

Parametric Optimisation of Two-Way Slabs on Beams for Early-Stage Low-Carbon Design

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Abstract—Floor systems contribute nearly 75% of the embodied carbon emissions associated with the superstructure of buildings, underscoring the need to identify early-stage design parameters that can reduce embodied emissions while still adhering to traditional design guidelines. This study investigates the potential for minimising embodied carbon in reinforced concrete two-way slabs through a parametric grid search approach. The design space was systematically varied by adjusting slab thickness, concrete grade, reinforcement ratios, and spans ranging from 4m to 10m. From all generated designs meeting flexural, serviceability, and detailing requirements, those with the lowest cradle-to-gate carbon emissions were selected. Results indicate that carbon savings of approximately 3–50% can be achieved compared to conventional Eurocode-based designs, with greater reductions observed as the span increases. The most efficient configurations featured thinner slabs, lower concrete grades, and higher reinforcement densities. Changes in emission factors had limited influence on the optimisation outcomes, except under extreme scenarios. Even when the emission factor was increased by 100%, the total embodied emissions rose by only 45%, and the optimum design parameters remained unchanged. Based on these findings, a set of early-stage design charts is proposed to aid the development of low-carbon slab systems under varying load and grid conditions.

Keywords—Embodied carbon, Life cycle assessment, Parametric design, Reinforced concrete, Sustainable structural design

I. INTRODUCTION

A. Background

The increasing concentration of carbon dioxide (CO₂) and other greenhouse gases (GHGs) in the Earth's atmosphere is a critical environmental challenge of our time. These gases act as a heat-trapping blanket, leading to a gradual rise in global temperatures, a phenomenon known as climate change. Several protocols & policies such as Kyoto protocol & Paris agreement have been adopted to minimize climate change. In the report from the UN's Intergovernmental Panel on Climate Change from 2018 it is mentioned that achieving a 1.5 °C target requires a reduction of 40%–50% in global carbon emissions as compared with the levels in 2010, which must be achieved by 2030 [1]. Unfortunately, the construction industry alone has contributed a whopping 37% of the global CO₂ emissions in 2020, including 27% from building operations & 10% from building material production [2]. Therefore, it is imperative

to identify solutions to reduce CO₂ emissions from building constructions.

Several factors such as raw material extraction, material production, transportation, installation, building operation & etc. contribute to the building related embodied carbon emissions; thus, simply reducing the material consumption or operational energy wouldn't give optimum solutions to reduce environmental impact. That's why a holistic approach known as Life Cycle Assessment (LCA), which considers the total embodied & operational carbon emission from cradle-to-grave, is practiced comparing the environmental performance of various building design solutions. The standard life cycle stages defined by EN 15978 [3] are: product stage, construction process stage, use stage, end of life stage & beyond the life cycle stage.

B. Aims & Objectives

Aim: Find optimum structural solutions for multi-story buildings in order to reduce the environmental impact. Here LCA will be used as a tool to assess environmental performance.

Objectives:

- Develop a parametric framework for assessing the structural and environmental performance of RC floor systems.
- Identify the optimal set of design parameters that minimise embodied carbon while satisfying Eurocode 2's structural requirements.
- Develop early-stage design tables/charts to assist in design selection based on the optimised parameters.

II. LITERATURE REVIEW

Reducing the environmental impact of buildings has become a global priority, with Life Cycle Assessment (LCA) emerging as a key methodology to quantify the embodied carbon (EC) of structural systems. Although many studies have investigated architectural and material-focused approaches, the optimisation of structural elements, especially reinforced concrete members, is still a relatively unexplored area with significant potential. Recent literature suggests that parametric optimisation techniques offer significant potential for early-stage structural design to reduce EC without compromising performance [4] [5].

