Comparative Analysis of Solutions in the Optimal Design of Composite Floor Systems for Different Beam Topologies

Luciano Dal Secco Silveira Amorim[1], Chayana Gomes Morgner da Silva[1], Sayonara Maria de Moraes Pinheiro[1], Élcio Cassimiro Alves[1]

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

Abstract: This study aims to present a comparative analysis of different optimized solutions for a composite floor system, considering different beam topologies from the literature and proposed by the present article. To formulate the problem, both the environmental and the economic impacts of the composite floor system will be addressed, and the Bonobo Algorithm (BO) will be implemented for optimization. A member element with 2 nodes and 3 degrees of freedom per node has been implemented for structural analysis. Structural verification will be dictated by the guidelines prescribed by Brazilian standards for tubular structures, steel structures, and composite steel and concrete structures. The analysis of the solutions will assess the environmental (and economic, if specified) impact of each composite floor system proposed.

Keywords: Composite Floor, Composite Tubular Trusses, Bonobo, Cost, Environmental Impact

1 Introduction

The construction industry, responsible for high energy consumption and natural resource use, has been developing technologies to reduce its environmental impact. In this context, structural system optimization is emerging as an expanding area of study for proposing more efficient designs, particularly in the pursuit of optimal topology with reduced material consumption.

Among the tools for optimization, metaheuristic algorithms stand out as iterative methods that are easily implemented computationally and capable of determining values for multiple variables to minimize an objective function and find an optimal solution. Among the new metaheuristic algorithms proposed in the literature, the Bonobo Algorithm (BO), proposed by Das e Pratihar [1], stands out as a robust algorithm for solving problems with multiple discrete variables. Studies demonstrating the versatility of the algorithm can be found in the works of Goodarzimehr et al. [2], applied to the optimization of trusses, and Das et al. [3] for the application of the BO algorithm in the medical field for the development of orthopedic devices, indicating that the BO algorithm was efficient in obtaining various solutions for different problems compared to other optimization algorithms. Silva et al. [4] applied the BO to analyze CO_2 emissions for floor systems with cellular beams. Silva et al. [5] demonstrated the efficiency of the BO for the study of composite slabs when comparing the results with the Grey Wolf Optimization (GWO) algorithm and Particle Swarm Optimization (PSO).

The objective of this work is to perform a comparative analysis between the solutions proposed by Arpini et al. [6], who used the Genetic Algorithm (GA) to optimize a composite floor system supported by solid web beams; by Silva et al. [4], who utilized the Bonobo Algorithm (BO) to optimize the same system, but with the use of cellular beams; and those proposed by this study, which were also optimized using the Bonobo Algorithm, but with the use of tubular trusses and two different optimization parameter options, allowing for an approach considering both the environmental and economic aspects of the floor design.

2 Optimization Formulation Problem

2.1 Objective Function

Optimization can be performed based on two distinct objective functions, aiming to minimize one of two parameters: CO_2 emissions ($kgCO_2$) or the structure costs (R$). The objective functions are described, respectively, in Eq. (1) and Eq. (2):

$$Min\ CO_2 = CO_{2(formwork)} + CO_{2(conc.slab)} + CO_{2(conc.filled)} + CO_{2(mesh)} + CO_{2(connectors)} + CO_{2(trusses)} \quad (1)$$

$$Min\ COST = COST_{(formwork)} + COST_{(conc.slab)} + COST_{(conc.filled)} + COST_{(mesh)} + COST_{(connectors)} + COST_{(trusses)} \quad (2)$$

