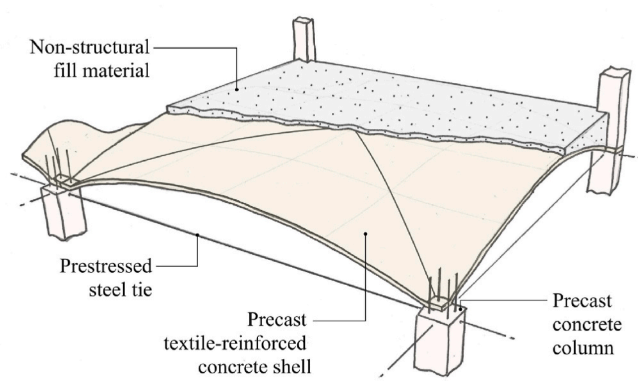


Fig. 4. Thin shell floor system with textile reinforced concrete and prestressed steel ties.

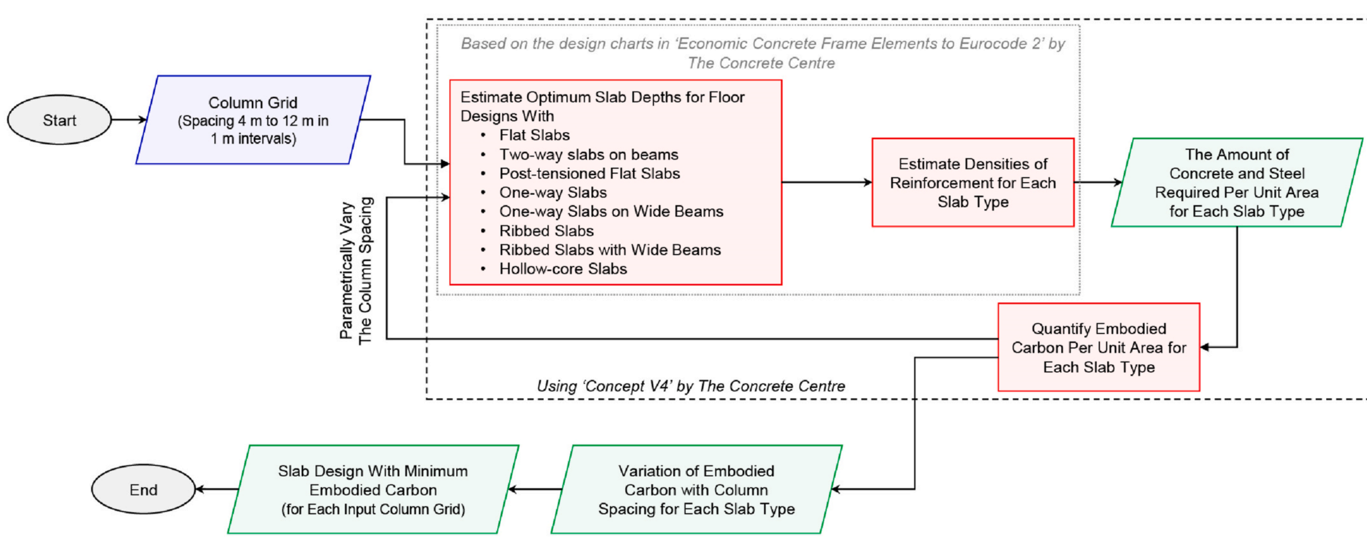


Fig. 3. Method of alternative analysis for concrete slabs.

3.4. Estimating embodied carbon

The embodied carbon of all the generated designs was calculated for the lifecycle phases from A1 to A3 according to BS EN 15978 (BSI, 2011), defined as 'cradle-to-gate'. Only the materials in slabs, beams, columns, and shells with fillers for one storey are considered in the estimation of embodied carbon. The effects outside the boundaries and one-storey structural frames such as formwork, construction process, foundations and common allowances were excluded in this scope. The carbon coefficients given in The Inventory of Carbon and Energy by Circular Ecology (2021) were adopted wherever available. The coefficients for concrete were based on average blends of cement. Since the thin shell floor designs for different spans recommended different grades of concrete, a consistent relationship between the grade of concrete and the embodied carbon was needed in this scope. Hence, the carbon coefficients for grades absent in the database were extrapolated based on the available data and Feret's law which states that the concrete strength is proportional to the square root of the cement content (de Brito et al., 2018). The fine-grained concrete used in the shell floors may be less dense and high carbon than the values assumed, depending on aggregate gradation and workmanship, hence not considered in this study. The carbon coefficient for glass fibre textile was based on a literature review in a previous study (Hawkins, 2019). The coefficients for hollow-core panels were extracted from recommended values in 'Concept V4' which had been obtained from environment product declarations and recalculations. The embodied carbon coefficients for steel reinforcement and post-tensioning tendons were considered the same in this scope. The densities of concrete, steel, glass fibre textile, and aggregate fill were taken as 2400 kg/m^3, 7850 kg/m^3, 2700 kg/m^3, and 1400 kg/m^3 respectively. The carbon coefficients used in this study are presented in Table A1 in Appendix. Embodied carbon per unit floor area was calculated for each design for comparison.

