









Beams unlock large carbon savings in reinforced concrete structures

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ABSTRACT

Reinforced concrete structures significantly contribute to buildings' embodied carbon, with floor design optimisation being crucial for material efficiency and structural decarbonisation. This study evaluates the embodied carbon, material use, cost, and labour intensity of seven cast-in-place reinforced concrete floor systems for a hypothetical four-story building in Brazil, considering four different column spans. The primary difference among the floor systems is the number of beams used. Results show a 3.4-fold variation in the embodied carbon intensity among the 28 alternatives, ranging from 48 to 167 kg CO₂/m². Beam-supported floors have lower material intensity and embodied carbon, while flat slabs perform worse, especially for larger spans due to post-tensioning requirements. Despite higher formwork complexity, floor systems with more beams remain cost-competitive due to material savings, demonstrating that low-carbon and low-cost designs can coexist. This study encourages structural designers to prioritise material-efficient solutions for decarbonising reinforced concrete structures. It shows that substantial savings can be achieved with current technology, offering practical ways to reduce buildings' environmental impact while ensuring economic feasibility.

1. Introduction

Reinforced concrete structures account for the largest portion of buildings' mass and embodied carbon [1,2], and are unlikely to be replaced at scale by alternative technologies soon [3]. Alongside reducing the embodied emissions of concrete and steel, optimising the structural design of reinforced concrete structures is essential for climate change mitigation in the built environment [3]. For instance, the Global Cement and Concrete Association's (GCCA) "Getting to Net Zero" strategy identifies "efficiency in design and construction" as a key lever, potentially contributing 22 % of the emissions reductions needed to reach net-zero carbon in the concrete sector by 2050 [4].

In typical buildings with usual heights, the greatest potential for optimisation lies in the floor system, which contributes about 60 % of the total concrete volume [5–8]. As a result, a growing body of research has focused on reducing the embodied carbon of reinforced concrete floors [9–13]. Many studies adopt a parametric approach, using various algorithms to explore structural optimisation by varying parameters

such as column spacing [5,9], concrete strength [13,14], reinforcement rate [15], among others. Such studies frequently centre on a single floor typology, most often flat slabs [5,10,13,14,16]. Flat slabs' simple geometry offers practical benefits including reduced reliance on skilled labour for their execution, minimal interference with building systems, and enhanced architectural flexibility [17].

However, studies comparing different floor typologies suggest that flat slabs may not be the most carbon-efficient option. Hafez et al. [7], for example, found that waffle slabs have around 25 % lower embodied carbon than flat slabs. Similar reductions have been reported for slabs supported by two-way beams [18]. Auburtin et al. [19] reported up to 40 % reduction in embodied carbon by introducing beams to help distribute slab loads. Broyles et al. [12] found that flat slabs can have up to 50 % higher embodied carbon than beam-supported or waffle slabs.

Nevertheless, the selection of floor typologies also affects the construction time and cost of reinforced concrete structures, which are critical factors for decision-making. Despite their relevance, few studies have simultaneously assessed the embodied carbon and cost of

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reinforced concrete floors [5,18,20]. Those that do have limitations, such as focusing exclusively on flat slabs [5], prioritising the optimisation methodology over the comparative performance of typologies [20], or excluding labour costs, considering only materials and formwork [18]. Thus, a gap remains in the literature concerning a comprehensive, consistent, and quantitative evaluation of the embodied carbon, cost, and productivity implications of choosing among commercially available floor typologies for reinforced concrete structures.

2. Objective

This study compares the material intensity, embodied carbon, labour intensity and cost of seven commercially available floor systems for cast-in-place reinforced concrete structures, considering four values of spans between columns, for a hypothetical four-story building in Brazil. Rather than employing a parametric or conceptual approach, this study involved the detailed structural design of the 28 distinct alternatives, following applicable codes and design procedures, to replicate conditions encountered in real-world engineering practice. The results reveal that geometries with more beams can deliver both environmental and economic advantages, including reduced labour intensity, compared to flat slabs. In doing so, the study fills a critical gap by providing comparative, design-level evidence to guide sustainable and economic choices for reinforced concrete structures.

3. Method

3.1. Description of the structural typologies

This study considered a hypothetical building (Fig. 1) with four storeys, each with 3.25 m floor-to-floor height, and external horizontal dimensions of 37.5×37.5 m or 40.0×40.0 m², depending on the span between columns. Four span options (column spacings) were analysed: 5.0 m, 7.5 m, 10.0 m, and 12.5 m. This layout is typical for multistorey offices but can also be applied to other uses, such as parking garages or warehouses.

Seven structural typologies for the horizontal elements of cast-in-place reinforced concrete structures were considered (Fig. 2). These typologies represent the most common structural solutions used in Brazil. The choice between beam-supported floors or flat slabs depends on the available floor-to-floor distance versus the desired unobstructed floor height, as well as construction company preferences. Other constraints include material and workforce costs and their availability on the construction site. For example, a reduced availability of formwork carpenters can lead to a preference for flat slabs.

