Influence of floor system and column spacing on embodied CO_2 of a reinforced concrete structure

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Summary
The embodied carbon (EC) of the building industry represents 9% of global greenhouse gas emissions, most of which contributed by structures. Therefore, the impact of structural design parameters on the EC of buildings requires further investigation. This paper assesses the effect of 7 different types of floor systems and two column grid spacings (5.0x5.0m and 10.0x10.0m) on the embodied CO_2 of a four-story reinforced concrete building, comprising 14 buildings designed according to Brazilian standards. Cradle-to-gate CO_2 emissions of concrete, rebar, unbonded tendons and formwork were modelled using Brazilian life cycle data. Results show emissions ranging from 48 to 131 kg CO_2/m^2, with smaller grid spacing and the combination of beams and thinner slabs helping to reduce the emissions when compared to flat slabs. Findings emphasize the significant impact of structural design parameters on carbon emissions, highlighting the potential contribution of structural engineers in decarbonization efforts.

1 INTRODUCTION

Reinforced concrete structures contribute significantly to buildings' embodied carbon [1], [2]. Therefore, the role of structural engineering in reducing carbon emissions is becoming increasingly relevant [3]. The major focus for embodied carbon mitigation has been material substitution [4] – [6] or reducing the embodied carbon of concrete materials [7]; however, these decisions rarely lie in structural engineers' hands. On the other hand, research on structural engineering for decarbonisation often focuses on advanced topics such as topology optimization and 3D printing [8], [9] or complex formwork [10]; or only proposes generic frameworks to mitigate the carbon in reinforced concrete buildings [11]. The role of practical decisions, such as the selection of the floor system [12], in reducing the embodied carbon of reinforced structures during the conceptual design stage [13], [14] remains largely unexplored.

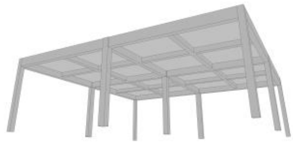
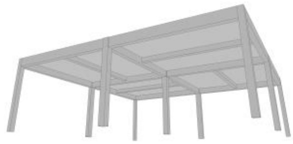
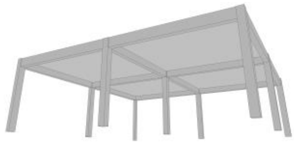
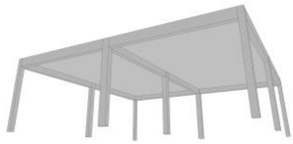
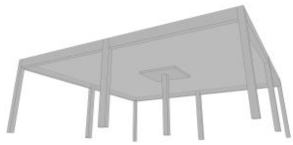
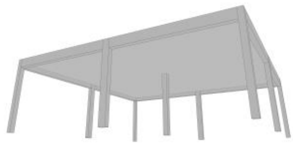
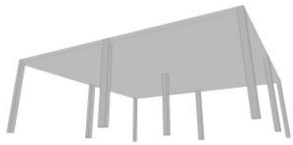
The present study examines how structural design decisions, such as the choice of floor typology and the definition of the span, impact the carbon emission of reinforced (and sometimes post-tensioned) concrete structures for a reference building. We compare the embodied carbon of seven distinguished floor typologies and two main spans (5.0m x 5.0m and 10.0m x 10.0m), providing insights for the structural engineers to develop more sustainable conceptual designs using available technology.

2 METHOD

2.1 Structures description

The fourteen structures analyzed in this study comprise two column grids (with 5.0 m x 5.0 m and 10.0 m x 10.0 m span between columns) and seven floor typologies (Table 1).

Table 1 Floor typologies analyzed in this study.

Typology	Description	Picture
A	Two-way primary beams + two-way secondary beams + slabs	
B	Two-way primary beams + alternate secondary beams + slabs	
C	Two-way primary beams + slabs	
D	One-way primary beams + slabs	
E	Flat slabs with drop panels + edge beams	
F	Flat slabs + edge beams	
G	Flat slabs without edge beams	

The analysed reference building has floor dimensions of 40 x 40 m (1600.0 m^2 floor area), 3.25 m floor-to-floor height, and four stories. It is a typical layout for garage parking or a warehouse.

