XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

Analysis of the Cost and CO_2 Emission in the Optimum Design of Trussed Composite Floor System Considering Floor Vibrations

[1]Chayana Morgner G. Silva, [1]Adenilcia Fernanda G. Calenzani, [1]Carolina Casotti R. Oliveira, [1]Élcio Cassimiro Alves

[1]*Dept. of Civil Engineering, Federal University of Espírito Santo*
Avenue Fernando Ferrari, 514, 29075-910, Vitória/ES, Brazil
chayana@edu.ufes.br, afcalenzani@ufes.br, carolina@edu.ufes.br, elcio.alves@ufes.br

Abstract. In recent decades, the pursuit of more cost-effective and environmentally sustainable construction methods has become increasingly important to lower expenses in the construction sector and reduce greenhouse gas emissions. Among the available alternatives, composite floor systems with tubular truss configurations stand out as a promising solution due to their ability to cover larger spans while using less steel compared to conventional systems. This study proposes the formulation of a topological optimization model for composite floor systems consisting of tubular trusses and steel deck slabs with additional reinforcement, taking floor vibration effects into account. The optimization focused on minimizing both CO_2 emissions and the overall costs of the floor system. To solve the problem, the Particle Swarm Optimization (PSO) algorithm was applied. The proposed approach was validated by comparison with examples from the literature that adopted different beam configurations. The findings revealed that using concrete-filled tubular trusses can significantly reduce emissions and costs. The most efficient solutions involved slabs with added reinforcement and upper chords filled with high-strength concrete (above 35 MPa), which contributed minimally to the system's environmental impact and total cost.

Keywords:

1 Introduction

With the advancement of the construction sector worldwide and the need to reduce greenhouse gas emissions from this industry due to the high consumption of steel and concrete, the search for environmentally and economically friendly structural systems has become necessary. Despite its socioeconomic benefits, in 2019 the construction industry was responsible for emitting 12 $GtCO_2$-eq, representing 21% of global greenhouse gas emissions. Additionally, in 2021, the sector accounted for 31% of global energy demand (Calvin et al. [1], IPCC [2]). Previous studies indicate that the environmental impacts caused by the construction sector (Bilec et al. [3]; Gonçalves and Haddad [4]; Lassio et al. [5]; Singh et al. [6]) have driven the pursuit of sustainable systems within the industry and among professionals in the field (Barba et al. [7]; Bissoli-Dalvi [8]).

Despite the progress made in proposed solutions using solid-web beams, Silva et al. [9] point out that studies on systems composed of tubular trussed beams remain limited. Floor systems composed of tubular trussed beams have the advantage of spanning longer distances at a lower cost than other beam typologies, as noted by Amorin et al. [10].

The literature still lacks optimization studies that integrate cost and CO_2 emission analyses for floor systems, especially those employing tubular trusses with concrete-filled top chords, while also considering the effects of floor vibration and the optimization of composite steel-concrete slabs. So far, no studies have been found that simultaneously address all these aspects. In light of this gap, the present work aims to formulate the structural optimization problem for these systems, incorporating the possibility of concrete filling in the top chord and the effects of vibration due to human walking. The proposed optimization problem considers as objective functions the minimization of both floor costs and CO_2 emissions. To solve

this problem, the Particle Swarm Optimization (PSO) algorithm was employed and implemented with the adaptive penalty method (APM), as proposed by Barbosa and Lemonge [11].

2 The Optimization Problem Formulation

The design variables of the optimization problem are presented in Figure 1, where x_1, x_7, x_{11} represent upper chord of secondary, girder and edge trusses, respectively; x_2, x_8, x_{12} represent lower chord of secondary, girder and edge trusses, respectively; x_3, x_9, x_{13} represent diagonals of secondary, girder and edge trusses, respectively; x_4 represents the truss height; x_5 and x_{14} represent the number of panels of secondary and edge trusses; x_6, x_{10}, x_{14} represent the filled concrete of of secondary, girder and edge trusses, respectively; x_{16} represents the choose of steel deck formwork; x_{17} the number of secondary beams; x_{18} represents the choose of slab's f_{ck}; x_{19} additional reinforcement; x_{20} the thickness of concrete slab and x_{21} the steel deck thickness.