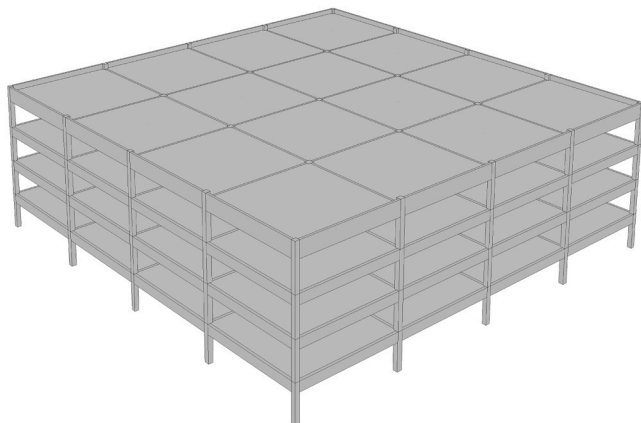


Fig. 1. Illustration of the analysed building.

3.2. Structural design

The structures were designed according to the Brazilian reinforced concrete structural design standard, ABNT NBR 6118, and the Brazilian standard on fire design of concrete structures, ABNT NBR 15200. Both standards are inspired by Eurocode 1992. All loads were considered according to ABNT NBR 6120 (for floor and use loads) and ABNT NBR 6123 (for wind loads). Table 1 summarises the loads considered in the structural design.

All structures were designed using concrete with a characteristic compressive strength of 30 MPa and elastic modulus of 26 GPa, and reinforcing steel with a characteristic yield stress of 500 MPa. Some structures also required unbonded tendons with post-tensioning steel grade with a characteristic yield stress of 1900 MPa and low relaxation.

The structural design procedure involved the following steps:

1. Determine minimum slab thickness and beam and column widths according to the standards.
2. For each of the four spans studied, locate the columns and beams (when used).
3. Determine slab thickness and beam width and height to comply with maximum deflection according to ABNT NBR 6118 and the usual deflection threshold (between 10 mm to 20 mm for shorter and larger spans, respectively). For structural typologies without secondary beams, with main spans of 10.0 m and 12.5 m, post-tensioning unbonded tendons were used to help limit slab deflections.
4. Determine column dimensions to ensure lateral stability (shear walls were necessary for greater spans and flat slab typologies).
5. Design the required reinforcement for all elements.
6. Reduce the dimension of structural elements if the slab or tip deflection is well below standard or usual deflection limits.
7. Increase the dimension of structural elements for easier reinforcement assembly on site or to enhance stiffness (where necessary).
8. Detail the required reinforcement (rebar or unbonded tendons) for all elements with the final dimensions in each solution.
9. Compile the concrete volume, formwork area, rebar weight and unbonded tendons weight for all solutions.

To improve constructability, secondary and alternate beams were designed with a height 50 mm to 100 mm less than the primary beams. The detailed structural design plans of each alternative are available in the [Supplementary Material](#).

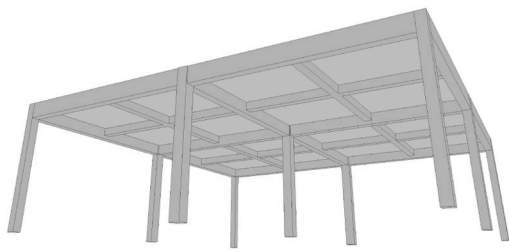
3.3. Embodied carbon and material intensity analysis

The embodied carbon intensity of the different structures was estimated using a simplified Life Cycle Assessment (LCA) approach [21]. The scope covers the reinforced concrete structure, including columns, beams, and slabs. The ground floor slab was not considered as it would be the same in all options. Although the different structural typologies could lead to differences in the foundation, it was not considered because it also depends on the geotechnical characteristics of each site.

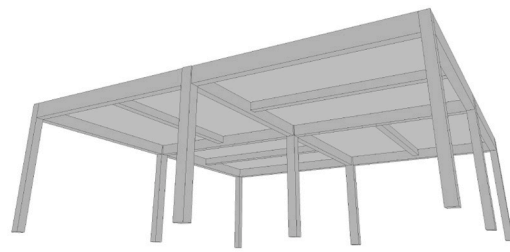
We considered the life cycle stages of materials production (modules A1-A3 according to EN 15804 [22]) for concrete and steel, as well as the material used for formwork (module A5). Materials transportation to the construction site was not accounted for because this study aimed to analyse the effect of structural design decisions, and transportation distances also depend on supplier selection and site location. Materials wastage at the construction site was also not considered, as it depends on construction site management practices.

Concrete and steel quantities were directly extracted from the structural design. For the formwork, the quantity of plywood and sawn wood was estimated using information from cost breakdown structures provided by the Brazilian National System for Survey on Construction Costs and Indices (SINAPI) [23], considering four reuses. Table 2 shows

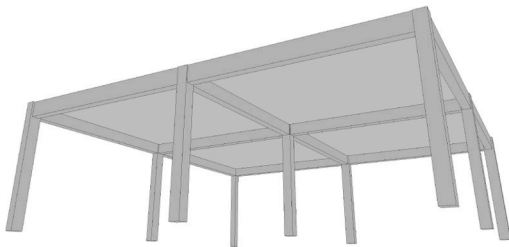
Typology A: two-way primary beams + two-way secondary beams + slab



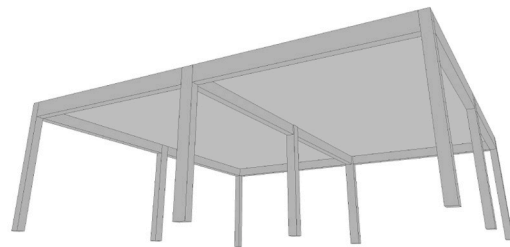
Typology B: two-way primary beams + alternate secondary beams + slab