4. Results and discussion

Fig. 5 presents the results of parametric optimisation of flat slabs with C30/37 for 9 m column spacing. As a rule of thumb conventional benchmark, a flat slab design with a span/depth of 28 referring to the guidelines by Brooker (2009) is also marked in the same plot. The shaded area represents the unfeasible designs. The feasible space has been limited by limiting span/depth ratio for deflection in this case, instead of either fire criterion or the need of compression reinforcement.

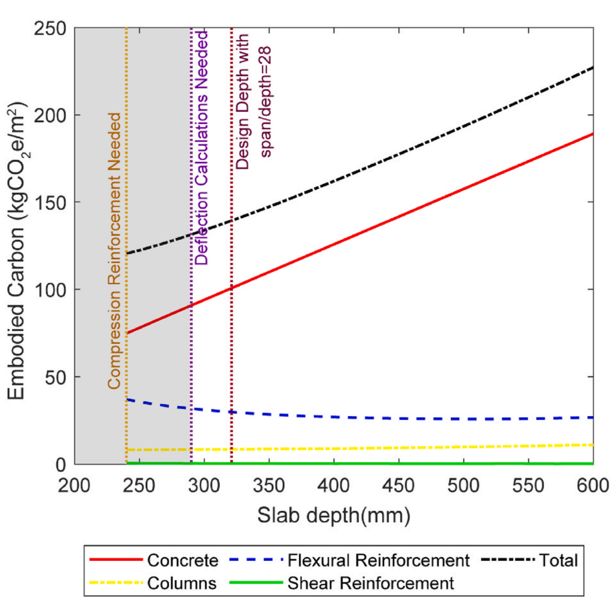


Fig. 5. Parametric design of flat slabs for 9 m span with C30/37.

Even though the contribution of embodied carbon from steel decreases when the design slab depth is increased, the subsequent share from concrete is increased at a higher rate. Also, at least 2/3 of the total embodied carbon of the slabs in this scope was from concrete. Therefore, design with minimum embodied carbon approached the minimum allowable slab thickness. The contribution from the shear reinforcement to total embodied carbon was negligible. Also, the embodied carbon share from columns was low compared to the other elements and had insignificant variation throughout the range of column spacings considered.

Expanding the scope of Fig. 5 for a range of column spacings, Fig. 6 shows the optimum depths identified in the parametric design of flat slabs with C30/37. Optimum depths coincided with the minimum possible depth in all the spans considered in this scope, leaving no room for trade-offs between slab depth and amount of reinforcement. The optimum depth of flat slabs for spans less than 6 m were governed by fire criterion, whereas deflection criterion governed the designs with longer spans. The selected conventional span/depth ratio of 28 did not satisfy the deflection criteria for spans longer than 11 m. Still, the parametric design could reduce slab by up to 35 mm from the conventional design depths, saving up to 8% of embodied carbon.

Repeating the methods used for Figs. 6 and 7 reports the variation of optimum slab depth and the embodied carbon with column spacing for three different grades of concrete. Using C40/50 instead of the conventional selection of C30/37 could reduce the optimum slab depths of flat slabs with spans longer than 6 m, but embodied carbon increased for all the spans. Lowering the grade of concrete to C20/25 increased the optimum slab depths but reduced the overall embodied carbon in all the spans considered. The embodied carbon curves kept decreasing for lower spans even if the slab depths remained at the same minimum allowable because of the less reinforcement needed. The savings of embodied carbon possible from lowering the grade of concrete compared to parametrically optimised flat slabs with C30/37 were up to 11%, but the savings for spans longer than around 7 m was marginal. Using C20/25 for office buildings may require further research in terms of durability concerns, but only the aspect of embodied carbon is included in this scope.