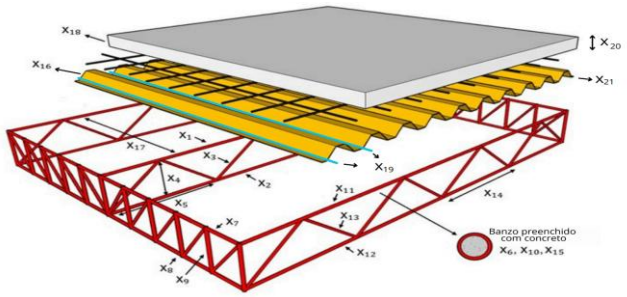


Fig. 1. Design Variables of Composite Floor with Composite.

The objective of the problem is to minimize the environmental impacts (CO_2 emissions) or the economic impacts (final costs), separately, characterizing a single-objective problem. With this purpose, the Equations (1) and (2) present the objective functions for minimizing CO_2 emissions and costs, respectively, to the floors with composite trussed beams and composite slabs.

$$CO_2 = CO_{2(slab)} + CO_{2(conc_up_sec)} + CO_{2(steel_trusses)} + CO_{2(steel_deck)} + CO_{2(additional_{reinf})} + CO_{2(connector)} + CO_{2(conc_up_girder)} + CO_{2(mesh)} \quad (1)$$

$$COST = COST_{(slab)} + COST_{(conc_up_sec)} + COST_{(steel_trusses)} + COST_{(steel_deck)} + COST_{(additional_{reinf})} + COST_{(conc_up_girder)} + COST_{(mesh)} \quad (2)$$

The variables $CO_{2(slab)}$, $CO_{2(\text{conc_up_sec})}$, $CO_{2(\text{steel_trusses})}$, $CO_{2(\text{steel_deck})}$, $CO_{2(\text{additional_reinf})}$, $CO_{2(\text{connector})}$, $CO_{2(\text{conc_up_girder})}$ and $CO_{2(mesh)}$ refer the emission and the variables $COST_{(slab)}$, $COST_{(\text{conc_up_sec})}$, $COST_{(\text{steel_trusses})}$, $COST_{(\text{steel_deck})}$, $COST_{(\text{additional_reinf})}$, $COST_{(\text{connector})}$, $COST_{(\text{conc_up_girder})}$ and $COST_{(mesh)}$ refer, respectively, to the costs of the slab concrete, the infill concrete of the upper chord of the secondary trusses (internal and edge), the profiles of the internal, edge, and main trusses, the steel formwork, the additional reinforcement, the shear connectors, the infill concrete of the upper chord of the main trusses, and the crack control mesh. The Table 1 shows all the adopted design constraints.

Table 1. Constraints

Description		Constraints	
ELU	Normal and compressive force on the upper chord of the trusses	$\frac{N_{Sd,bs}}{N_{c,Rd}} - 1 \leq 0$	(3)
	Normal and compressive force on the lower chord of the trusses	$\frac{N_{Sd,bi}}{N_{t,Rd}} - 1 \leq 0$	(4)

	Normal and compressive force on the diagonals of the trusses	$\frac{N_{Sd,dm}}{N_{c,Rd}} - 1 \leq 0$	(5)
	Combined bending in the upper chord of the trusses	$\begin{cases} if\ \frac{N_{Sd,ac}}{N_{Rd}} \geq 0.2 \Rightarrow\ \frac{N_{Sd,ac}}{N_{Rd}} + \frac{8}{9}\frac{M_{Sd,ac}}{M_{Rd}} - 1 \leq 0 \\ if\ \frac{N_{Sd,ac}}{N_{Rd}} < 0.2 \Rightarrow \frac{N_{Sd,ac}}{2\ N_{Rd}} + \frac{M_{Sd,ac}}{M_{Rd}} - 1 \leq 0 \end{cases}$	(6)
	Shear connectors	$\frac{n_{total,cs}}{n_{máx,cs}} - 1 \leq 0$	(7)
	Bending moment of composite section	$\frac{M_{Sd,composite}}{M_{Rd}} - 1 \leq 0$	(8)
	Bending moment	$\frac{M_{Sd}^{+}}{M_{Rd}^{+}} - 1 \leq 0$	(9)
	Longitudinal shear	$\frac{V_{Sd}}{V_{l,Rd}} - 1 \leq 0$	(10)
	Vertical shear	$\frac{V_{Sd}}{V_{v,Rd}} - 1 \leq 0$	(11)
ELS	Vertical displacement	$\frac{\delta_{Total}}{\delta_{Adm}} - 1 \leq 0$	(12)
	Peak acceleration	$\frac{a_p}{a_{p,lim}} - 1 \leq 0$	(13)
	Response Factor	$\frac{R}{R_{máx}} - 1 \leq 0$	(14)