Where: $CO_{2(formwork)}$ and $COST_{(formwork)}$ refer to the CO_2 emissions and costs, respectively, generated by the steel deck formwork; $CO_{2(conc.slab)}$ and $COST_{(conc.slab)}$ correspond to the CO_2 emissions and costs, respectively, generated by the floor slab concrete; $CO_{2(conc.filled)}$ and $COST_{(conc.filled)}$ represent the total CO_2 emissions and costs resulting from the concrete filling of the upper chords of the truss, if filling is opted for; $CO_{2(mesh)}$ and $COST_{(mesh)}$ refer to the CO_2 emissions and costs generated by the reinforcing steel mesh; $CO_{2(connectors)}$ and $COST_{(connectors)}$ represent the CO_2 emissions and costs generated by the shear connectors used; and $CO_{2(trusses)}$ and $COST_{(trusses)}$ correspond to the total CO_2 emissions and costs generated by the girder, edge and internal truss profiles. Table 1 represents the CO_2 emissions and costs of each of the components and materials that compose the structural system to be optimized.

Table 1. Material costs and CO_2 emissions

Material	Characteristic	CO_2 Emission	Unit	Source	Cost	Unit	Source
Concrete	20 MPa	140.05	$kgCO_2/m^3$	Santoro and Kripka [7]	463.14	R$/m^3	SINAPI (2023) [9]
	25 MPa	149.26			474.87		
	30 MPa	157.65			491.01		
	35 MPa	171.64			504.22		
	40 MPa	182.14			518.15		
	45 MPa	194.7			532.09		
	50 MPa	225.78			546.02		
Circular profile	VMB350	1.12	$kgCO_2/kg$	World Steel Association [8]	4.5	R$/kg	Guimarães et al. [10]
Steel deck formwork (280 MPa)	MF50/0.80 mm	2.64			90.5	R$/m^2	Local supplier (2024)
	MF50/0.95 mm				107.64		
	MF50/1.25 mm				141.64		
	MF75/0.80 mm				99		
	MF75/0.95 mm				117		
	MF75/1.25 mm				154.48		
Reinforcing Steel Mesh	600 MPa	1.92			10.48	R$/kg	SINAPI (2023) [9]
Connectors	(ø19mm, 105mm)	0.23	$kgCO_2/m^3$		11.4	R$/unit	Cordeiro [11]

2.2 Design Variables

The design variables of the optimization problem for the composite floor system with composite trusses are presented in Fig. 1.

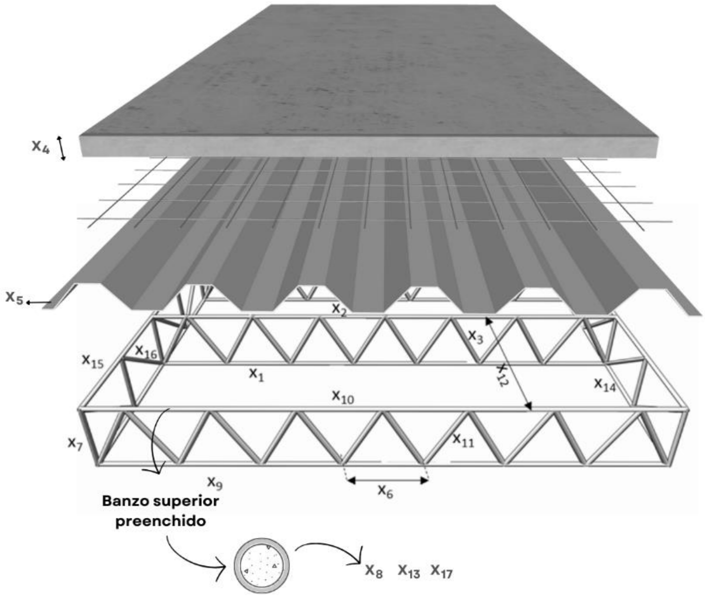


Figure 1. Design variables of the composite floor system with tubular composite trusses.