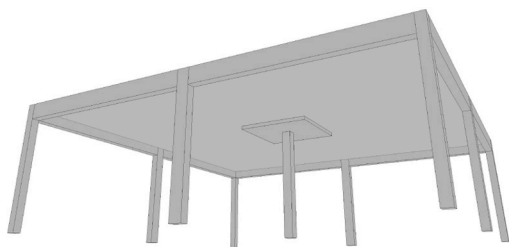
Typology C: two-way primary beams + slab



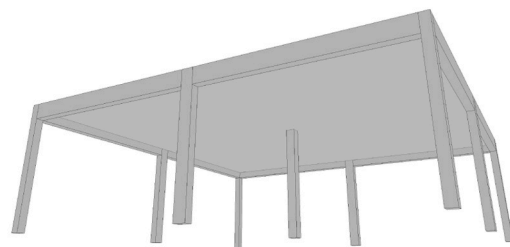
Typology D: one-way primary beams + slab



Typology E: edge beams + drop panels + flat slab



Typology F: edge beams + flat slab



Typology G: flat slab

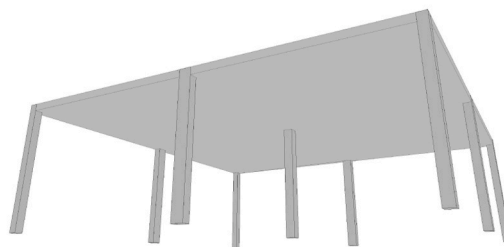


Fig. 2. Illustration of the floor systems analysed in this study.

the embodied CO₂ coefficients of each material and the corresponding data sources.

The embodied carbon intensity (EC) was calculated according to Eq. (1), where Q_i is the quantity of each material “i”, ECC_i is the embodied CO₂ coefficient of each material “i”, and A is the floor area.

$$EC = \sum_i (Q_i \times ECC_i) / A \tag{1}$$

We also calculated the structural material intensity (SM) according to Eq. (2), where $Q_{concrete}$ is the quantity of concrete (in m³), converted into mass considering a density of 2400 kg/m³, Q_{steel} is the quantity of steel (in kg), and A is the floor area.

$$SM = [(Q_{concrete} \times 2400) + Q_{steel}] / A \tag{2}$$

Table 1
Loads considered in the structural design.

Parameter		Value	Unit
Floor dead load	Intermediate floors	1.0	kN/m ²
	Last floor	3.0	kN/m ²
Floor live load	Intermediate floors	2.5	kN/m ²
	Last floor	3.0	kN/m ²
Wind load	Mean pressure	0.54	kN/m ²
Perimeter wall load	Intermediate floors	2.7	kN/m
	Last floor	1.9	kN/m
Time in standard fire exposure		60	min
Atmospheric exposure class		II (urban)	-

Table 2
Embodied CO₂ coefficients for the materials.

Material	embodied CO ₂ coefficient (kg CO ₂)	Unit	Source
Concrete f_{ck} 30 MPa	284	m ³	[24]
Rebar f_{yk} 500 MPa	0.74	kg	[24]
Unbonded tendons f_{yk} 1900 MPa	2.3	kg	[25]
Sawn wood, raw, dried	26.0	m ³	[24]
Plywood	9.1	m ²	[26,27]
Formwork			
Columns	3.4	m ²	[23,24]
Beams	7.3	m ²	[23,24]
Slabs	3.3	m ²	[23,24]

3.4. Cost and productivity analysis

Material cost data were retrieved from the Brazilian National System for Survey on Construction Costs and Indices (SINAPI) [23] and are summarised in Table 3.

We also assessed the workload to execute each structure, as they differ significantly in complexity level, which affects the labour cost and, consequently, the total cost. The SINAPI database [23] was again used to retrieve the number of hours spent per service, on a unit basis, as well as labour costs (including payroll taxes). Table 4 shows the labour costs for each service by structural element; the detailed cost breakdown structures are available in the Electronic Supplementary Material.

4. Results

4.1. Low spans and more beams reduce embodied carbon

Fig. 3 and Fig. 4 show the embodied carbon intensity of the analysed structures by structural typology and span.

Embodied carbon intensity varies from 48 to 167 kg CO₂/m², representing a 3.4-fold difference. We can distinguish three groups of typologies based on their embodied carbon. Typologies with secondary beams (A and B) consistently exhibit lower embodied carbon intensity for spans of 7.5 m or more, and their carbon intensity is less sensitive to span variation. Typologies with only primary beams (C and D) and flat slabs with drop panels (E) perform similarly, with the flat slab with drop panels having a slightly higher carbon footprint. Flat slabs without drop

Table 3
Material unit costs according to SINAPI (except for unbonded steel tendons cost, which was informed by contractors).

Material	Cost (BRL)	Unit
Concrete f_{ck} 30 MPa	478.96	m ³
Rebar f_{yk} 500 MPa (cut and bent)	7.56	kg
Unbonded post-tensioning steel tendons f_{yk} 1900 MPa	11.00 ^a	kg
Formwork for	Columns	34.56
	Beams	80.20
	Slabs	18.81

Table 4
Labour costs per service and structural element.