2.2 Material description and embodied carbon

The adopted concrete characteristic compressive strength was 30 MPa (f_{ck} = 30 MPa), the rebar steel was grade CA-50 (characteristic yield stress of 500 MPa), and the unbonded tendons were considered with CP190-RB (characteristic yield stress of 1900 MPa with low relaxation).

The embodied carbon of each material was estimated using a simplified Life Cycle Assessment (LCA) approach [15]. The system boundary included the production of all materials required for building the structure (concrete, rebar, tendons and formwork for columns, beams and slabs), which is expected to contribute to a major part of the structural embodied carbon. Material transportation to the site and materials' wastage were not considered, as these aspects are beyond the structural designers' influence. The ground floor slab was not included as it would be the same for all options. Foundations were also not considered, although there could be some differences given the different dead loads.

The volume of concrete and the total weight of rebar and unbonded tendons were obtained directly from the structural design. The quantity of plywood and sawn wood for the formwork was estimated using information from cost breakdown structures provided by the Brazilian National System for Survey on Construction Costs and Indices (SINAPI) [16], considering four reuses. Embodied carbon data were retrieved from the Brazilian database Sidac [17], except for plywood where we used data from Environmental Product Declarations (EPDs). Table 2 shows the embodied carbon for each material.

Table 2 Material embodied carbon data.

Material	Embodied Carbon			Unit	Source
	minimum	midpoint	maximum		
Concrete (f_{ck} = 30 MPa)	228	284	339	$kgCO_2/m^3$	[18]
Rebar Steel grade CA50	0.43	0.74	1.06	$kgCO_2/kg$	[18]
Unbonded tendons (CP190 RB)	1.9	2.3	2.6	$kgCO_2/kg$	[19]
Sawn wood, raw, dried	16.7	26.0	35.3	$kgCO_2/m3$	[18]
Plywood	7.9	9.1	10.4	$kgCO_2/m2$	[20], [21]
Beams formwork	6.1	7.3	8.4	$kgCO_2/m^2$	[18], [16]
Slabs formwork	2.8	3.3	3.7	$kgCO_2/m^2$	[18], [16]
Columns formwork	0.1	0.2	0.3	$kgCO_2/m^2$	[18], [16]

The minimum and maximum values for embodied carbon indicated in Table 2 represent different manufacturers and manufacturing processes within the Brazilian territory. The midpoint, that was chosen as representative value, is simply an arithmetic mean between maximum and minimum values and is not the mean of embodied carbon producers in Brazil.

2.3 Standards and design parameters used

The buildings were designed to comply with Brazilian standards [22] – [25]. Table 3 shows the considered floors, wind, cladding and walls loads on buildings. The fire resistance class was 60 minutes under standard fire exposure.

Table 3 Loads considered in the structural design.

	Dead load (floor) [kN/m²]	Live load (floor) [kN/m²]	Exterior walls + cladding [kN/m]	Wind load (mean pressure over the facade) [kN/facade m²]
Intermediate floors	1.0	2.5	2.7	0.54
Top floor	3.0	3.0	1.9	0.54

2.4 Design procedure

Each building was designed and detailed by the authors. The development of conceptual design and detailing of structure was made to comply with the Brazilian standards and according to authors expertise in structural engineering. A schematic approach to design the buildings is illustrated in Fig. 1.