Reinforced concrete (RC) provides strength and versatility but carries high embodied carbon from cement and steel production. Historically, optimisations prioritized material reduction for cost savings. However, this same principle has recently been adapted to EC reduction. Jayasinghe et al [6] explored the shape optimisation of simply supported flanged RC beams, incorporating both structural and construction feasibility. Their results indicate that optimized prismatic beams can reduce EC by up to 38% compared to conventional designs, with an additional 8% savings from further shape refinement. However, some optimised solutions approached the deflection limits suggested by the codes, highlighting the need for balanced design considerations.

Further studies extended these principles to slabs, components that often dominate a building's EC. Jayasinghe et al. [7] investigated flat slab systems using a parametric framework, varying slab thickness, reinforcement details, concrete grade, and column configurations. Their findings emphasize that refined design constraints, especially deflection limits, significantly influence optimisation outcomes. A related study compared several slab types using Pareto optimisation, concluding that hollow core slabs outperform other systems for spans exceeding 8 meters. Two-way slabs, however, remained optimal across a broader range due to their structural efficiency. Post-tensioning was also assessed, achieving EC reductions comparable to hollow core systems, although at a higher cost [8]. Beyond individual components, recent efforts have explored the potential of structural systems that exploit alternative load transfer mechanisms. For instance, thin-shell floor systems, as proposed by W. Hawkins [9], leverage membrane action rather than bending, yielding up to 65% reduction in EC. Although still in the experimental phase, such systems highlight the promise of geometry-driven design in minimizing material use and environmental impact.

To navigate the multi-variable nature of structural design, researchers have increasingly turned to computational techniques such as genetic algorithms (GAs) for optimisation. GAs are stochastic search techniques that mimic natural selection, offering efficient solutions in complex, multi-objective design spaces. Zhang et al. [10] applied Pareto-based GA optimisation to RC beam cross-sections, balancing EC and cost. Their study showed a 14.7% reduction in EC could be achieved for a marginal 5–6% increase in cost, revealing the trade-offs involved in sustainable design. Slab optimisation using GAs has also been explored. A. H. Whitworth and K. D. Tsavdaridis [11] applied genetic algorithms to steel-concrete composite beams, optimizing for multiple objectives including embodied energy. Trinh et al. [12] too implemented a similar framework to parametrically optimise RC flat slabs. Their methodology demonstrates how evolutionary algorithms can be tailored to different structural systems.

Despite their promise, algorithm-based approaches face challenges in terms of data quality and regional adaptability. The effectiveness of any EC-based optimisation depends heavily on emission factors, which vary significantly by location, production method, and supplier. To address this, X. Zhang

and F. Wang [13] integrated Monte Carlo simulations with genetic algorithms to account for uncertainty in carbon emission factors. This hybrid method allowed for robust identification of design trends across multiple scenarios, improving the reliability of EC optimisation under variable data inputs.

Many studies achieve theoretical reductions in EC by designing reinforced concrete members beyond code-prescribed span-depth ratios while still meeting flexural requirements. Such compromises cast uncertainty on whether these theoretical gains can translate into safe, code-compliant solutions in practice. This presents a clear opportunity: a systematic parametric approach that optimises designs within full code compliance could transform these theoretical gains into practical, low-carbon solutions.

III. METHODOLOGY

This study presents a parametric optimisation framework aimed at minimising the embodied carbon of reinforced concrete two-way slabs on beams, while adhering to Eurocode 2 (EN 1992-1-1) safety and serviceability requirements [14]. The methodology is structured into four sequential phases: definition of design parameters, definition of constraints, embodied carbon estimation, and optimisation via a discrete grid search algorithm.

A. Problem Definition & Design Parameters

A typical two-way slab supported on beams, representative of residential buildings or other low-traffic structures, is considered. Heavily serviced structures such as hospitals and laboratories - where vibration control is critical - are excluded from the scope of this study. Specifically, uniformly loaded interior slab panels are considered. The slabs were designed in accordance with Eurocode 2 [14], referring to guidelines by The Concrete Centre [15] and IStructE [16]. Design loads include a live load of 2.5 kN/m² and a superimposed dead load of 1 kN/m². A minimum slab thickness of 120 mm is enforced to meet fire resistance requirements (R120), in line with Eurocode provisions. Flexural reinforcement spacings and sizes were considered in four distinct layers (T1, T2, B1, and B2) as design variables.