Where: x_1, x_2, x_3 represent the circular profiles of the lower chord, upper chord, and diagonals, respectively, of the internal trusses; x_4 refers refer to the compressive strength of the concrete (f_{ck}) of the concrete in the slab; x_5 is the thickness of the steel formwork; x_6: refers to the number of panels; x_7 corresponds to the height of the trusses; x_8, x_{13}, x_{17} refer to the f_{ck} used in the filling, if any, of the upper chord of the internal truss, edge truss, and girder, respectively; x_9, x_{10}, x_{11} correspond to the circular profiles of the lower chord, upper chord, and diagonals, respectively, of the edge trusses; x_{12} represents the span between internal trusses; x_{14}, x_{15}, x_{16} represent the circular profiles of the lower chord, upper chord, and diagonals, respectively, of the girder.

2.3 Constraints

For the topological optimization, the Ultimate Limit States (ULS) and the Serviceability Limit States (SLS) were considered, according to the Brazilian standards ABNT NBR 8800:2008 [12] and ABNT NBR 16239:2013 [13], as described in eq. (3) to eq. (7) in Tab. 2.

Table 2. Constraints imposed on the design of composite slabs with composite trusses.

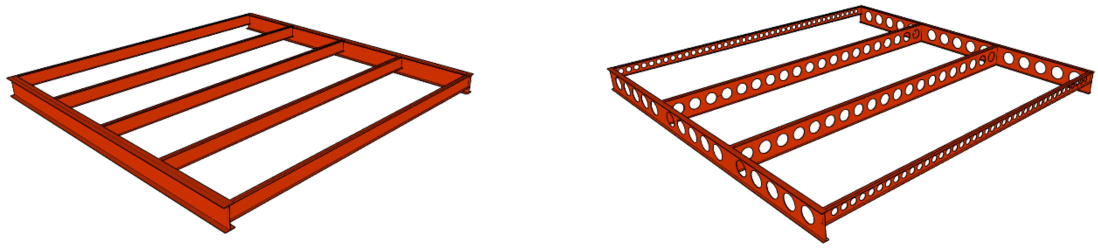
	DESCRIÇÃO	RESTRIÇÃO	
ULS	Axial force in the upper, lower, and diagonal chords, and verticals of the girder, edge, and internal trusses	$C(1) = \frac{N_{Sd}}{N_{Rd}} - 1 \leq 0$	(3)
	Combined bending in the upper chord of the girder, edge, and internal trusses	$C(2) = \begin{cases} if\ \frac{N_{Sd}}{N_{Rd}} \geq 0.2 \Rightarrow \frac{N_{Sd}}{N_{Rd}} + \frac{8}{9}\frac{M_{Sd}}{M_{Rd}} - 1 \leq 0 \\ if\ \frac{N_{Sd}}{N_{Rd}} < 0.2 \Rightarrow \frac{N_{Sd}}{2\,N_{Rd}} + \frac{M_{Sd}}{M_{Rd}} - 1 \leq 0 \end{cases}$	(4)
	Shear connectors	$C(3) = \frac{n_{total,cs}}{n_{máx,cs}} - 1 \leq 0$	(5)

	Composite section bending	$C(4) = \dfrac{M_{Sd,composite}}{M_{Rd}} - 1 \leq 0$	(6)
SLS	Vertical displacement	$C(5) = \dfrac{\delta_{Total}}{\delta_{Adm}} - 1 \leq 0$	(7)