Service	Structural element	Cost (BRL)	Unit
Formwork assembly	Columns	33.77	m ²
	Beams	40.35	
	Slabs	24.74	
Rebar placement	Columns	0.99	kg
	Beams	0.99	
	Slabs	0.55	
Post-tensioning	Slabs	3.99	kg
	Concrete placement	54.07	
	Columns	53.51	m ³
	Beams	53.51	
	Slabs	53.51	

panels have the highest embodied carbon, as they require greater thickness to comply with displacement limits and provide the punching shear resistance needed around columns. Moreover, flat slabs without drop panels are more sensitive to span variation, especially the version without the edge beam, which has an embodied carbon up to 20 % higher than the version with the edge beam. The presence of edge beams (typology F) contributes to two crucial aspects: reducing the displacement of the slab edge with their inertia, and enhancing the building's lateral resistance, which allows smaller columns or shear walls.

For the investigated spans between columns, introducing beams shortens slab spans, allowing for thinner slabs, which reduces concrete use and lowers structural embodied carbon. However, once the slab thickness reaches the minimum standard requirement (80 mm), additional beams only increase material use without further benefits. This explains why typologies with secondary beams do not exhibit the lowest embodied carbon results for the 5.0 m span. Regarding the span between columns, reducing it can also lead to material savings, but only down to the point where the minimum beam height is achieved, which is estimated to be between 3.0 m and 4.0 m based on the authors' experience; similar values are also reported by literature, varying according to the floor typology [9,10]. Below this threshold, adding columns does not reduce slab or beam thicknesses and only increases embodied carbon.

4.2. Lower concrete intensity means lower embodied carbon

Concrete is the primary contributor to embodied carbon, accounting for 62–79 % of the total result (Fig. 5). The contribution of steel increases with the span, particularly for typologies without secondary beams and spans of 10.0 and 12.5 m, where post-tensioning tendons are required [18]. These tendons are three times more carbon-intensive than conventional rebar, further increasing the embodied carbon of these typologies.

Embodied carbon intensity is strongly correlated with concrete intensity (Fig. 6), as already reported in the literature [15,28]. Flat slabs require more concrete due to their reduced efficiency in limiting mid-span deflection compared to beam-supported floors. Additionally, the lack of rigid frames in flat slabs necessitates shear walls for lateral stability, resulting in larger column sizes.

Furthermore, more concrete necessitates more reinforcement steel. Although structures with higher concrete consumption do not always have higher steel rates in kg/m³ (Fig. 7a), they do exhibit higher steel intensity in kg/m² (Fig. 7b), contradicting some findings from existing literature [15].

4.3. More beams do not always imply more labour

Typologies with secondary beams generally have the lowest embodied carbon but require more complex formwork, which increases the working hours needed for construction. However, our estimation of the total working hours indicates that these typologies are more labour-intensive only for shorter spans (5.0 and 7.5 m). While formwork

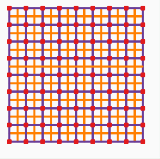
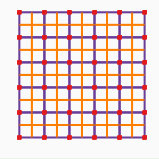
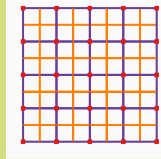
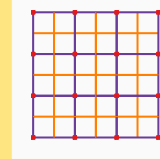
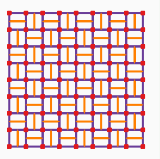
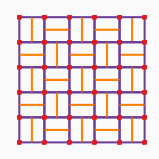
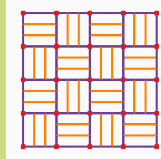
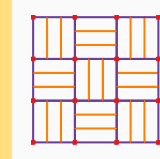
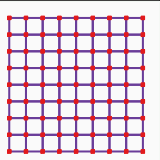
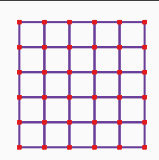
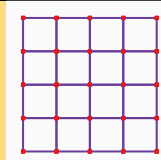
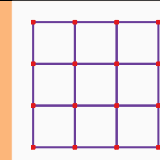
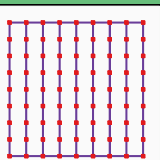
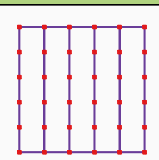
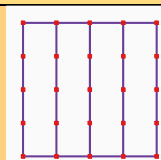
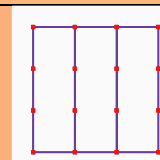
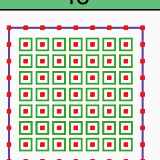
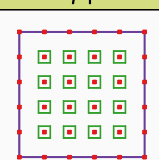
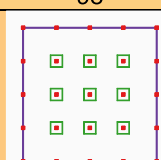
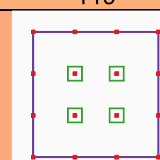
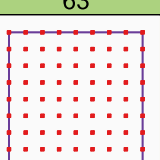
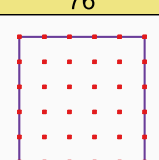
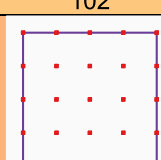
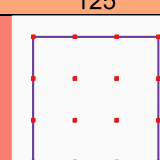
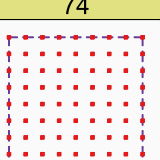
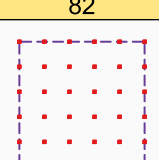
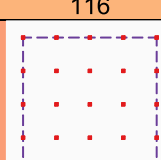
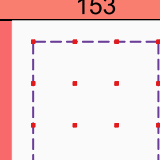
Typology	Embodied carbon intensity (kg CO ₂ /m ²)			
	span = 5.0 m	span = 7.5 m	span = 10.0 m	span = 12.5 m
A	 53	 58	 71	 83
B	 51	 55	 69	 87
C	 49	 64	 90	 115
D	 48	 71	 98	 119
E	 63	 76	 102	 125
F	 74	 82	 116	 153
G	 73	 99	 131	 167
Legend	<p>— PRIMARY BEAMS ■ COLUMNS - - - SLAB BOUNDARY (WITHOUT BEAMS)</p> <p>— SECONDARY BEAMS □ DROP PANELS</p>			

Fig. 3. Embodied carbon intensity by structural typology and span, with schematic representation of the floor plans. Green cells correspond to lower embodied carbon intensity, while red cells correspond to higher embodied carbon intensity.