The parametric space includes:

- Grid size: 4 m–10 m with 0.5 m intervals (square-shaped grids)
- Concrete grade: C20/25 to C40/50
- Slab thickness: 120 mm to 300 mm (discrete steps of 1 mm)
- Reinforcement bar diameters: 8 mm – 20 mm
- Reinforcement spacing: 75 mm to 250 mm (discrete steps of 25 mm)
- Steel yield strength: 500 MPa
- Concrete cover: 25 mm (assuming 20 mm diameter reinforcement + 5 mm for deviations)

The total design ultimate load was considered as $1.35G_k + 1.5Q_k$ based on (1) from Eurocode 0 (EN 1990:2002) [17]. The bending moments per unit width were calculated based

on (2) from IStructE [14], and the corresponding co-efficients β_{sx}, β_{sy} were obtained from table 5.3 in the same manual. Also, 15% moment redistribution was considered in the design because the fire resistance tables in EN 1992-1-2 [18] hold only for 15% moment redistribution.

$$n = 1.35G_k + 1.5Q_k \quad (1)$$

$$\begin{aligned} m_{sx} &= \beta_{sx} n l_x^2 \\ m_{sy} &= \beta_{sy} n l_x^2 \end{aligned} \quad (2)$$

B. Design Constraints

This section outlines the key constraints governing the optimisation process, ensuring that all proposed designs comply with deflection limits, flexural capacity, and reinforcement detailing rules. These constraints are critical in balancing material efficiency with structural performance, while minimising embodied carbon.

Instead of directly enforcing the constraint for flexural performance as $M_{Ed} < M_{Rd}$, it was applied in the form of reinforcement required. It was made sure that the reinforcement provided ($A_{s,prov}$) is greater than both flexural reinforcements required ($A_{s,req}$) obtained from (5) & the minimum reinforcement required in a section ($A_{s,min}$) for crack control obtained from (6). Additionally, the constraint in (3) was applied to ensure that the sections are singly reinforced. Also, the constraint for the maximum reinforcement was applied based on (7).

$$k = \frac{M_{Ed}}{bd^2 f_{ck}} \leq 0.168 \quad (3)$$

$$z = d \left[0.5 + \sqrt{0.25 - \frac{k}{1.134}} \right] \leq 0.95d \quad (4)$$

$$A_{s,req} = \frac{M_{Ed}}{0.87 f_{yk} z} \quad (5)$$

$$A_{s,min} = \max \left\{ 0.26 \left(\frac{f_{ctm}}{f_{yk}} \right) b_t d, 0.0013 b_t d \right\} \quad (6)$$

$$A_{s,max} = 0.04 A_c \quad (7)$$

M_{Ed} – design bending moment

M_{Rd} – design resistance provided

f_{ck} – characteristic compressive cylinder strength of concrete at 28 days

d – effective depth of the section

b – breadth of the section

f_{yk} – characteristic yield strength of reinforcement

f_{ctm} – mean value of axial strength of concrete

A_c – area of the concrete section

In order to ensure that the deflections are within acceptable limits, $(l/d)_{act}$ should be lesser than (l/d) given by (8) from Eurocode 2 [12].