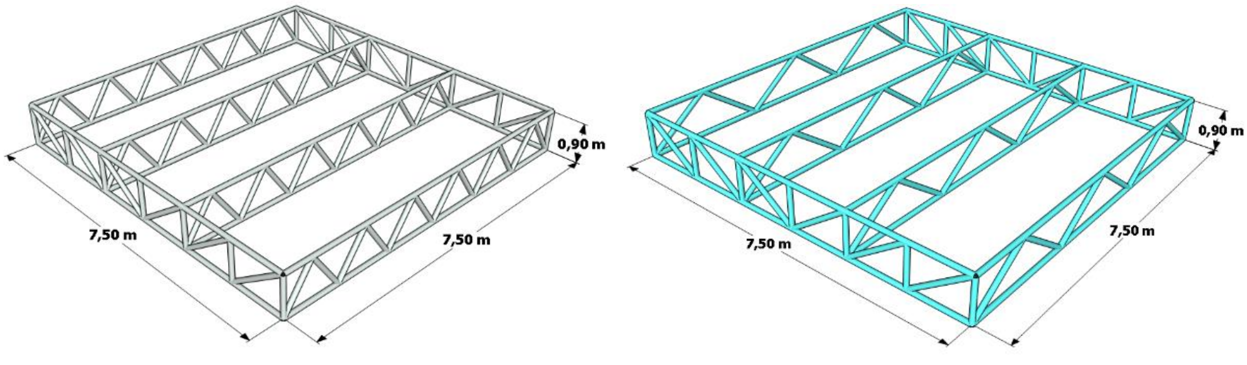
The first constraint $C(1)$ corresponds to the demanding and resistant normal forces for the upper chords, lower chords, diagonals, and verticals, before and after the curing of concrete in the girder, internal, and edge trusses. Constraint $C(2)$ relates to the combined verification due to demanding and resistant normal forces and bending moments, before and after concrete curing, for the upper chords of edge and internal trusses. Constraint $C(3)$ corresponds to the quantity of shear connectors in the girder, internal, and edge trusses. Constraint $C(4)$ refers to the limitation of composite trusses bending moments for calculation before and after curing for the composite section. Constraint $C(5)$ refers to the limitation of imposed displacements.

3 Results and Discussions

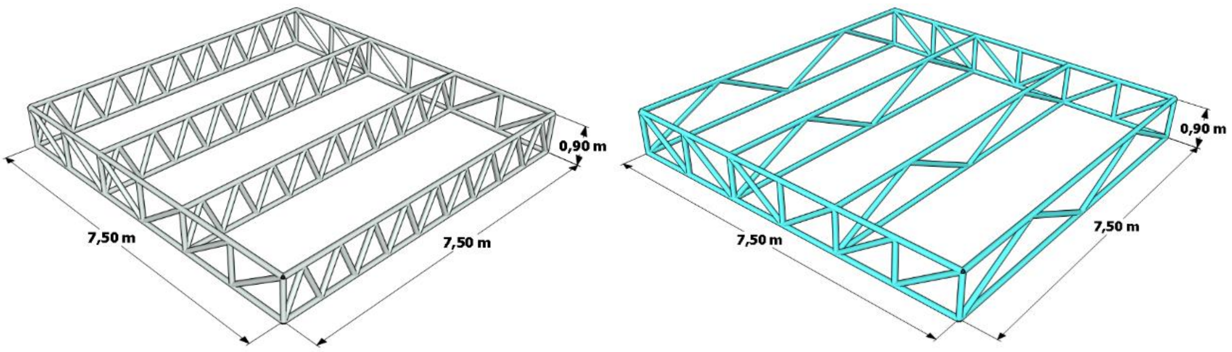
In the study conducted by Arpini et al. [6], an optimization of the composite floor system with dimensions of 7.50 m x 7.50 m, supported by full web beams, was proposed using a Genetic Algorithm (GA). Silva et al. [4] proposed an alternative solution for the span using the same floor system but supported by cellular beams and optimized via the Bonobo Algorithm (BO). Both studies aimed at minimizing CO_2 emissions from the structural system, as shown in eq. (1), while this study proposes solutions through optimization for both emissions and cost minimization. The steel considered for the beams in all solutions was ASTM GR 42 steel with a yield strength (f_y) of 345 MPa, and for the formwork, according to the Metform catalog [14], galvanized steel ASTM A653 with f_y of 280 MPa was used. The loading considered in the floor system includes the self-weight of the slab and beams, along with an accidental load of 5 kN/m^2. The optimal topological configurations of the floor system, considering the differences in proposed profiles in each study, are represented in Fig. 2. This study will analyze floors with circular hollow tubes (CHT) and trusses with the upper chord filled with concrete (CCFT).