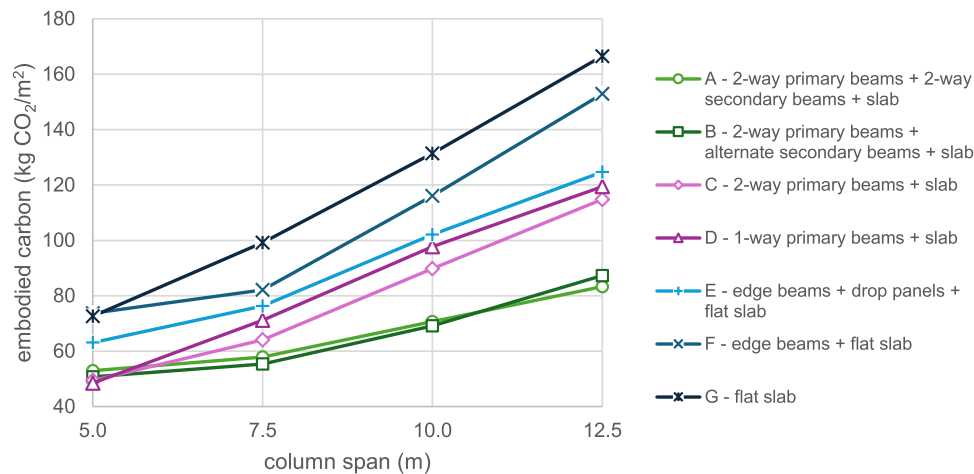


Fig. 4. Embodied carbon intensity by structural typology and span.

assembly constitutes a significant portion of the total labour intensity, the installation and post-tensioning of tendons substantially increase the labour requirements for structures without secondary beams for spans greater than 10 m (Fig. 8).

It is important to note that these results are based on how cost estimates are modelled in SINAPI, where the hours required for an activity are calculated by multiplying a standard productivity index by the corresponding quantity, such as formwork area, concrete volume, or steel mass. However, in practice, the productivity indexes for formwork and reinforcement assembly vary according to the complexity of the structural elements. For example, it is unlikely that structures with two-way secondary beams (A) will have lower labour requirements than structures with alternate secondary beams (B), even for long spans, due to the complexity of beam intersections.

4.4. Low-carbon structures can have low cost

As low-carbon structures consume fewer materials and generally require fewer working hours, they can have lower costs, challenging the common belief that sustainable construction is more expensive [29]. Fig. 9 shows the total cost results by structural typology and span. For a 5.0 m span, typologies with primary beams have lower costs; at 7.5 m, typologies with secondary beams start to become cost-competitive, and they become even more so for spans larger than 10.0 m. Flat slabs without drop panels are consistently more expensive.

To evaluate the sensitivity of this conclusion to workforce costs, which vary between and within countries, we analysed the correlation between embodied carbon intensity and cost, including scenarios where labour costs are multiplied by factors of 2, 5, and 10 (Fig. 10). The strong correlation between cost and embodied carbon persists even with significantly increased labour costs.

5. Discussion

Our results show that beams help to reduce material use and decarbonise reinforced concrete structures. For a 5.0 m span, the slab with one-way primary beams (typology D) is the best alternative. From a 7.5 m span onwards, secondary beams are more efficient. Alternate two-way secondary beams (typology B) have the lowest embodied carbon and cost for 7.5 and 10.0 m spans, making them an attractive alternative to the more complex two-way secondary beams (typology A). For a large span of 12.5 m, the two-way secondary beams perform best, closely followed by the alternate two-way secondary beams.

Although existing studies had already demonstrated the lower embodied carbon of beam-supported floors and waffle slabs compared to flat slabs [7,12,18,19], there are significant differences in our results.

We found a significantly higher variation in embodied carbon between floor typologies, with the relative difference between the minimum and maximum results varying between 52 % (for the 5.0 m span) and 100 % (for the 12.5 m span), whereas the relative difference reported by the literature is usually below 50 % [7,12,18]. Some studies even report no significant difference among the floor typologies: for instance, Broyles et al. [30] show very similar results for reinforced concrete floors (one- and two-way beam-supported floors and flat slabs) for a column span of 5.0 m, with the difference between typologies appearing only for larger spans. On the other hand, the results of Jayasinghe et al. [18] indicate that the relative difference between some floor typologies remains constant or even decreases with increasing span.

Another key difference is the ranking of the floor typologies by their embodied carbon: while according to our results, flat slabs always perform worse than beam-supported alternatives (with increasing difference with increasing span), other studies suggest that they can perform better than slabs on beams for low spans, [12], for large spans when post-tensioned [18], or even regardless of the span [11]. Different structural design assumptions may explain these discrepancies, as all cited studies with different conclusions employ parametric approaches.