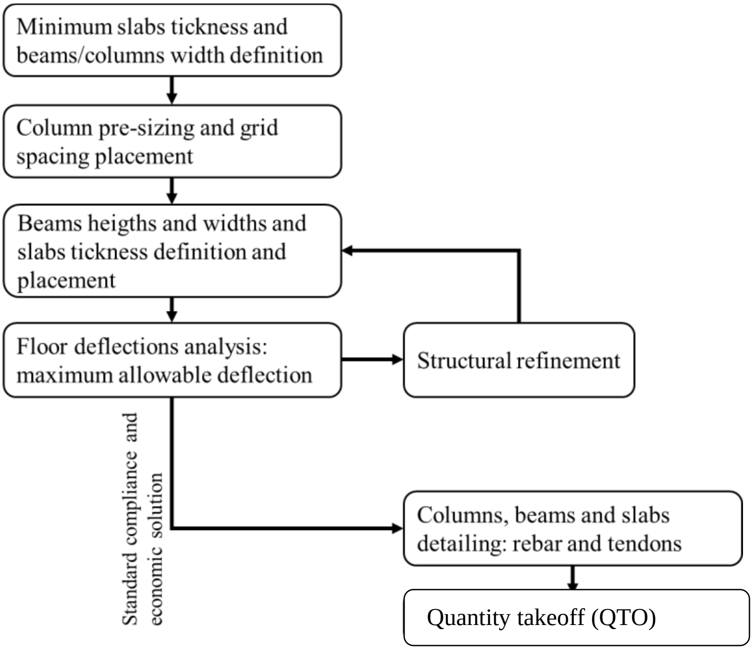


Fig. 1 Scheme for structural design procedure

TQS® software (Brazilian commercial software for reinforced concrete structural design) was used to design all structures and provide materials quantities, such as concrete volume, rebar / unbonded tendons weight, and formwork area.

3 RESULTS

Fig. 2 shows the embodied carbon of all typologies analyzed in this study. The shaded area indicates the results range considering the minimum and maximum values for materials' embodied carbon. Overall, the results vary between 38 $kgCO_2/m^2$ (for the 5.0m span of typology D: One-way primary beams + slabs with minimum embodied carbon for each material) to 160 $kgCO_2/m^2$ (for the 10.0m span of typology G: Flat slabs with maximum embodied carbon for each material). The highest value (worst scenario for material and structural decisions) is 4.2 times higher than the lowest value (best scenario for material and structural decisions). Considering only the midpoint values, the difference between the lowest and the highest embodied carbon results corresponds to 2.5 times, meaning structural design decisions can more than double the embodied carbon for the same building. The material choice can potentially increase the embodied carbon by up to 60%.

The results show that some typologies are more sensitive to the span between columns than others. For instance, typologies A and B increased their embodied carbon by 34% and 36%, respectively, when shifting from a 5.0 to 10.0m span. In contrast, typologies C, D, and G increased their embodied carbon by 82%, 102%, and 81%, respectively. The typology and span choice impact the embodied carbon more than the material choice. The decision between typologies results in an increase of 2% up to 90% in embodied carbon, and the span increase (from 5.0m to 10.0m) causes a variation from 34% to 102% in embodied carbon.

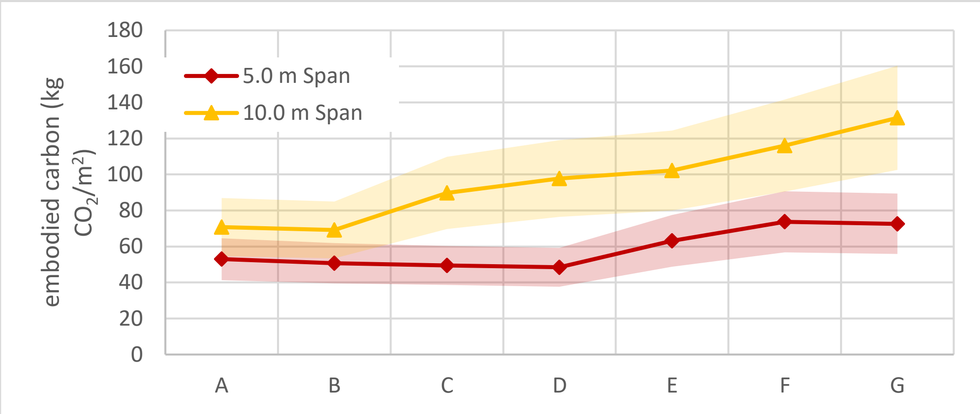


Fig. 2 Embodied carbon results for the different typologies and spans.

Fig. 3 shows the contribution of the different structural elements to the total structural embodied carbon, based on midpoint values for the materials' embodied carbon. The results show that slabs are the prevailing element, contributing at least 45% of total embodied carbon but reaching up to 98%. On the other hand, columns only represent 3.9% to 8.8% of total embodied carbon in these buildings. The joint impact of beams and slabs in the beam-supported typologies (A-D) is lower than the impact of slabs (and edge beams, where applicable) in flat slab typologies (E-G). Furthermore, for a 10.0m span, the joint impact of beams and slabs for typologies A and B is lower than that of impacts C and D, showing that, for this span, secondary beams help to reduce the embodied carbon. The results also show that the columns' impact increases for typologies E, F, and G. This is due to the lack of beams helping to withstand lateral loads, which need to be resisted by the columns.