(a) Full-web Beam – Arpini et al. [6] (b) Cellular Beam – Silva et al. [6]



(c) CHT (CO_2 Emissions Min.) – Authors (2024) (d) CCFT (CO_2 Emissions Min.) – Authors (2024)



(e) CHT (Cost Min.) – Authors (2024) (f) CCFT (Cost Min.) – Authors (2024)

Figure 2. Final topologies

Regarding the number of beams, the proposal by Arpini et al. [6] features five secondary beams, whereas the topologies proposed by Silva et al. [4] and this study feature only four beams, all with symmetric spacing between them. Regarding the beam topologies, it is also observed that the truss height (0.9 m) is greater in all cases compared to the height of the solid-web beam proposed by Arpini et al. [6] and the cellular beam proposed by Silva et al. [4]. All six solutions share the same characteristics for slab elements: MF 50 formwork with a thickness of 0.95 mm, 6 cm concrete cover, f_{ck} of 25 MPa, and reinforcing steel mesh Q-75 (ø3.8-150x150). The characteristics of the steel profiles for the six optimal solutions are detailed in Tab. 3 below.

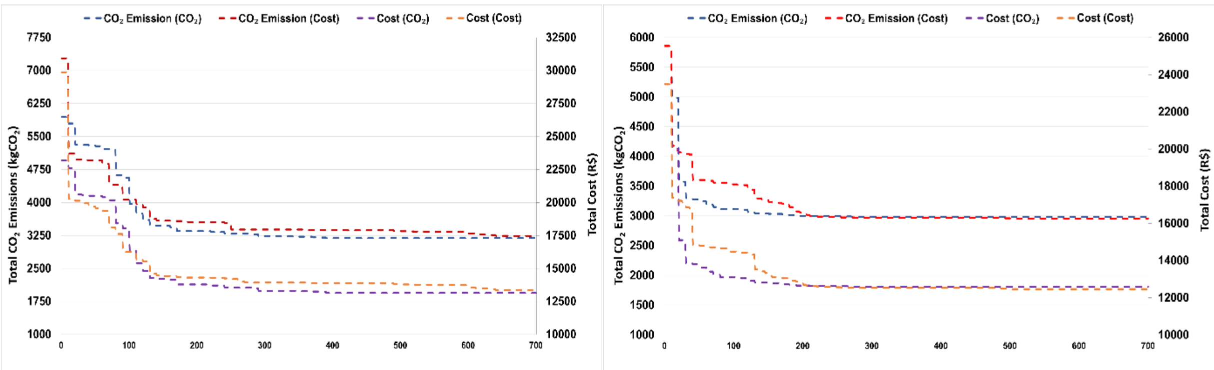
Table 3. Steel Profiles

	Shape of profile	Alg.	Min.	Edge Truss Profile(mm)	Internal Truss Profile (mm)	Girder Profile (mm)	Height (cm)	Nº Panels
Arpini et al. (2022) [6]	Full web Profile	GA	CO_2	W310x21	W310x21	VS450x51	--	--
Silva et al. (2024) [4]	Cellular	BO	CO_2	W150x13	W310x23.8	W310x28.3	--	--
Authors (2024)	Tubular Profile (CHT)	BO	CO_2	LC: TC38.1x3.6 UC: TC73.0x3.6 WM: TC33.4x3.2	LC: TC48.3x4.5 UC: TC48.3x3.6 WM: TC48.3x4.0	LC: TC48.3x3.6 UC: TC88.9x4.0 WM: TC33.4x3.6	90	6
			Cost	LC: TC38.1x4.0 UC: TC48.3x4.5 WM: TC33.4x3.2	LC: TC60.3x4.5 UC: TC101.6x4.0 WM: TC38.1x3.2	LC: TC48.3x3.6 UC: TC88.9x4.0 WM: TC33.4 x3.6	90	9
	Tubular Profile (CCFT)	BO	CO_2	LC: TC33.4x3.2 UC: TC33.4x3.2 WM: TC33.4x3.2 f_{ck}: 50 MPa	LC: TC48.3x4.5 UC: TC48.3x3.6 WM: TC48.3x4.0 f_{ck}: 30 MPa	LC: TC42.2x4.0 UC: TC60.3x4.0 WM: TC38.1x3.6 f_{ck}: 25 MPa	90	3
			Cost	LC: TC33.4x3.2 UC: TC33.4x3.2 WM: TC33.4x3.2 f_{ck}: 25 MPa	LC: TC48.3x4.5 UC: TC48.3x3.6 WM: TC 48.3x4.0 f_{ck}: 30 MPa	LC: TC42.2x3.6 UC: TC60.3x3.6 WM: TC 33.4x3.6 f_{ck}: 50 MPa	90	2