The emission and costs parameters of each material adopted in the problem contained in Silva's [12] master's dissertation.

3 Numerical Results

The example proposed by Poitras et al. [13] features a composite floor system with dimensions of 10 m × 12 m, with secondary beams (internal and edge beams) arranged in the direction of the longer span, as shown in Figure 3. The loading conditions adopted as design parameters were 1.6 kN/m² for dead loads and 4.8 kN/m² for live loads. To account for loads from adjacent spans and external walls, additional line loads were applied to the edge beams and girders: 4 kN/m (dead and live loads) on the edge beams, and 12 kN/m (dead load) and 20 kN/m (live load) on the main beams. Poitras et al. [13] analyzed the vibration behavior of the composite slab system supported by solid-web beams, considering only the cost objective function.

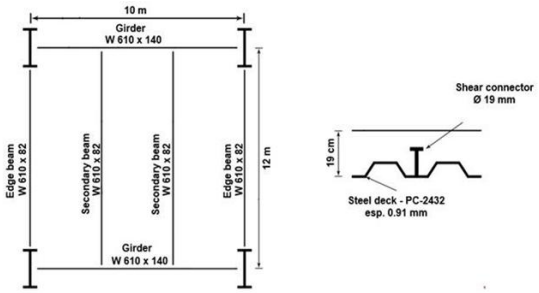
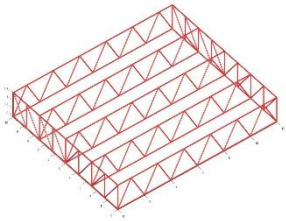
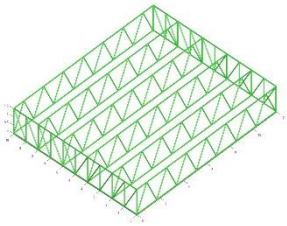
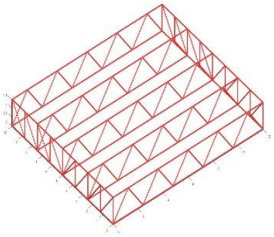
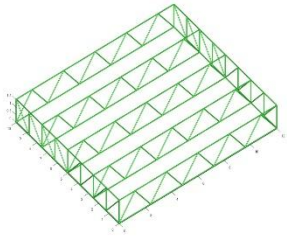
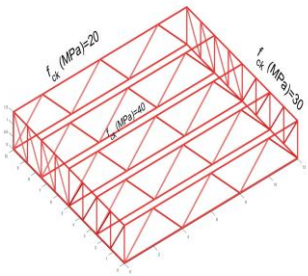
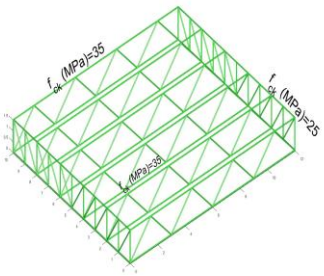
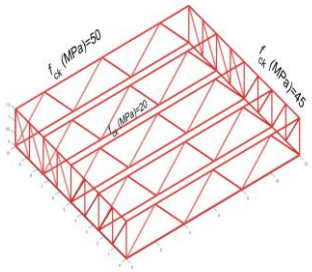
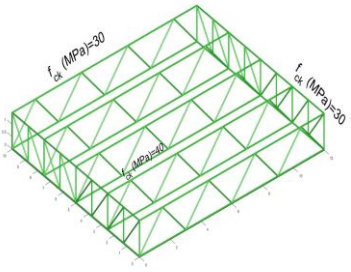


Fig. 2 Solution presented by Poitras et al. [13] via PSO.
Source: Poitras et al. [13].