Furthermore, our results show that beam-supported floors have not only lower embodied carbon but also lower labour intensity for larger spans, contradicting the common belief that flat slabs would always outperform beams in terms of productivity [17]. Our cost estimates also indicate that beam-supported floors are more cost-effective than flat slabs, allowing for carbon savings at cost-negative values. This constitutes a novel contribution from our work, as previous studies considering embodied carbon and cost have either focused on flat slabs only [5, 14] or on material and formwork costs, disregarding labour costs [18].

However, an important limitation of our study is that the productivity indexes we used do not differentiate between the complexity of structural elements. This is particularly critical when quantifying the number of working hours spent for the typologies with secondary beams, which have formwork and rebar that are more difficult to assemble due to complicated intersections. Previous studies also faced a similar limitation, adopting productivity indexes even less detailed than those we applied [14,20]. Therefore, future studies could measure the productivity of individual operations – formwork assembly, rebar placement, concrete placement, and post-tensioning – for different floor systems to enhance data quality for productivity estimates.

Another limitation of our study is that we consider single values for the compressive strength and elastic modulus of concrete, as well as the yield strength of steel [31]. Varying these parameters, as done by other studies [12,13], could lead to different findings and eventually alter the ranking of the preferred floor typologies for carbon and cost efficiency. Similarly, varying the embodied carbon factors of the materials [12,15],

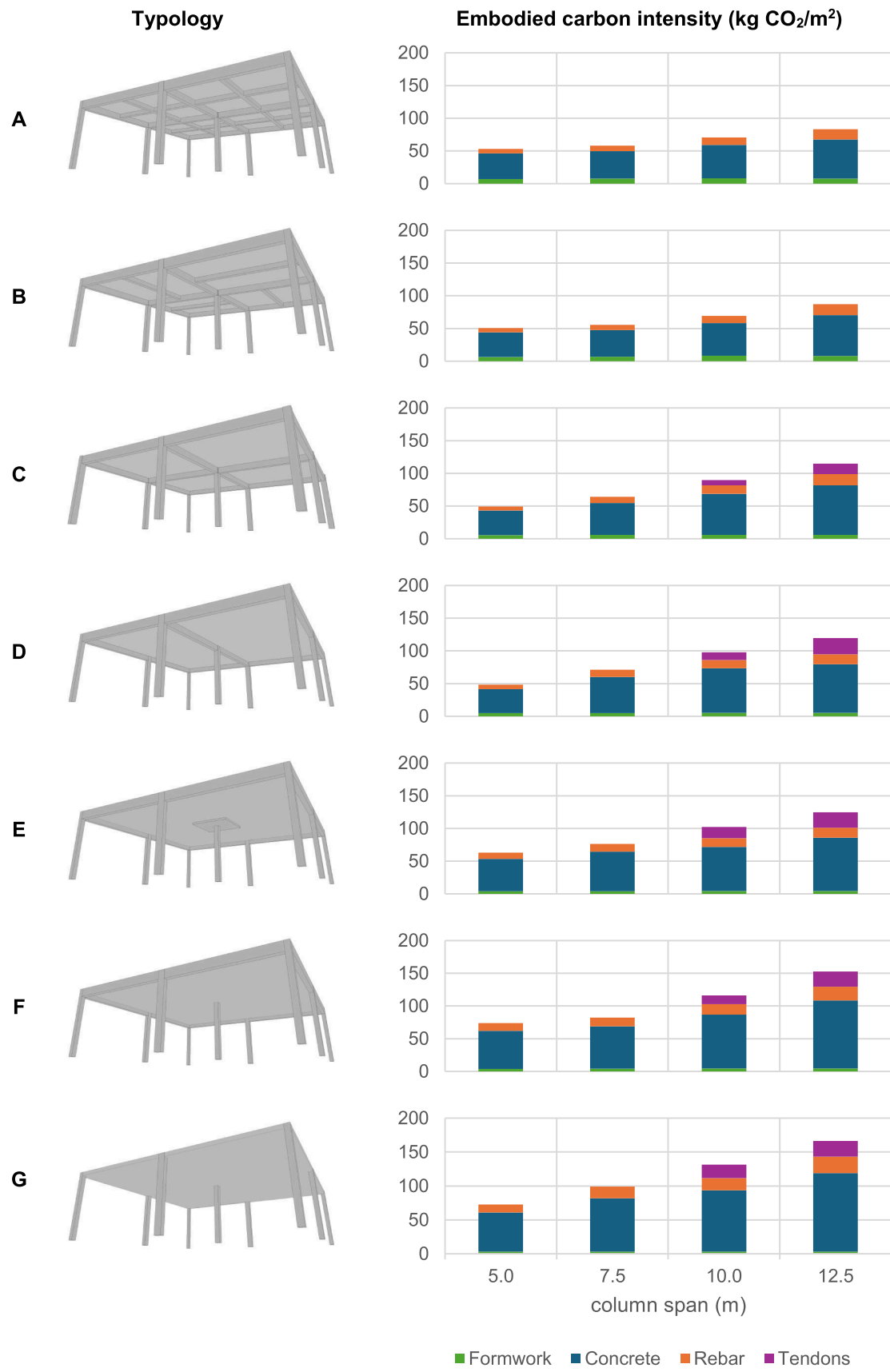


Fig. 5. Embodied carbon intensity by material, presented by structural typology and span (in m). schematic floor plans are presented for the 10.0 m span to facilitate the identification of the different typologies.