The outcome of considering alternative conventional slab types is presented in Fig. 8. To provide some degree of verification, the results for optimised flat slab designs from both Concept V4 and the parametric optimisation in this study are presented together in Fig. 8. Both the

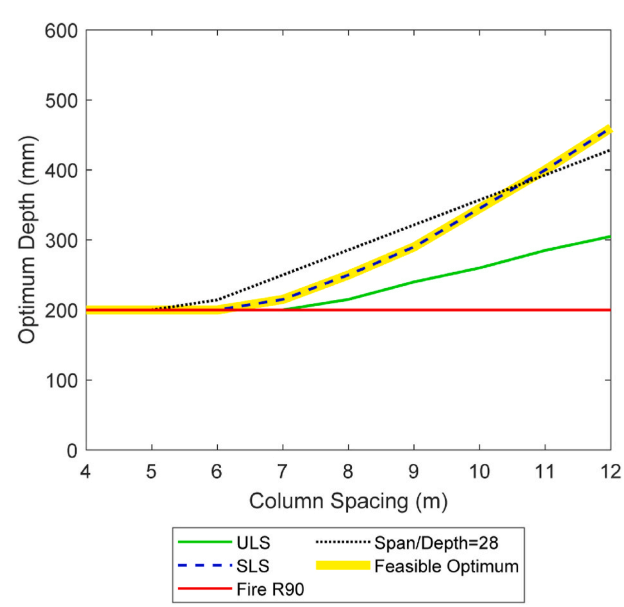


Fig. 6. Variation of optimum depth and governing criteria with column spacing for flat slabs with C30/37.

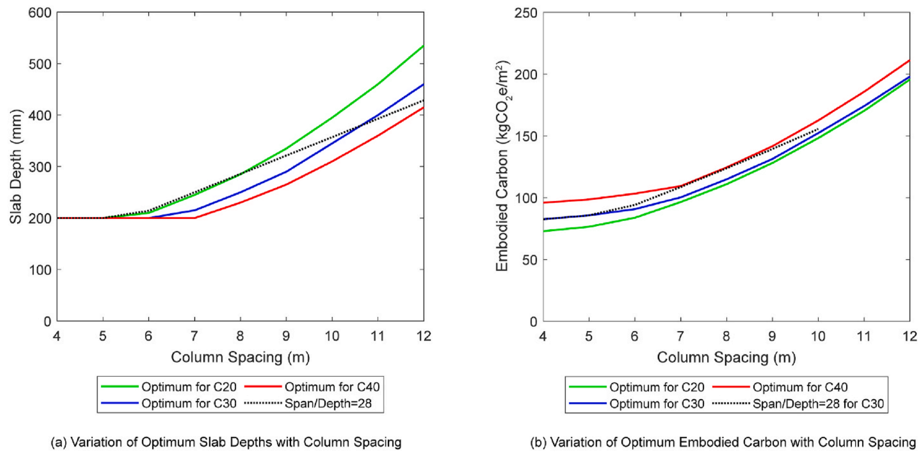


Fig. 7. Variation of the optimum slab depth and the corresponding minimum possible embodied carbon with column spacing for flat slabs with different grades of concrete.

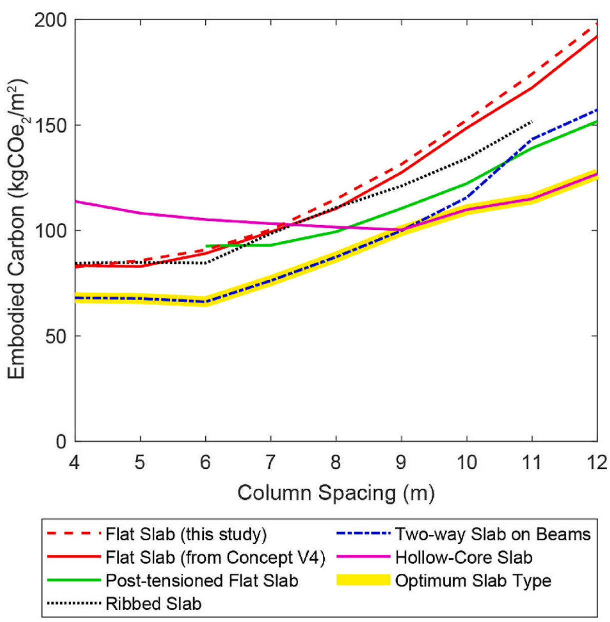


Fig. 8. Variation of embodied carbon with column spacing for different alternative conventional floor systems.

