A progressive approach to optimise embodied carbon in concrete floors based on parametric design

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Abstract

Minimising the carbon footprint of concrete buildings is vital in the presence of the climate emergency. In this paper, a framework to reduce the embodied carbon of concrete floors with the resources available at the market and adopting cutting-edge construction methods are investigated in a progressive approach. Starting from conventional reinforced concrete flat slabs, the embodied carbon was minimised by progressively introducing changes to design and construction practice depending on the effort required. The design changes applicable with present construction practice, alternative slab systems available in the marked, and novel shape optimised construction methods were considered to reduce embodied carbon in concrete floors. The evolution of the optimum floor design through parametric design for slab thickness, varying grade of concrete, deviating from the construction system, and substituting with novel thin shell floors is illustrated along with the potential savings of embodied carbon at each step.

1 Introduction

The construction industry is under the spotlight in the context of the climate emergency, due to its environmental concerns. Cement production alone is responsible for around 6% of global carbon emissions from human activities [1]. Embodied carbon can be used to quantify the environmental impact of buildings as the amount of CO_2 emitted during raw material extraction, manufacturing, transportation, maintenance, and end of life activities. Therefore, minimising embodied carbon in buildings is of vital importance in the present circumstances.

Different researchers have developed various methods to minimise embodied carbon in concrete floors by proposing changes to the conventional design and construction practice. Eleftheriadis et al. [2], Bae et al. [3], Trinh et al. [4] and Oh et al. [5] demonstrated the possibility of reducing embodied carbon in concrete slabs through optimising slab thickness, reinforcement design, and column layout without alterations of the construction methods. Furthermore, Kaethner and Burridge [6], Drewniok et al. [7] and Miller et al. [8] illustrated the opportunity to save embodied carbon of floors by considering alternative conventional slab types. Also, Block et al. [9] Rippmann et al. [10] Liew et al. [11] Hawkins et al. [12],[13] developed novel construction techniques to minimise concrete consumption of floors by transferring the loads through compressive arching rather than flexure. Despite such attempts, the stakeholders of the construction industry are resistant to new changes due to a range of economical, legislative, cultural and knowledge barriers [14],[15]. While some of the low carbon techniques can be implemented by only changing the design methods, some changes require new investments for the construction methods. Therefore, this paper brings together such optimisation methods to presents a progressive approach to minimise embodied carbon in concrete floors, introducing stepwise changes to the conventional design and construction practice based on the effort required. The possible savings of embodied carbon by each optimisation strategy are quantitatively illustrated.

2 Methodology

The embodied carbon in conventional flat slab design is progressively reduced by adopting parametric optimisation of flat slabs (Step A), alternative conventional slab types (Step B), and novel optimised construction methods (Step C). Fig. 1 shows the optimisation steps considered in this study arranged according to the effort required in implementing. As the benchmark for conventional practice, flat slabs were designed based on a span-to-depth ratio of 28 [16]. Two different cases were studied, having square-shaped slab panels with column spacings of 6 m and 10 m. The column sizes were taken as 360 mm and 600 mm respectively. A superimposed dead load of 1.5 kN/m^2 and an imposed load of 2.5 kN/m^2 was considered to represent a typical office building environment [16],[17].

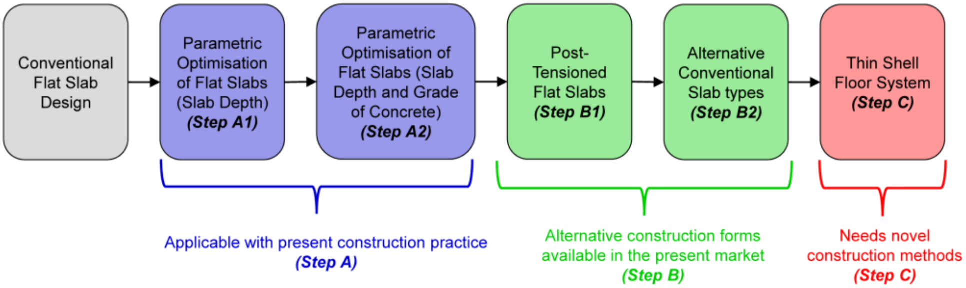


Fig. 1 Carbon optimisation strategies progressively adopted according to the effort required

2.1 Parametric Design Optimisation of Flat Slabs (Step A)

An optimisation algorithm was developed in MATLAB to minimise embodied carbon of reinforced concrete flat slabs based on parametric design. The first phase of the optimisation identified the design slab depth with minimum embodied carbon (Step A1). The second phase optimised the designs by varying slab depth and grade of concrete together (Step A2). The slabs were designed for 3 bay x 3 bay column layout for 6 m and 10 m column spacing. A series of designs were generated varying slab depth from 200 mm and 500 mm with 5 mm intervals, using grades of concrete C20/25, C30/37, and C40/50. The durability recommendation in BS EN 1992-1-1 requires the grade of concrete to be C30/37 or higher for environments that resembles the conditions in office buildings. Further research may be required to justify the use of lower grades of concrete. This study focuses on minimising embodied carbon in this scope.