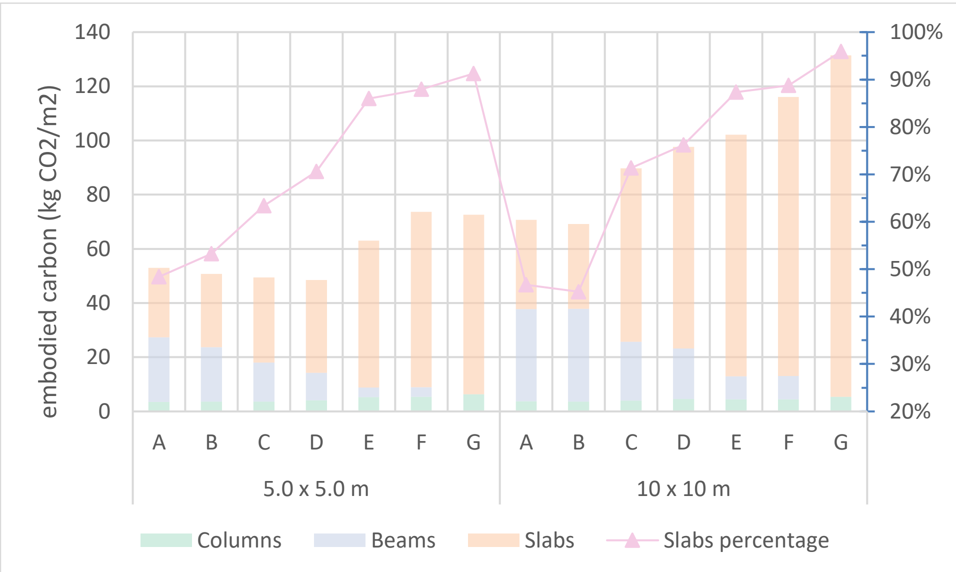


Fig. 3 Embodied carbon per element (based on midpoint values for materials' embodied carbon).

Another relevant aspect to guide structural engineers' decisions is the embodied carbon associated with each material, which is shown in Fig. 4. Concrete alone contributes 66% to 79% of total embodied carbon. Tendons for post-tensioning have a non-negligible impact for typologies C-G for a span of

10.0m (9% to 20%). Despite reducing rebar quantity, these tendons have 3 times higher embodied carbon than conventional rebar. Formwork contributes little to structural embodied carbon.

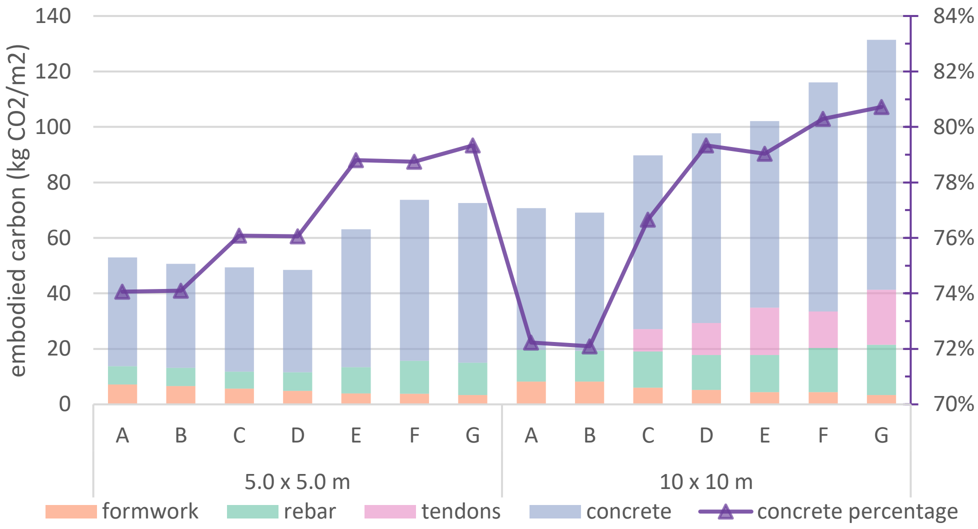


Fig. 4 Embodied carbon per material.