In this example, the composite slab system supported by composite tubular trusses was analyzed using both the cost objective function and the CO_2 emission objective function, considering the top chord as a hollow steel tube filled with concrete. The final geometries are presented in Table 2.

Table 2. Final Geometries

Description	Cost Optimization	CO_2 Emission Optimization
CHT – Manufacturer's composite slab		
CHT – Optimized composite slab		
CCFT – Manufacturer's composite slab		

CCFT – Optimized composite slab		
Note: In the CHT solution, the top chord of the truss is not filled with concrete. In the CCFT solution, the top chord is filled with concrete. The "Manufacturer's composite slab" refers to the configuration provided by the supplier, while the "Optimized composite slab" refers to a configuration obtained through optimization procedures.		

It can be observed that, for the solutions with the top chord filled with concrete, the concrete strengths reached the maximum value for the edge truss when optimizing the slab and the cost. The use of concrete-filled steel tubes allowed for a reduction in their dimensions, minimizing both CO_2 emissions and the total cost of the structure when compared to the results of Poitras et al. [13], even with truss heights around 1.50 m, as presented in Table 3.

Table 3. Profiles of the truss beams from the optimal solutions and Poitras et al. [13].

	PROFILE	OBJECTIVE FUNCTION	SLAB DESIGN METHOD	INTERIOR TRUSSS PROFILE (mm)	EDGE TRUSS PROFILE (mm)	GIRDER PROFILE (mm)	TRUSS HEIGHT	Nº. PANELS	FINAL EMISSIOS ($kgCO_2$)	FINAL COST (BRL)
Poitras et al (2011) - PSO	**Solid web**	**COST**	**OT**	W610x82	W610x82	W610x140	-	-	13723.22	106611.89
Authors - PSO	**Tubular Profile (CHT)**	**CO_2**	**MANUF**	TC 73.0 x 5.0 TC 60.3 x 4.5 TC 38.1 x 4.0	TC 73.0 x 3.6 TC 73.0 x 3.6 TC 38.1 x 4.0	TC 73.0 x 5.0 TC 114.3 x 5.0 TC 88.9 x 4.0	150	7	7574.77	46059.14
			OT	TC 114.3 x 4.0 TC 88.9 x 4.0 TC 48.3 x 4.0	TC 101.6 x 4.0 TC 101.6 x 4.0 TC 48.3 x 3.6	TC 114.3 x 4.0 TC 101.6 x 6.4 TC 88.9 x 3.6	150	5	7557.66	45700.59
		COST	**MANUF**	TC 114.3 x 4.0 TC 88.9 x 3.6 TC 48.3 x 4.0	TC 73.0 x 4.0 TC 88.9 x 3.6 TC 48.3 x 3.6	TC 101.6 x 4.0 TC 114.3 x 5.6 TC 60.3 x 5.6	150	6	7535.09	45506.38
			OT	TC 73.0 x 5.0 TC 101.6 x 4.0 TC 48.3 x 4.5	TC 88.9 x 3.6 TC 101.6 x 4.0 TC 48.3 x 4.0	TC 73.0 x 4.5 TC 114.3 x 5.6 TC 101.6 x 4.0	150	5	8509.94	45048.47
	Tubular profile (CCFT)	**CO_2**	**MANUF**	TC 101.6 x 4.0 TC 60.3 x 3.6 TC 48.3 x 3.6 fck = 35 MPa	TC 73.0 x 3.6 TC 33.4 x 3.2 TC 48.3 x 3.6 fck = 25 MPa	TC 73.0 x 4.5 TC 101.6 x 4.0 TC 88.9 x 4.0 fck = 35 MPa	150	4	7432.49	44331.87
			OT	TC 88.9 x 3.6 TC 88.9 x 3.6 TC 60.3 x 3.6 fck = 40 MPa	TC 73.0 x 4.0 TC 33.4 x 3.2 TC 48.3 x 4.0 fck = 30 MPa	TC 73.0 x 6.4 TC 101.6 x 4.5 TC 73.0 x 4.5 fck = 30 MPa	145	4	7104.87	41797.67
		COST	**MANUF**	TC 114.3 x 4.5 TC 60.3 x 3.6 TC 48.3 x 5.0 fck = 40 MPa	TC 101.6 x 4.0 TC 33.4 x 3.2 TC 48.3 x 4.5 fck = 30 MPa	TC 88.9 x 4.0 TC 114.3 x 4.0 TC 88.9 x 3.6 fck = 20 MPa	150	3	7354.82	43529.31
			OT	TC 88.9 x 4.0 TC 101.6 x 4.0 TC 48.3 x 5.0 fck = 20 MPa	TC 88.9 x 4.0 TC 33.4 x 3.2 TC 60.3 x 3.6 fck = 45 MPa	TC 73.0 x 5.6 TC 114.3 x 4.0 TC 73.0 x 4.5 fck = 50 MPa	150	3	7582.48	38278.26