The viable design space was confined to ensure that all the designs are under-reinforced (to ensure ductile failure), do not exceed the maximum reinforcement ratio of 4%, with fire safety for R90 rating, and satisfy limiting deflection. The reinforcements for each case were designed based on BS EN 1992-1-1 [17], referring to the guidelines given by The Concrete Centre [18]–[20]. The amount of flexural reinforcement was considered as a continuous variable for the convenience of calculations. The design moments were calculated by treating the column and middle slab strips as beams, allowing 15% moment redistribution. The detailing recommendations at the column strips and slab edges were considered. The simplified curtailing percentages recommended by The Concrete Centre were also applied. The deflection requirement was checked using the adjusted span-to-depth ratio according to BS EN 1992-1-1.

The amount of shear reinforcement for columns at internal, corner and side grid points were designed. The design reinforcement for columns was also estimated assuming the load from three floors to achieve realistic values. The amount of concrete, flexural reinforcement, shear reinforcement in slabs and columns were quantified to estimate embodied carbon of each design.

2.2 Alternative Conventional Slab Types (Step B)

The program named ‘Concept V4’ by The Concrete Centre [21] which was based on design charts developed by Goodchild et al. [22] was used to generate alternative designs with different conventional slab types. The program outputs the estimations of the embodied carbon of different conventional concrete slab types designed for input column grids and loads. The similar loads and column grids as in flat slab design optimisation were input to generate floor designs with two-way slabs on beams, post-tensioned flat slabs, hollow-core slabs, and ribbed slabs. The other slab types considered in the programme which did not result in minimum embodied carbon are not presented in this paper to avoid congestion in the graphs. The outcome of 'Concept V4' was used in this scope to estimate embodied carbon of post-tensioned flat slabs (Step B1) and to identify the slab type with minimum embodied carbon (B2).

2.3 Novel Optimised Floor Construction Methods (Step C)

The textile-reinforced thin shell floor system with prestressed steel ties developed by Hawkins et al. [12],[13] was considered in this study as the state-of-the-art low carbon alternative (Fig. 2). The uniform thickness shells were designed to primarily act in compression, as groin vaults. A low-density fill was used to create a level surface on the top of the shell system. The design details and material quantities were based on the charts established by Hawkins [23]. The design charts had been developed to minimise embodied carbon for each case by selecting the optimum shell thickness, steel tie diameter, overall depth, and amount of textile reinforcement.

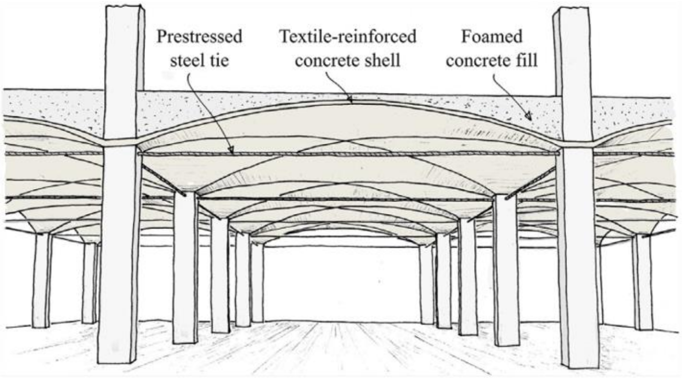


Fig. 2 Thin Shell Floor System Concept Sketch [13]

2.4 Estimation of Embodied Carbon

Embodied carbon of each design was estimated based on quantified material quantities per unit floor area. Cradle-to-gate embodied carbon was considered in this scope, acknowledging the comparably low contribution from other lifecycle stages [24], [25]. Carbon coefficients presented in Inventory of Carbon and Energy by Circular Ecology [26] was used wherever available. The values for hollow-core slab panels were extracted from recommended values by The Concrete Centre in Concept V4, which had been based on environmental product declarations and recalculations. Embodied carbon of Glass Fibre Textile was based on a previous review by Hawkins et al. [12]. The densities of concrete, steel, glass fibre textile, and aggregate fill were selected as 2400 kg/m^3, 7850 kg/m^3, 2700 kg/m^3, and 1400 kg/m^3 respectively. The adopted carbon coefficients in this study are listed in Table 1.