curves followed a similar pattern, having a difference under 4% throughout. The variation of embodied carbon with column spacing only for flat slabs, post-tensioned flat slabs, two-way slabs on beams, hollow-core slabs, and ribbed slabs are plotted to avoid congestion. The other slab types considered in the programme did not result in designs with the lowest embodied carbon for any of the spans considered. The different slab types considered in this scope had different optimum column spacings, 9 m for hollow-core slabs and within 5 m–7 m for others. Post-tensioning reduced embodied carbon in the flat slabs with spans longer than 7 m, and the savings increased with the span. However, the slab type with the least embodied carbon changed with the column spacing. The optimum slab system was two-way spanning slabs on beams for spans shorter than 9 m, and hollow-core slabs for longer spans. Hence, considering two-way slabs on beams and hollow-core slabs instead of flat slabs could reduce embodied carbon by 18%–33%.

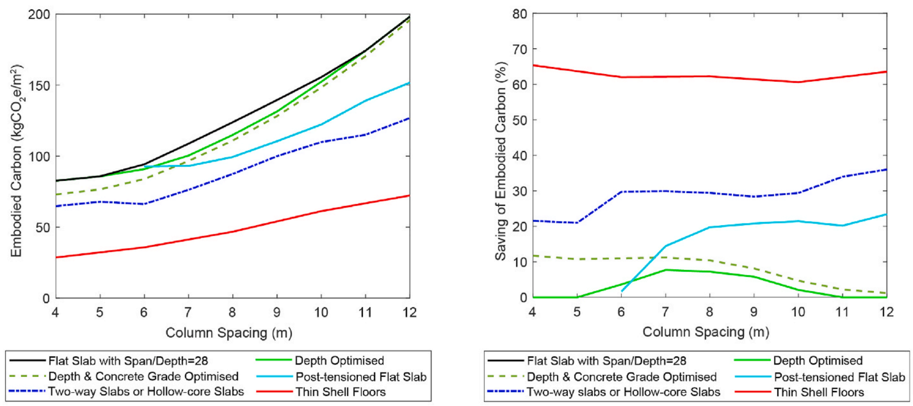
Table 1 contains the design details of the optimised floor at each step. Conventional flat slabs were designed with C30/37 based on the span/depth ratio of 28. Since the span/depth ratio of 28 was not sufficient for spans longer than 11 m, the conventional flat slab designs for those spans were considered to be the same as the parametrically optimised designs with C30/37. The slab thicknesses optimised for C30/37 and C20/25 are subsequently reported. The solutions with post-tensioned flat slabs and other alternatives are directly extracted from the output of Concept V4. The thickness and the grade of concrete for the thin shell floor system are presented whereas the vault rise is fixed to be 10% of the span.

Based on the designs in Table 1, Fig. 9 describes the variation of optimum embodied carbon and possible savings of each optimisation strategy with column spacing. Compared to the conventional design of flat slabs with C30/37, embodied carbon can be reduced by 2%–8% by optimising design depth for column spacings between 6 m and 10 m. Parametric design of flat slabs varying both design depth and grade of concrete can reduce embodied carbon up to 12% from traditional designs. Optimising the design of flat slabs for a given span converged to minimising slab thickness and adopting lower grades of concrete in this scope where office buildings were considered. Such changes in the design process can be easily facilitated with professional training, without changes in the construction methods. Post-tensioning the flat

Table 1
Optimum floor designs at each optimisation step.

Span (m)	Conventional FS	Optimum FS	Optimum FS with C20	PT FS	Alternative Slab Type	Thin Shell Floors
4	200 mm	200 mm	200 mm		TW 125 mm *(250 mm)*	32 mm C40 *(400 mm)*
5	200 mm	200 mm	200 mm		TW 125 mm *(250 mm)*	
6	214 mm	200 mm	205 mm		TW 125 mm *(275 mm)*	43 mm C45 *(600 mm)*
7	250 mm	215 mm	245 mm	200 mm	TW 141 mm *(350 mm)*	
8	286 mm	250 mm	285 mm	215 mm	TW 166 mm *(450 mm)*	61 mm C45 *(800 mm)*
9	321 mm	290 mm	335 mm	240 mm	TW 191 mm *(575 mm)*	
10	357 mm	345 mm	395 mm	275 mm	HC 250 mm *(750 mm)*	83 mm C45 *(1000 mm)*
11	400 mm	400 mm	460 mm	310 mm	HC 250 mm *(750 mm)*	
12	460 mm	460 mm	535 mm	340 mm	HC 300 mm *(900 mm)*	93 mm C50 *(1200 mm)*

FS- Flat Slab; PT- Post-tensioned; TW- Two-way slabs on beams; HC- Hollow-Core Slabs; *(Total Structural Depth)*.