LEGEND:		
	CHT	CHT: Hollow Circular Profile
	CCFT	Concrete-Filled Circular Tube
	CO2	Objective Function for CO_2 Emission Minimization
	COST	Objective Function for Cost Minimization
	MANUF	Manufacturer Slab
	OT	Slab Designed According to ABNT NBR 8800:2024

Tables 4 and 5 present the final configurations of the slab and the corresponding floor, respectively, for the solutions obtained using the slabs provided by the manufacturer and for the solutions in which the slabs were optimized.

When comparing the optimized solutions with the solution proposed by Poitras et al. [13], a significant reduction in the thickness of the concrete topping of the slab is observed. On the other hand, the number of secondary beams increased, consequently reducing the spacing between beams in all analyzed cases.

Table 4. Comparative analysis of the solutions with the manufacturer's composite slab

Data	Unit	Poitras et al. (2011)	Author (2025) MANUF - CHT		Author (2025) MANUF - CCFT	
		PSO	CO2	COST	CO2	COST
Total Slab Height	cm	19	11	11	11	11
Concrete Topping Thickness	cm	11.4	6	6	6	6
f_{ck} of concrete slab	MPa	20	20	20	25	25
Steel formwork	--	PC 2432	MF 50	MF 50	MF 50	MF 50
Steel Formwork Thickness		0.91	0.8	0.8	0.8	0.8
Maximum Span of Steel Formwork	m	3.33	2	2.5	2	2.5
Crack Control Mesh	--	-	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150× 150)	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)
Number of Beams	un	4	6	5	6	5
Beam spacing	m	3.33	2	2.5	2	2.5
Total Number of Edge Truss Connectors	un	55	12	10	12	10
Total Number of Internal Truss Connectors	un	64	25	25	25	25
Total Number of Main Truss Connectors	un	64	84	84	84	84

Table 5. Comparative analysis of the solutions with optimized composite slabs

Data	Unit	Poitras et al. (2011)	Author (2025) OT - CHT		Author (2025) OT - CCFT	
		PSO	CO2	COST	CO2	COST
Total Slab Height	cm	19	10	12.5	10	10
Concrete Topping Thickness	cm	11.4	5	7.5	5	5
f_{ck} of concrete slab	MPa	20	20	35	25	35
Steel formwork	--	PC 2432	MF 50	MF 50	MF 50	MF 50
Steel Formwork Thickness		0.91	0.8	0.8	0.8	0.8
Maximum Span of Steel Formwork	m	3.33	2.5	2.5	2.5	2.5
Crack Control Mesh	--	-	Q-75 (ø3.8 - 150 × 150)	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)	Q-75 (ø3.8-150 × 150)
Number of Beams	un	4	5	5	5	5
Beam spacing	m	3.33	2.5	2.5	2.5	2.5
Total Number of Edge Truss Connectors	un	55	15	10	15	30
Total Number of Internal Truss Connectors	un	64	30	20	30	30
Total Number of Main Truss Connectors	un	64	63	78	63	25
Additional Reinforcement (%)		-	0.0005	0.0015	0.0005	0.001