Table 1 Cradle-to-gate Embodied Carbon Coefficients

Material	Carbon Coefficient
Steel (85% recycled)	1.20 kgCO$_2$e/kg
Glass Fibre Textile	3.00 kgCO$_2$e/kg
C20/25 Concrete	0.112 kgCO$_2$e/kg
C30/37 Concrete	0.132 kgCO$_2$e/kg
C32/40 Concrete	0.138 kgCO$_2$e/kg
C40/50 Concrete	0.159 kgCO$_2$e/kg
C45/55 Concrete	0.171 kgCO$_2$e/kg
C50/60 Concrete	0.180 kgCO$_2$e/kg

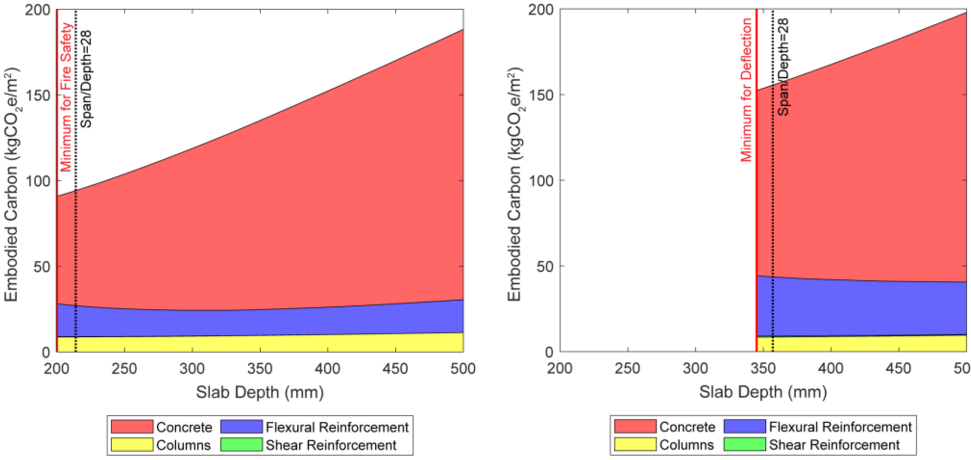
Material	Carbon Coefficient
Hollow-core 150 mm	50 kgCO$_2$e/m^2
Hollow-core 200 mm	57 kgCO$_2$e/m^2
Hollow-core 250 mm	65 kgCO$_2$e/m^2
Hollow-core 300 mm	75 kgCO$_2$e/m^2
Hollow-core 350 mm	85 kgCO$_2$e/m^2
Hollow-core 400 mm	95 kgCO$_2$e/m^2
Hollow-core 450 mm	105 kgCO$_2$e/m^2
Aggregate Fill	0.0061 kgCO$_2$e/kg

3 Results and Discussion

Fig. 3 illustrates the variation of embodied carbon in flat slabs for a range of slab depths designed for column spacings of 6 m and 10 m (Step A1). The contribution from concrete, flexural reinforcement, shear reinforcement and columns for total embodied carbon per unit floor area are separated in the plots. The minimum allowable depth and the conventional depth are also marked. In both cases, the design with minimum embodied carbon had a lower slab thickness than the conventional choice. The design space was limited by the fire criterion for the flat slab with 6 m spans, while the deflection criterion limited the designs with 10 m spans. In all the cases, the amount of concrete in the slab is responsible for more than 60% of the overall embodied carbon. Also, the share of embodied carbon from flexural reinforcement increased for slabs thicker than 350 mm for a 6 m span because of the minimum required reinforcement. Hence, optimum depth coincided with the minimum allowable depth in both column spacings considered.

The content of Fig. 3 was repeated for three different grades of concrete, and the results are presented in Fig. 4 (Step A2). Increasing the grade of concrete from C30/37 to C40/50 decreased the minimum allowable slab thickness but increased overall embodied carbon in both cases. Reducing the grade of concrete to C20/25 reduced overall embodied carbon, even with deeper slab designs. In all three grades of concrete, optimum design depth corresponded with the minimum allowable depth. In both the spans considered, optimum slab depth with C30/37 and C40/50 was lower than the conventional design depths, while C20/25 required deeper slabs. Hence, using lower grades of concrete in concrete slabs have the potential of reducing overall embodied carbon.