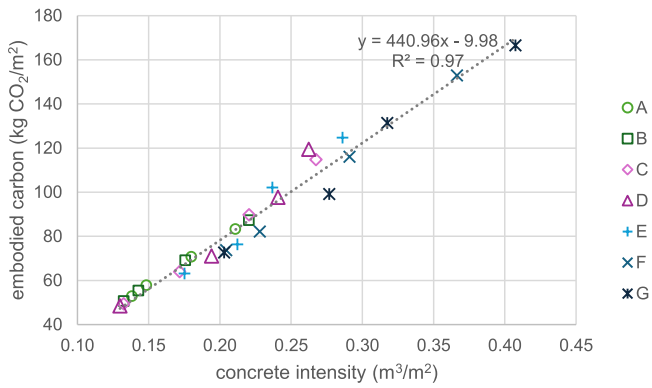


Fig. 6. Correlation between the embodied carbon intensity and the concrete intensity.

including innovative low-carbon concrete mix designs [3], could also lead to different findings. Building on the parametric approaches frequently used for structural optimisation, future studies could integrate all these factors [25], including cost and productivity, to better inform decision-making.

Finally, although our study has designed structures to withstand the same loads and with the same fire rating, we did not consider differences

in the acoustic performance of the floor systems due to different slab thicknesses [19]. However, acoustic performance can be achieved by different solutions and should not impede structural optimisation for embodied carbon reduction. Moreover, as we standardised the floor-to-floor height, using beams implies losing between 22 and 57 cm of unobstructed height, meaning that, from an architectural point of view, one could question whether the alternatives compared in this study are functionally equivalent. Future studies should conduct a sensitivity analysis on this aspect, including other construction elements potentially affected by varying the unobstructed height, such as partitions and ceilings [18]. Lastly, seismic loads were not considered, as the building was assumed to be in Brazil. We do not expect seismic loads to change our conclusions, since adding these loads would increase the concrete and steel intensities for all alternatives due to the introduction of more shear walls.

6. Conclusion

This study demonstrates that structural design decisions can alter the embodied carbon of reinforced concrete structures by up to a factor of 3.4, even when using essentially the same technology without major innovations, simply by varying the span between columns and the number of beams. Even when the span is predetermined by the architectural design, the choice of floor typology alone can alter the

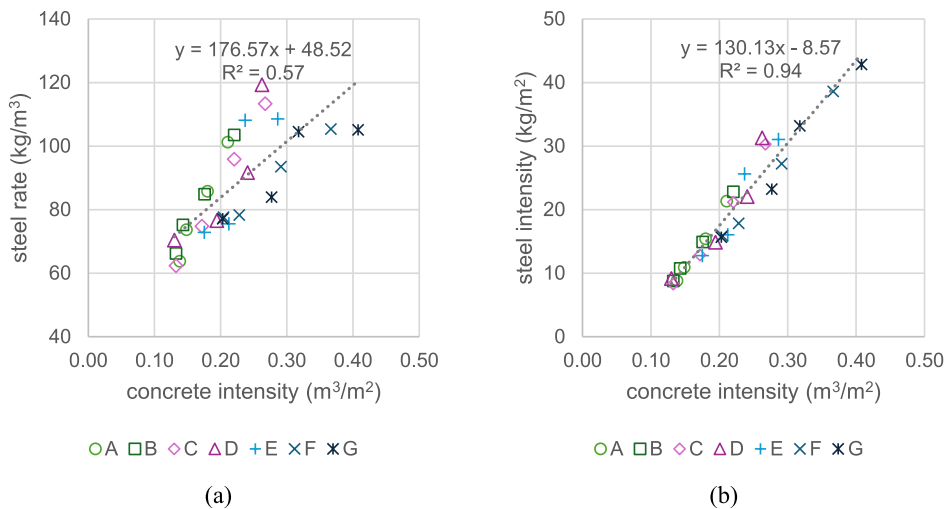


Fig. 7. Correlation between a) the steel rate and the concrete intensity and b) the steel and concrete intensities. Steel includes both rebars and tendons.

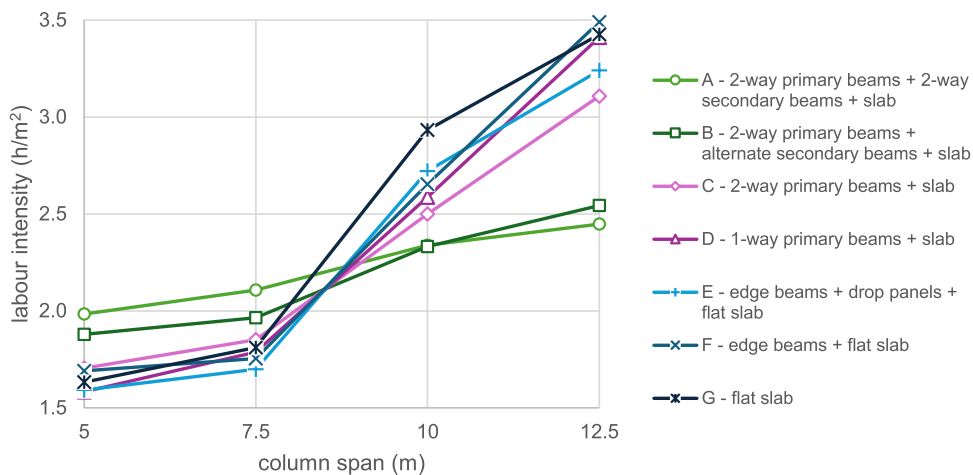


Fig. 8. Labour intensity by structural typology and span.