(a) Variation of Embodied Carbon with Column Spacing

(b) Variation of Savings of Embodied Carbon with Column Spacing

Fig. 9. Variation of optimum embodied carbon and possible carbon savings with column spacing for different optimisation approaches.

slabs result in a decrease in embodied carbon by 14%–23% for spans longer than 7 m. Carbon savings of about 21%–36% can be achieved by considering two-way slabs on beams and hollow-core slabs as conventional alternatives. The technical knowledge and the required resources are available in the present market for these conventional alternatives. Moving towards novel floor systems that transfer loads through membrane actions rather than flexure to reduce concrete consumption such as thin shell floors can achieve significant carbon savings up to 65%. In all the optimisation strategies considered, embodied carbon generally increased with the column spacing, highlighting the importance of minimising the spans.

The outcomes of each optimisation strategy considered in this study aligned well with the other studies referred to in the literature review. The design charts developed by Goodchild et al. (2009) provide thicknesses with the optimum cost for flat slabs with C30/37 for a range of spans. The flat slab designs parametrically optimised in this study using C30/37 closely followed the embodied carbon values given by Concept V4 which used the above guide. Both Ferreiro-Cabello et al. (2016) and Trinh et al. (2021) also had proved that minimising slab thickness and adopting lower grades of concrete can reduce embodied carbon of reinforced concrete flat slabs. The aspects which were not discussed in this article such as reinforcement detailing, deflection control, and the adopted carbon coefficients can have an impact on the optimisation of flat slab designs. The authors plan to discuss parametric optimisation of flat slabs further in a separate article. The list of conventional slab alternatives considered in this study has some differences from those of similar previous studies by Kaethner and Burridge (2012) and Drewniok (2021). Still, all three studies commonly agreed that the slab type with the minimum embodied carbon will depend on the column grid. The state-of-the-art floor systems discussed in this study are based on removing unwanted concrete by switching from slab systems that are based on bending to vault systems that predominantly act as compressive membranes. Even though the potential savings of embodied carbon are promising, further research is needed in terms of vibration, acoustics, fire safety and lateral stability (Hawkins et al., 2020). Thus, this study applied different optimisation strategies which have different levels of maturity in the literature for the same set of building designs to compare the potential carbon savings.

Despite the rising environmental concerns, the construction industry resists adopting low carbon methods due to various concerns regarding knowledge, perception, and economy. Therefore, understanding the possible carbon savings from different optimisation strategies which need different levels of effort in implementation is crucial in the present context. This study compared five strategies to reduce embodied carbon in concrete floors that require different levels of modifications to the conventional design and construction practice. Each strategy was implemented in a typical office building design for a range of column spacings to compare their potential of reducing embodied carbon and to understand how the effectiveness of each strategy varies with span. Parametrically developing a series of designs and scanning through the feasible solutions can reduce embodied carbon of reinforced concrete flat slabs up to 8% from conventional designs. If the same optimisation algorithm is applied to designs with C20/25, the savings can be up to 12%. These carbon savings can be achieved by changing only the design approach of flat slabs, without changing the construction methods currently used in the industry. Post-tensioning requires some modifications to the construction procedure of reinforced concrete flat slabs, but the potential reductions of embodied carbon can be even up to 23%. Switching from flat slabs to other slab types such as two-way slabs on beams or hollow-core slabs needs changes to the method of construction, but the industry has the matured knowledge of such alternatives. Considering available alternatives can decrease embodied carbon of concrete floors by up to 36% compared to conventional flat slab designs. The novel shape optimised floor systems can cut down embodied carbon up to 65% but need to be further researched and invested to reach the construction market as an available solution. Hence, the comparison in this study shows that the potential carbon reductions are higher for the strategies which deviate more from the traditional design and construction practice of flat slabs. However, the present climate emergency suggests that the construction industry should take multiple approaches to minimise embodied carbon in concrete floor designs. Therefore, it is crucial in the upcoming construction projects to parametrically optimise the designs, to compare conventional alternatives available, and to move towards shape optimised floor systems.