Table 3 highlights the differences in solutions found by the BO algorithm for circular profile trusses when using objective functions for cost and CO_2 emissions, particularly concerning the number of panels, as discussed earlier, and the concrete strength classes for the upper chord filling in CCFT. Additionally, for CHT, the emissions-minimizing optimization found a lower number of panels compared to cost optimization, while the opposite occurred for CCFT. The emissions optimization obtained the highest value for the f_{ck} of the concrete filling in the edge trusses and the lowest for the girder, while cost optimization found the opposite. In this analysis, Tab. 4 presents the final CO_2 emissions and final costs (when calculated) for each proposed optimal solution. For the ratio between normalized solutions, CO_2 emissions were considered as the comparison parameter. Figure 3 shows the convergence progress of the solutions for each of the four optimal solutions proposed in this study.

Table 4. Comparative analysis of CO_2 emissions and costs

	Shape of profile	Algorithm	CO_2 emissions	Cost	Ratio between normalized solutions (CO_2)
Arpini et al. (2022) [6]	Full web Profile	GA	4062.5	-	100%
Silva et al. (2024) [4]	Cellular	BO	3488.9	-	85.88%
Authors (2024)	Tubular Profile (CHT)	BO	3188.6 (Minimized)	13141.2	78.49%
			3240.6	13350.7 (Minimized)	79.77%
	Tubular Profile (CCFT)	BO	2985.5 (Minimized)	12591.8	73.49%
			2954.8	12466.4 (Minimized)	72.73%



(a) CHT – BO

(b) CCFT – BO

Figure 3. Optimization problem evolution.

By analyzing Tab. 4, it is observed that the solutions using tubular profile trusses showed a reduction in CO_2 emissions ranging from 20.2% to 27.3% compared to the solid-web profile solution proposed by Arpini et al. [6], and a reduction from 7.1% to 15.3% compared to the solution using cellular beams proposed by the study of Silva et al. [4]. The effectiveness of filling the upper chord of the trusses in reducing CO_2 emissions and the cost generated by the structure is also noteworthy, with both CCFT solutions showing lower emissions and costs than the CHT solutions. Regarding optimization, it is evident that for CHT, optimization using CO_2 emissions as the parameter to be minimized found a better solution than optimization using costs, while the opposite occurred for CCFT. This result suggests a difference in the effectiveness of the objective function for different proposed problems, encouraging the possibility of implementing a multi-objective optimization, with simultaneous minimization of two or more parameters in the search for solutions.

4 Conclusions

Based on the results obtained, a considerable improvement in the performance of the structure is observed, whether in environmental or economic aspects, when using tubular composite trusses compared to full web profiles and cellular beams. Additionally, the effectiveness of filling the upper chord with concrete is evident in accentuating this improvement. Regarding the objective functions, it is noted that optimization by minimizing CO_2 emissions and minimizing costs converges to similar solutions, suggesting the possibility of future implementation of multi-objective optimization by mutually complementing these minimizations.