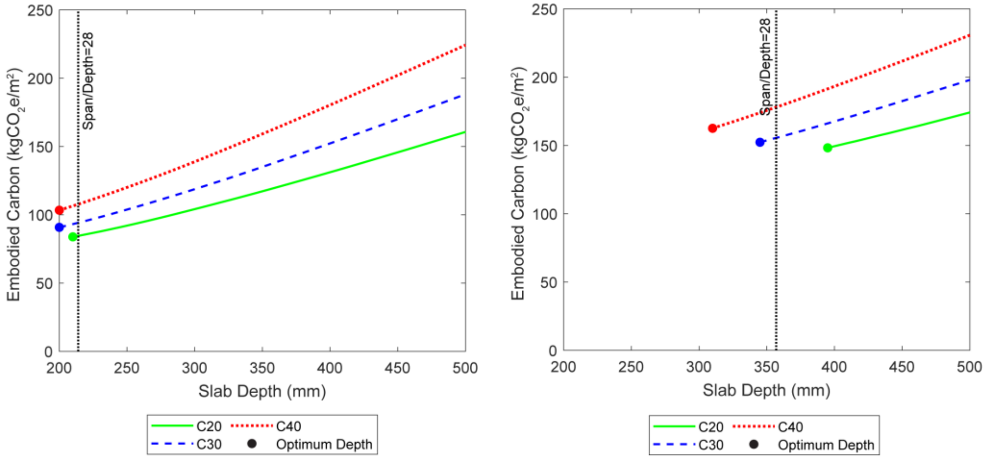
The outcomes of Concept V4 for alternative conventional slab solutions are compared in Fig. 5 (Step B). The flat slabs plotted here are the results from Concept V4. As presented in Fig. 5, different conventional concrete slab types designed for the same column grid and loads can have different levels of embodied carbon. Therefore, considering conventional alternatives and selecting the slab type with the minimum embodied carbon for the given design criteria can reduce embodied carbon. Post-tensioning 6 m span flat slabs did not reduce overall embodied carbon since the slab depth could not be reduced further due to the fire criterion. However, in both cases, post-tensioned flat slabs did not have the minimum embodied carbon out of the considered solutions. Two-way slabs on beams had minimum embodied carbon for column spacings of 6 m, while hollow-core slabs were optimum for slabs with 10 m spans. Therefore, considering alternative conventional slab types can reduce embodied carbon, but the optimum slab type can change with design span.



(a) Slab Designs for 6 m Column Spacing

(b) Slab Designs for 10 m Column Spacing

Fig. 3 Variation of Shares of Embodied Carbon in Flat Slabs with Depth (Step A1)



(a) Slab Designs for 6 m Column Spacing

(b) Slab Designs for 10 m Column Spacing

Fig. 4 Variation of Embodied Carbon in Flat Slabs with Depth for Different Grades of Concrete (Step A2)

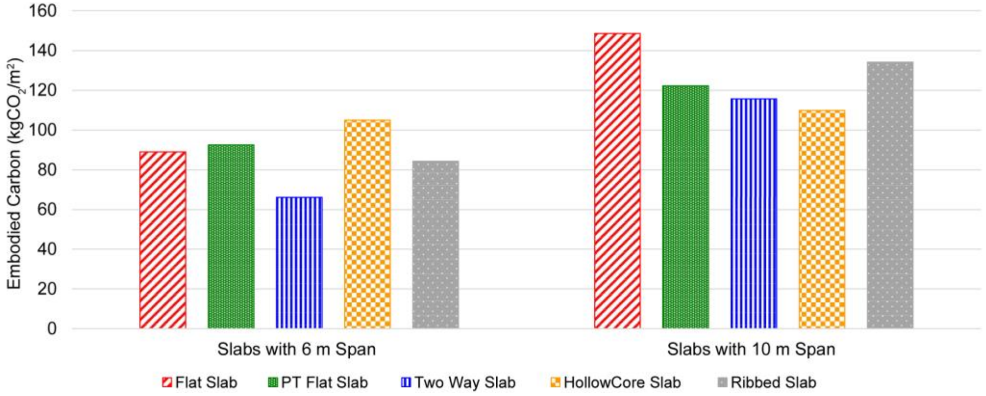


Fig. 5 Variation of Embodied Carbon in Flat Slabs with Depth for Different Grades of Concrete (Step B)

At the end of the study, the conventional design of flat slabs with 6 m and 10 m spans were optimised in five steps, progressively introducing the changes to traditional design and construction practice. Table 2 summarises the key design details of the outcomes of each optimisation strategy. The outline of this progressive approach suggests that the optimisation has mainly resulted in minimising the embodied carbon from concrete by reducing the member thickness and trading-off with the grade of concrete.