If $\rho \leq \rho_0$,

$$\frac{1}{d} = K \left[11 + 1.5 \sqrt{f_{ck}} \left(\frac{\rho_0}{\rho} \right) + 3.2 \sqrt{f_{ck}} \left(\frac{\rho_0}{\rho} - 1 \right)^{3/2} \right] \quad (8)$$

If $\rho > \rho_0$,

$$\frac{1}{d} = K \left[11 + 1.5 \sqrt{f_{ck}} \left(\frac{\rho_0}{\rho} (\rho - \rho_0) \right) + \frac{1}{12} \sqrt{f_{ck}} \sqrt{\frac{\rho'}{\rho}} \right]$$

l/d – limit span/effective depth

K – factor depending on the structural system

ρ_0 – reference reinforcement ratio = $10^{-3} \sqrt{f_{ck}}$

ρ – required tension reinforcement ratio at mid-span to resist the moment due to the design loads

ρ' – required compression reinforcement ratio at mid-span to resist the moment due to the design loads

$(l/d)_{act}$ = actual span/ effective depth

C. Embodied Carbon Estimation

In this study, the embodied carbon of the slabs were assessed from 'cradle-to-gate' (A1-A3) in accordance with EN 15978 [3] & EN 15804 [19]. The following values, sourced from Circular Ecology's Inventory of Carbon and Energy [20], were used. The values used in this study are based on realistic average cement contents for each concrete strength class rather than minimum theoretical cement requirements.

- Concrete C20/25 – 0.109 kgCO₂e/kg
- Concrete C25/30 – 0.115 kgCO₂e/kg
- Concrete C28/35 – 0.122 kgCO₂e/kg
- Concrete C32/40 – 0.134 kgCO₂e/kg
- Concrete C35/45 – 0.144 kgCO₂e/kg
- Concrete C40/50 – 0.154 kgCO₂e/kg
- Grade 500 Steel – 1.20 kgCO₂e/kg

$$\text{Total embodied carbon} = V_s \times D_s \times E_s + V_c \times D_c \times E_c \quad (9)$$

V_s, V_c – Volume of steel and concrete respectively

D_s, D_c – Density of steel and concrete respectively

E_s, E_c – Emission factors of steel and concrete

The total carbon emissions were calculated by (9) given above where D_s – 7850 kg/m³ & D_c – 2400 kg/m³. The effect of varying reinforcement diameters and spacings was incorporated through the total steel volume. Additionally, the steel reinforcement layout accounted for curtailment at the top layers, with an assumed 100% of the designed reinforcement retained within 0.15L (where L is the span) and at least the minimum required reinforcement provided throughout the remaining span.

D. Discrete Grid Search

Given the vast number of variable combinations in the design space, a manual search would be impractical. Instead, a systematic grid search algorithm was implemented in MATLAB to evaluate all feasible designs. Unlike stochastic methods, this approach ensures full transparency by exhaustively analyzing each combination while enforcing all specified constraints.

IV. RESULTS & COMPARISONS

The results obtained demonstrate a promising potential for significant reductions in the embodied carbon of two-way slabs on beams during the early stages of design. Furthermore, the findings provide valuable insights into how various design parameters influence the final embodied carbon, offering key considerations for optimizing sustainability in structural design.

For varying grid sizes, the lowest possible embodied carbon and the corresponding design parameters were obtained. Figure 1 illustrates the variation in embodied carbon per unit area of the optimal designs with respect to grid size. It clearly shows that smaller grid sizes (4–6 meters) yield the lowest embodied carbon per unit area, with emissions remaining minimal and constant within this range, suggesting their preference for efficient span accommodation. However, this study does not account for potential increases in column or foundation requirements, which may offset savings from reduced structural depths. Future research should examine trade-offs between grid size and additional structural elements, such as varying grid sizes with fixed column counts, to better assess their impact on total embodied carbon.

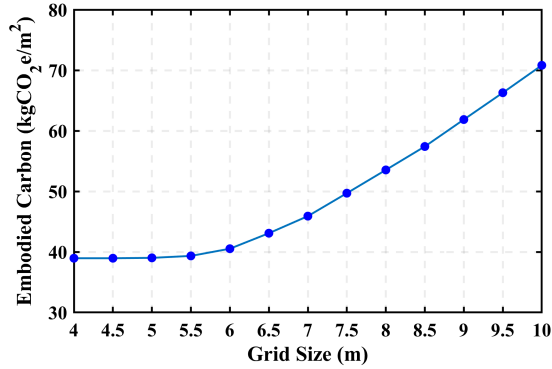


Fig. 1. Carbon per unit area vs grid size for total embodied carbon.