Comparing Table 4 and Table 5, it can be noted that, for the CO_2 emission minimization objective, there was a reduction of 1 cm in the concrete topping thickness when the optimization of the composite slab was also considered. Conversely, concrete topping thicknesses of approximately 8 cm were obtained for CHT and CCFT profiles for the cost minimization objective. Furthermore, similar results were observed across the different cases. It is worth noting that the slab optimization did not lead to significant improvements in the reduction of CO_2 emissions or the costs of the composite slab, although it resulted in higher computational cost (processing time). Figures 3 and 4 present the normalized solutions for the emission and cost optimization cases, respectively, compared with the solution proposed by Poitras et al. [13].

It is observed that, even when considering the vibration analysis, the composite floor system with tubular composite trusses shows a significant reduction (around 48%) in final CO_2 emissions for the case involving trusses with a concrete-filled tube as the top chord, an optimized composite slab, and CO_2 emissions minimization (model OT CCFT CO_2). The other floor systems also exhibited reductions in CO_2 emissions, with values ranging from 38% (minimum) to 46% (maximum). Figure 5 presents the convergence history of the analyzed problems.

As shown in the convergence history in Figure 5, the cost and CO_2 emissions minimization functions exhibit parallel behavior across the scenarios analyzed without presenting any conflict between them. This indicates that, in a future multi-objective optimization of the system, a third objective function would be necessary to promote effective competition between the criteria.

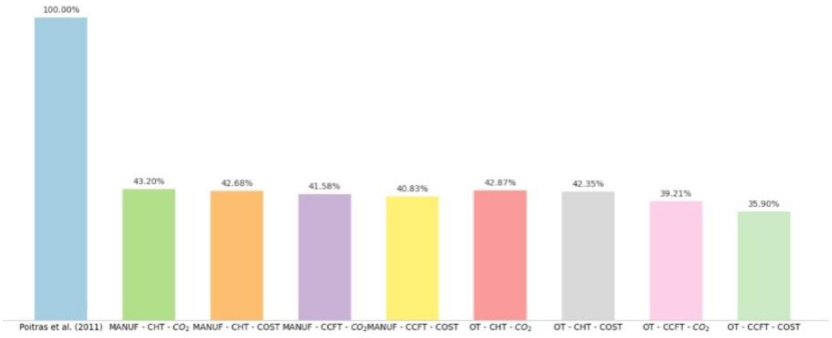


Fig. 3 Normalized total CO_2 emissions relative to the results of Poitras et al. [13]

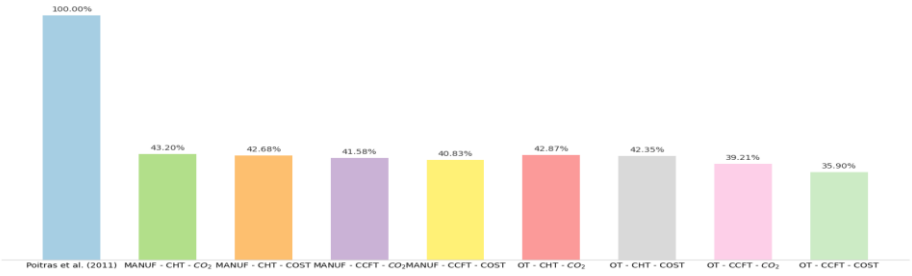


Fig. 4 Normalized solutions for total cost relative to the results of Poitras et al. [13]