Fig. 6 illustrates the embodied carbon of the floor designs listed in Table 2, along with the possible savings of embodied carbon by each step for the two cases studied. In all the designs, 10 m span floors had embodied carbon higher than 6 m span floors by around 40% on average. This highlights the importance of column layout optimisation at the preliminary design stage of buildings. Parametric optimisation of the depth of flat slabs reduced embodied carbon up to 4%. The possible savings of parametric optimisation increased up to 11% when lower grades of concrete are considered. The benefit of post-tensioning increased with the span, reaching 21% carbon savings for a flat slab with 10 m spans. Adopting alternative conventional slab solutions reduced embodied carbon up to 29%. Much significant carbon savings up to 62% were possible by implementing novel shape optimised floor systems.

Table 2 Optimum Design Details at Each Optimisation Strategy

Optimisation Strategy	6 m Column Spacing	10 m Column Spacing
Conventional Flat Slab Design with span-to-depth of 28	214 mm with C30	357 mm with C30
Depth Optimised Flat Slab (Step A1)	200 mm with C30	345 mm with C30
Depth and Grade of Concrete Optimised Flat Slab (Step A2)	205 mm with C20	395 mm with C20
Post-Tensioned Flat Slab (Step B1)	200 mm with C32	275 mm with C32
Alternative Conventional Slab Type (Step B2)	125 mm two-way slabs on beams	250 mm hollow-core slabs
Thin Shell Floors (Step C)	43 mm thick, 600 mm deep shell with C45	83 mm thick, 1 m deep shell with C50

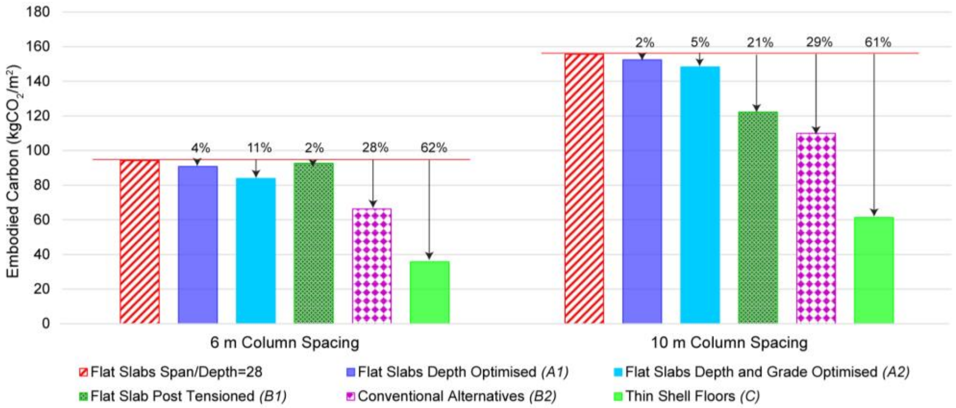


Fig. 6 Savings of Embodied Carbon Possible from Each Optimisation Strategy

4 Conclusion

Embodied carbon in concrete floors was progressively minimised in this study by introducing stepwise changes to the conventional design and construction practice. The following can be concluded from this study as guidelines to minimise embodied carbon in floor designs.

- Minimising the design depth of flat slabs rather than conventional simplified rules can reduce embodied carbon by 4% without changing available construction methods.
- Selecting lower grades of concrete for flat slabs coupled with parametric optimisation can increase the savings of embodied carbon up to 11%.
- The possible reductions of embodied carbon in flat slabs by post-tensioning increases with span. Considering alternative conventional floor solutions can reduce embodied carbon by up to 29%, but the optimum construction form may change with the column layout.
- Substantial carbon reductions up to 62% can be achieved by approving cutting-edge optimised construction methods.
- More than 60% of the embodied carbon of floors are associated with the amount of concrete. Optimisation procedures mainly target minimising embodied carbon from concrete by reducing the thickness and trading-off with the grade of concrete.
- Column layout optimisation plays a major role in all the optimisation strategies considered.

Hence, embodied carbon of concrete floors for a given layout can be reduced up to 11% only with changes to the design of flat slabs, 29% with available conventional slab alternatives, and 62% by adopting state-of-the-art floor solutions. Therefore, the construction industry should start to adopt shape optimised low carbon floor systems while utilising the resources in the market to minimise embodied carbon in present floor designs to effectively face the climate emergency.

Future Work

In the next step of this study, the progressive approach is to be applied for a range of design criteria to develop a basis of a set of design guidelines to minimise embodied carbon of concrete floors. Also, parametric design optimisation of flat slabs is to be explored regarding how the deflection criterion limits the potential of further reducing embodied carbon.

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