An analysis of the embodied carbon emissions across all feasible solutions that satisfy the flexural and serviceability requirements reveals a clear trend, indicating that designs with lower slab thicknesses and concrete grades are linked to more sustainable outcomes. Figure 2 illustrates the variation in embodied carbon for a 7×7 grid slab, showing how both thickness and concrete grade influence the carbon footprint. For a fixed concrete grade of C30/37, the average embodied carbon decreases as the slab thickness reduces. In contrast, Figure 3 demonstrates that, regardless of the grid size, embodied carbon increases with the concrete grade. This is due to the fact that the carbon intensity of concrete increases significantly more than its contribution to strength. These results collectively highlight that selecting the lowest possible thickness and concrete grade that still meet the structural requirements during the early design stage contributes to more optimal, sustainable designs.

Figure 4 presents the slab thicknesses corresponding to the lowest carbon designs for various grid sizes. For nearly

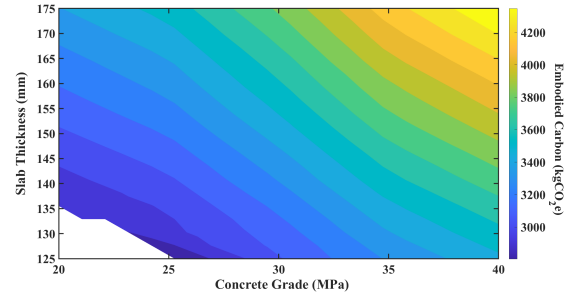


Fig. 2. Embodied carbon variation of a 7×7 grid slab with concrete grade and thickness

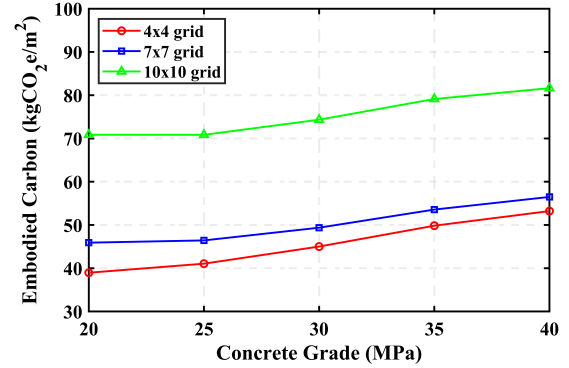


Fig. 3. Embodied carbon variation with concrete grade

all grid sizes, the optimal concrete grade recommended was C20/25 except in the extreme case of 10×10m grid where the savings are slightly greater by using C25/30 concrete with lower thickness. Additionally, it is evident that for smaller grid sizes, the primary governing criterion is the 2-hour fire safety requirement outlined by IStructE [16].

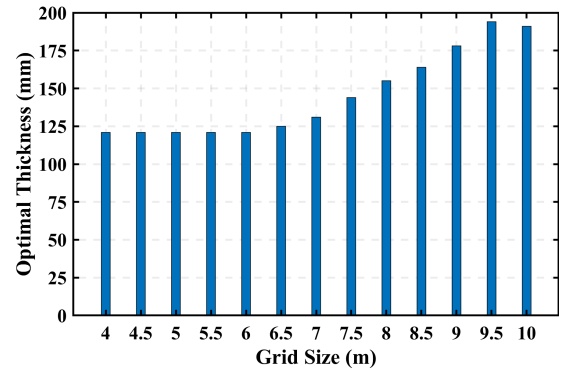


Fig. 4. Variation of optimum thickness with grid size

Steel reinforcement is another critical component of reinforced concrete, and accurately estimating the required amount of reinforcement is essential for achieving a low-carbon design. Figure 5 illustrates how the optimal reinforcement quantity in each region varies with grid size. Similarly, Figure 6 demonstrates the variation in the optimal reinforcement ratio with grid size. The plot indicates that the optimal main