Estimating environmental performance of different concrete floor solutions in this study considered 'cradle-to-gate' embodied carbon, only the life cycle phases A1 to A3. Even though the previous studies (Monahan and Powell, 2011; Li et al., 2013; Nadoushani and Akbarnezhad, 2015; Meneghelli, 2018; Moncaster et al., 2018) demonstrated that 'cradle-to-gate' embodied carbon is responsible for around 70%–90% of life cycle embodied carbon, the different solutions considered in this study have differences in other life cycle stages. The different conventional floor solutions considered have different construction times, complexities of the formwork, and transportation needs. Also, the state-of-the-art optimised floor systems are associated with complex shapes without flat soffits and potential involvement with construction robotics. Also, this study focused on designs for typical office floor loading, and the conclusions may be different for buildings with different functionalities. Therefore, the findings presented in this study are limited to the 'cradle-to-gate' phase, and future studies are needed to scrutinise the effect of other life cycle phases. Furthermore, comparing the cost of the different low carbon strategies is also important for the multi-objective optimisation of concrete floors. However, the economic aspects have not been discussed in this scope since it is challenging to compare the cost of construction techniques that have different levels of maturity and availability in the present market.

5. Conclusions

Parametric design optimisation, alternative slab types, and novel optimised floor systems have different levels of success in reducing embodied carbon in concrete floors and need different levels of effort in implementation. The flat slab designs with optimum embodied carbon coincide with minimum possible depth, which is often governed by either fire criterion or deflection criterion. Parametric design optimisation of slab thickness without changing the construction methods or material selection can reduce embodied carbon by up to 8% for spans between 6 m and 10 m. Considering lower grades of concrete in parametric optimisation can reduce embodied carbon up to 12% for spans less than 7 m, although the design depths are increased. Switching to other conventional alternative slab types available in the market can further reduce embodied carbon but the optimum slab type depends on the column spacing. Post-tensioning flat slabs with column spacings more than 7 m can reduce embodied carbon, and the benefit increases with the span, reaching 23% for 12 m spans. Moving to two-way slabs on beams for spans less than 9 m or hollow-core slabs for longer spans can cut embodied carbon by 21%–36%. Much higher savings of embodied carbon up to 65% can be achieved by adopting novel floor systems which transfer loads through compressive membrane actions rather than flexure. The comparison of the optimisation strategies considered in this scope suggested that the potential savings of embodied carbon increased with the required level of modifications to the conventional design and construction practice. Also, embodied carbon per unit floor area for different carbon reduction strategies and the differences among them increases with column spacing, highlighting the importance of optimising column layout. Hence, the construction industry should move towards optimised floor systems based on compressive membranes in future, while optimising the designs and considering alternatives in the present context to effectively meet the carbon targets.

6. Future work

Optimisation of flat slab designs should be further scrutinised concerning deflection control since the design space was limited by the adjusted span/depth ratios in most of the cases considered. Also, the effect of the life cycle phases beyond 'cradle-to-gate' for different optimisation strategies should be further investigated.

CRediT authorship contribution statement

Amila Jayasinghe: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **John Orr:** Project administration, Resources, Supervision, Writing – review & editing. **Will Hawkins:** Formal analysis, Validation, Resources, Writing – review & editing. **Tim Ibell:** Resources, Supervision, Writing – review & editing. **William P. Boshoff:** Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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

Appendix

Table A1
The Cradle-to-Gate Embodied Carbon Coefficients of The Building Materials

Material	Carbon Coefficient
Steel (85% recycled)	1.20 $kgCO_2e/kg$ (Circular Ecology, 2021)
Glass Fibre Textile	3.00 $kgCO_2e/kg$ (Hawkins, 2019)
C20/25 Concrete	0.112 $kgCO_2e/kg$ (Circular Ecology, 2021)
C30/37 Concrete	0.132 $kgCO_2e/kg$ (extrapolated)
C32/40 Concrete	0.138 $kgCO_2e/kg$ (Circular Ecology, 2021)
C40/50 Concrete	0.159 $kgCO_2e/kg$ (Circular Ecology, 2021)
C45/55 Concrete	0.171 $kgCO_2e/kg$ (extrapolated)
C50/60 Concrete	0.180 $kgCO_2e/kg$ (extrapolated)
Hollow-core panel 150 mm	50 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Hollow-core panel 200 mm	57 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Hollow-core panel 250 mm	65 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Hollow-core panel 300 mm	75 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Hollow-core panel 350 mm	85 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Hollow-core panel 400 mm	95 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Hollow-core panel 450 mm	105 $kgCO_2e/m^2$ (The Concrete Centre, 2020)
Recycled Aggregate Fill	0.0061 $kgCO_2e/kg$ (Circular Ecology, 2021)

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