Acknowledgements. The authors acknowledge the Brazilian Federal Government Agency CAPES and State Agency of Espírito Santo FAPES for the financial support provided during the development of this research. The fourth author thanks the State Agency of Espírito Santo FAPES for the productivity research grant.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work and that all material that has been herein included 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] A. K. Das and D. K. Pratihar, "Optimal preventive maintenance interval for a Crankshaft balancing machine under reliability constraint using Bonobo Optimizer," *Mechanisms and Machine Science*, vol. 73, pp. 1659–1668, 2019, doi: 10.1007/978-3-030-20131-9_164.

[2] V. Goodarzimehr, U. Topal, A. K. Das, and T. Vo-Duy, "Bonobo optimizer algorithm for optimum design of truss structures with static constraints," *Structures*, vol. 50, pp. 400–417, Apr. 2023, doi: 10.1016/j.istruc.2023.02.023.

[3] A. K. Das, S. Sahoo, and D. K. Pratihar, "An Improved Design of Knee Orthosis Using Self-Adaptive Bonobo Optimizer (SaBO)," *Journal of Intelligent and Robotic Systems: Theory and Applications*, vol. 107, no. 1, Jan. 2023, doi: 10.1007/s10846-022-01802-1.

[4] G. F. Silva, M. Kripka, and E. C. Alves, "CO2 emission optimization of composite floor systems with cellular beams via metaheuristics algorithms," *Structural Engineering and Mechanics*, vol. 89, pp. 1–14, 2024.

[5] I. O. M. Silva, M. O. Teixeira, É. C. Alves, and A. F. G. Calenzani, "Optimization of Continuous Composite Slabs via Bonobo Algorithm," *Brazilian Congress of Composite Structures (CBEM)*. 15, Apr. 2024.

[6] P. A. T. Arpini, M. C. Loureiro, B. D. Breda, A. F. Calenzani, and É. C. Alves, "Optimum design of a composite floor system considering environmental and economic impacts," *Revista IBRACON de Estruturas e Materiais*, vol. 15, no. 3, 2022, doi: 10.1590/s1983-41952022000300002.

[7] J. F. Santoro and M. Kripka, "Minimizing environmental impact from optimized sizing of reinforced concrete elements," *Computers and Concrete*, vol. 25, no. 2, pp. 111–118, 2020, doi: 10.12989/cac.2020.25.2.111.

[8] World Steel Association, "Life cycle inventory (LCI) study, 2020 data release." May 2020. Accessed: Nov. 13, 2023. [Online]. Available: https://worldsteel.org/wp-content/uploads/Life-cycle-inventory-LCI-study-2020-data-release.pdf

[9] SINAPI, Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil (SINAPI), Dezembro (2023)

[10] S. A. Guimarães, D. Klein, A. F. G. Calenzani, and É. C. Alves, "Optimum design of steel columns filled with concrete via genetic algorithm: environmental impact and cost analysis," *REM - International Engineering Journal.*, vol. 75, no. 2, pp. 117–128, 2022, doi: 10.1590/0370-44672021750034.

[11] F. C. R. Cordeiro, "Análise de produtividade da mão-de-obra e composição de custos do serviço de execução da laje steel deck," *Graduation thesis in civil engineering*, UFSC, Florianópolis, 2016.

[12] Associação Brasileira de Normas Técnicas, *NBR 8800: Projeto de Estruturas de Aço e de Estruturas de Aço e Concreto de Edifícios*. Rio de Janeiro, Rio de Janeiro: ABNT, 2008.

[13] Associação Brasileira de Normas Técnicas, *NBR 16239: Projeto de estruturas de aço e de estruturas mistas de aço e concreto de edificações com perfis tubulares*. Rio de Janeiro: ABNT, 2013.

[14] Metform, "Telha-fôrma (steel deck)." Accessed: Nov. 13, 2023. [Online]. Available: https://metform.com.br/wp-content/uploads/2022/08/Cata%CC%81logo-Steel-Deck-Ed.-2019.pdf