reinforcement ratio falls within the range of 0.15% to 0.35%, with comparable values observed for the reinforcement in other regions. For smaller grid sizes (5-7 meters), optimal slab thickness remains constant, but reinforcement increases to meet higher flexural demands. This likely occurs because concrete's strength-to-carbon ratio is lower than steel's. However, as grid size grows, minimum slab thickness must increase to prevent concrete compression failure, eventually balancing reinforcement requirements.

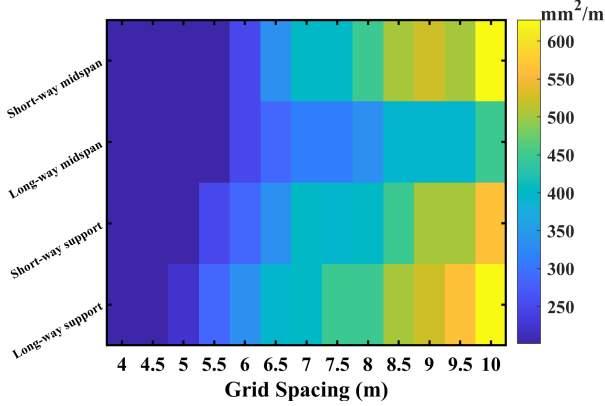


Fig. 5. Variation of optimal reinforcement amount with grid size

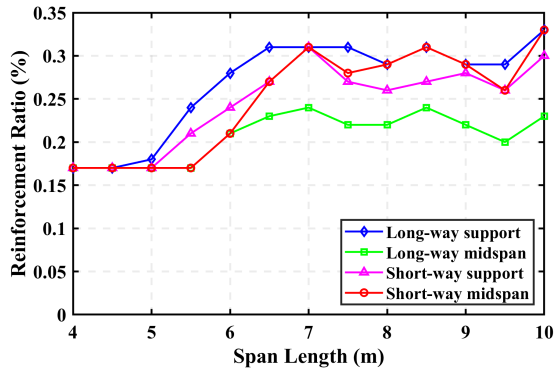


Fig. 6. Variation of reinforcement ratios with grid size

It is crucial to evaluate the potential savings offered by the optimal solutions when compared to traditional design parameters recommended by various codes. Eurocode 2 suggests a span-effective depth ratio of 30 for lightly reinforced two-way spanning interior panels, based on the use of C30/37 grade concrete. Similarly, the Economic Frame Elements guide by the Concrete Centre [21], in alignment with Eurocode 2 [14], recommends slab thicknesses for low-cost designs, also based on C30/37 concrete.

Thus, the slab thicknesses corresponding to the lowest carbon emissions for C30/37 concrete, derived from the grid search approach, were compared with those suggested by the aforementioned codes (Fig. 7). The slab thicknesses obtained from the grid search method are significantly lower than those prescribed by both codes, and for smaller grid sizes,

the thickness is predominantly constrained by the fire safety requirement.