Fig. 5 and Fig. 6 show, respectively, how the equivalent concrete thickness and the steel intensity vary among the typologies. From Fig. 5 we see that the reduction in concrete consumption by removing the beams (in typologies E, F, and G) is significantly surpassed by the increase in slab thickness to withstand the loads. For the 10.0 m span, slab thickness also increases for typologies with primary beams only (C and D) compared to those with secondary beams (A and B). Not only does the concrete consumption increase in the floor systems but also the steel required by beams and slabs, as shown in Fig. 6. Moreover, for the 10.0 m span, typologies without secondary beams require post-tensioning, further increasing their steel consumption and corresponding carbon footprint.

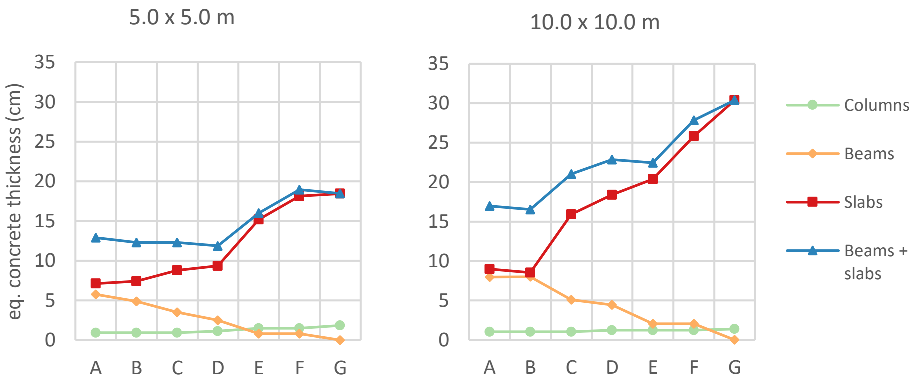


Fig. 5 Equivalent concrete thickness, or concrete intensity, by typology and span.

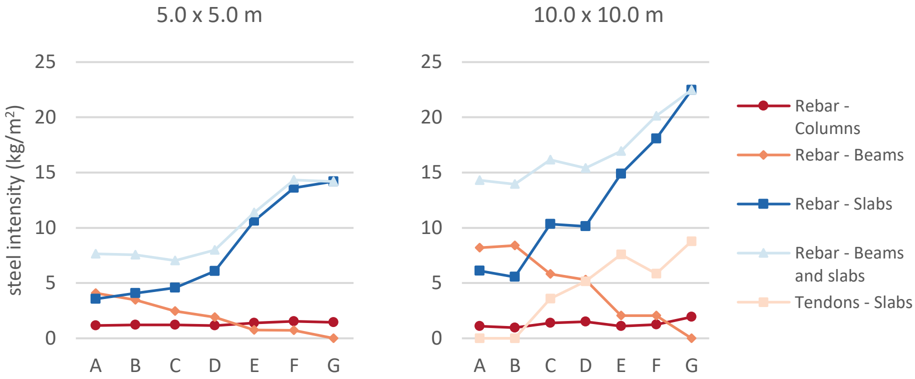


Fig. 6 Steel intensity, including rebar and tendons, by typology and span.

4 CONCLUSION

The present study has shown that architectural and structural decisions such as the definition of spans and floor typology significantly influence structural embodied carbon. The midpoint results ranged between 48 and 131 kgCO_2/m², mainly because of the variation in concrete consumption among the alternatives, as well as due to the use of post-tensioning for larger spans. Design decisions that result in less concrete may lead to better environmental solutions. Regarding the contribution of the different structural elements to embodied carbon, slabs represent the highest percentage. Therefore, beam-structured floors, with thinner slabs, are recommended to reduce concrete consumption and embodied carbon in reinforced concrete structures.

While spans are usually defined by the architectural design, floor systems choice depends on architectural, site and/or construction restrictions. Our results demonstrate the significant dematerialization and decarbonization potential underlying the choice of structural floor systems, a decision usually taken by structural engineers in mutual agreement with the constructor. Therefore, we encourage these stakeholders to consider this choice among the possibilities to improve the environmental performance of buildings with reinforced concrete structures and, consequently, foster a more sustainable built environment.

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