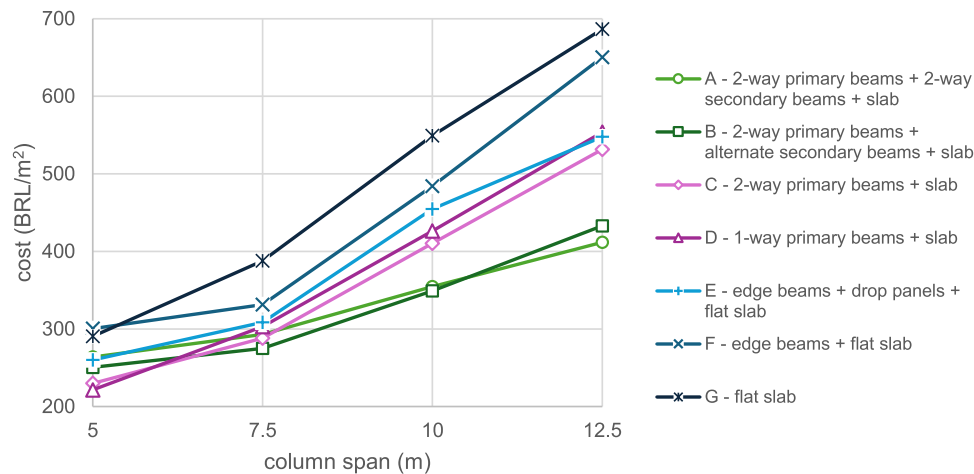


Fig. 9. Total cost (material and labour) by structural typology and span.

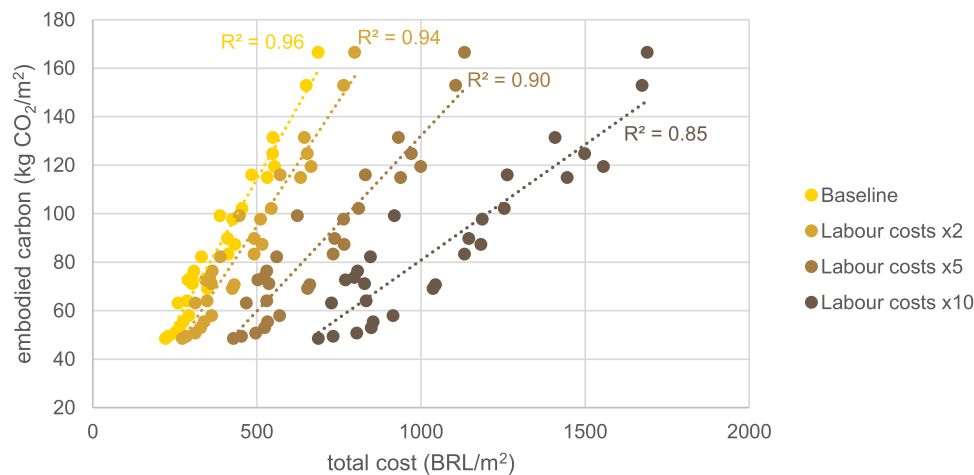


Fig. 10. Correlation between embodied carbon and cost intensity.

embodied carbon by up to a factor of 2, a level of variation much higher than previously reported. Beams offer significant material and embodied carbon savings, while flat slabs are consistently more material- and carbon-intensive. Despite requiring more complex formwork, floor typologies with more beams are not only environmentally preferable but also more cost-effective than flat slabs due to lower material use. These findings remain robust even under scenarios with increased labour costs.

Our results challenge the widespread adoption of flat slabs in reinforced concrete structures, especially in contexts where this practice is not yet dominant and skilled labour remains available, such as in Brazil. While flat slabs may be favoured for their faster construction times, our findings suggest that prioritising speed may come at a high environmental cost. Rather than only optimising flat slab systems, research and practice should also explore strategies to enable broader adoption of more efficient typologies, such as improving beam formwork methods or rethinking construction timelines to support lower-carbon outcomes.

Ultimately, the significant differences in embodied carbon between floor typologies underscore the crucial role of structural design in mitigating the environmental and economic impacts of buildings. Structural engineers, though rarely recognised as part of the sustainability workforce, hold significant leverage in climate change mitigation. This study provides practical insights and evidence that low-carbon, cost-effective designs are not only feasible but also readily achievable with existing technology.

CRediT authorship contribution statement

Cassio Gomes de Oliveira: Writing – original draft, Formal analysis. **Gustavo Fortes:** Writing – original draft, Methodology, Formal analysis. **Vanderley M John:** Writing – review & editing, Supervision, Conceptualization. **Leila Cristina Meneghetti:** Writing – original draft, Supervision, Conceptualization. **Ricardo Leopoldo e Silva França:** Writing – review & editing, Supervision. **Matheus Carvalho:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Fernanda Belizario-Silva:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 4.0 and Microsoft Copilot with the exclusive purpose of improving readability and language. After using these tools, the authors reviewed and edited the content and take full responsibility for the content of the publication.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.istruc.2025.109427](https://doi.org/10.1016/j.istruc.2025.109427).

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