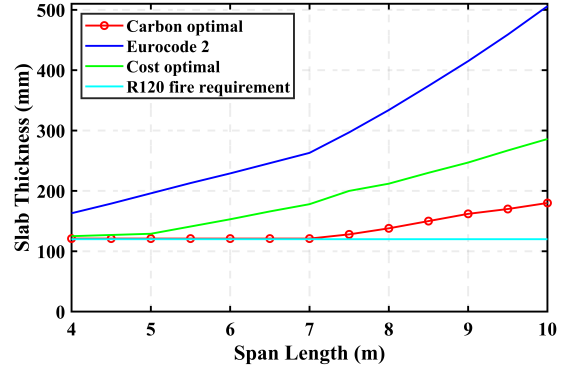


Fig. 7. Initial slab thicknesses suggested by different codes

The embodied carbon values for the slab thicknesses derived from the grid search approach are considerably lower than those recommended by the codes (Fig. 8). When compared to the Concrete Centre guidelines, the carbon savings range from 2.9% to 29.6%, while savings relative to Eurocode range from 24.3% to 49.1%. These results highlight that significant reductions in carbon emissions can be achieved by adopting slab thicknesses identified through the grid search method.

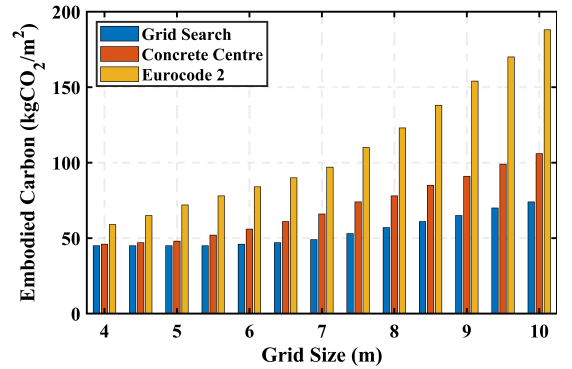


Fig. 8. embodied carbon variation with approach

Based on the grid search approach, optimal slab thicknesses for the early-stage design of two-way spanning interior slab panels with square grids are provided below for various imposed loads (Table. 1). The slab thicknesses were determined using 1 mm increments to obtain accurate theoretical values and to better understand the design variations. However, designers are expected to round up to the nearest 25 mm based on engineering judgment and standard modular sizing. For instance, instead of selecting a 121 mm thick slab, designers should choose a 125 mm thickness, ensuring the design meets the necessary load and span requirements.

V. CONCLUSION

This study demonstrates the potential for significant reductions in embodied carbon for two-way slabs on beams through optimization of slab thickness and concrete grade during the

TABLE I
PROPOSED SLAB THICKNESSES FOR EARLY STAGE DESIGN

Square Grid, m	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
Overall Depth (mm)													
IL = 2.5 kN/m ²	121	121	121	121	121	121	121	128	138	150	162	170	180
IL = 5.0 kN/m ²	121	121	121	121	121	124	135	147	153	165	178	193	202
IL = 7.5 kN/m ²	121	121	121	121	128	135	143	156	171	181	200	209	225

early design stages. The newly proposed slab thicknesses (Table. 1), derived from the grid search approach, are considerably lower than those suggested by Eurocode 2 and the Concrete Centre guidelines, with carbon savings ranging from 2.9% to 49.1%. These savings highlight the effectiveness of adopting grid search-derived slab thicknesses, which are constrained mainly by fire safety requirements for smaller grid sizes. The optimised results obtained can be considered robust since significant variations in the emission factors didn't change the outcome of the optimised results though the total embodied carbon changes.

But practical detailing constraints limit the direct use of these optimised parameters in construction. The reinforcement provided to a slab panel will be constrained by the reinforcement size and spacing used for adjoining slab panels. Therefore, further study should be done to analyse the optimum design parameters when an entire floor system is considered. Additionally, this study should be extended to analyse the optimum design parameters of exterior slab panels where the design loadings will be different.

Also, the results indicate that smaller grid sizes (4-6 meters) contribute to minimal carbon emissions, and lower slab thicknesses and concrete grades lead to more sustainable designs. However, the additional embodied carbon due to increased foundation or column requirement needs to be studied further.

Overall, the study emphasizes that optimizing slab thickness and concrete grade, while adhering to necessary design criteria, can significantly reduce embodied carbon in reinforced concrete slabs, with the newly proposed thicknesses providing a practical and convenient approach for early-stage design and sustainable outcomes.

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