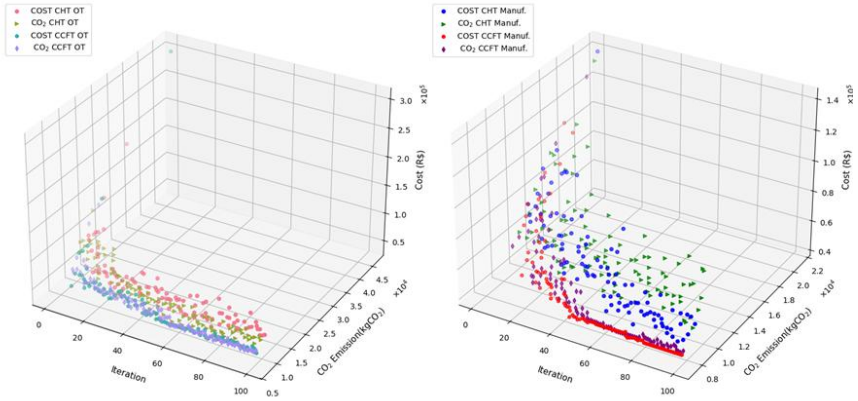


Fig. 5 Convergence History

4 Concluding Remarks

Based on the analyses, it can be concluded that the use of reinforcement bars in the slab and the use of filled tubes were the most effective solutions for the problem analyzed. It was observed that the reductions in the final solutions were over 40% in CO_2 emissions and over 50% in costs. This significant difference is possibly because the authors of the proposed problem did not optimize the number of secondary beams, as well as the formwork thickness and the concrete cover of the slab, which have a considerable impact on the final solution. Finally, it can be observed that the cost and emission functions exhibit a proportional behavior, indicating the need to introduce a third function for a possible analysis of the problem, considering a multi-objective optimization.

Acknowledgements. The author would like to thank CAPES for the support given to the postgraduate program in civil engineering at UFES and FAPES for the research grant provided to the second and fourth authors.

Authorship statement. The author hereby confirms that they are the sole liable persons responsible for the authorship of this work and that all material that has been included herein as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

References

[1] Calvin, K. et al. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. [s.l.] Intergovernmental Panel on Climate Change (IPCC), 25 jul. 2023. Disponível em: <https://www.ipcc.ch/report/ar6/syr/>. Acesso em: 17 nov. 2023.

[2] Intergovernmental Panel On Climate Change (IPCC). "Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change". 1. ed. [s.l.] Cambridge University Press, 2023.

[3] M. M. Bilec, R. J. Ries, H. S. Matthews, "Life-Cycle Assessment Modeling of Construction Processes for Buildings". Journal of Infrastructure Systems 2010, v. 16, n. 3, p. 199–205.

[4] J. G. L. Gonçalves, N. Haddad, "A. Life cycle assessment of building construction materials: case study for a housing complex". Revista de la construcción 2016, v. 15, n. 2, p. 69–77.

[5] J. Lassio et al. "Case Study: LCA Methodology Applied to Materials Management in a Brazilian Residential Construction Site". Journal of Engineering 2016, p. 1–9.

[6] A. Singh, et al. Review of Life-Cycle Assessment Applications in Building Construction. Journal of Architectural Engineering, v. 17, n. 1, p. 15–23, mar. 2011.

[7] D. J. Barba, J. O. Gomes, J. F. S. B. Lacerda, "Sustainability assessment in conventional and industrialized systems built in Brazil". Procedia CIRP 2015, v. 29, p. 144–149.

[8] M. Bissoli-Dalvi, "Ismas: A sustentabilidade como premissa para a seleção de materiais. Facultad de Arquitectura", Construcción y Diseño: Universidad del Bío-Bío, Bío-Bío, 2014.

[9] C. G. M. Silva, B. V. Afonso, I. O. M. Silva, A. F. G. Calenzani, e Alves E.C., "Analysis of CO2 Emissions in the Topological Optimization of Floor Systems Composed by Composite Trusses", em XLIV Ibero-Latin American Congress on Computational Methods in Engineering, Porto, nov. 2023.

[10] L. D. S. S. Amorim, L. D. Nitz, Silva, G. M. Chayana, S. M. P. Moraes, E. C. Alves, "Comparative analysis in the optimum design of composite floor system with different beams topologies". Innovative Infrastructure Solutions 2025, v. 10, p. 1-18.

[11] H. J. C. Barbosa e A. C. C. Lemonge, "An adaptive penalty scheme in genetic algorithms for constrained optimization problems", GECCO, vol. 2, p. 287–294, 2002.

[12] Silva, C. G. M. , Otimização Topológica de Pisos em Treliças Mistas Tubulares com Lajes Mistas: Análise de Custos e Emissões de CO_2, Dissertação de Mestrado, UFES, 2025.