Optimization of Composite Tubular-Floor Trusses Considering Costs and Environmental Impacts

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Abstract: The objective of this study is to propose a formulation for the topological and dimensional optimization of composite floor systems, which comprise composite trusses while considering both the costs and environmental impacts resulting from the consumption of floor materials. To address this optimization problem, the Bonobo algorithm (BO) will be employed. For structural analysis, a member element with 2 nodes and 3 degrees of freedom per node has been implemented. Structural verification will adhere to the guidelines outlined in Brazilian standards for tubular structures, steel structures, and composite steel and concrete structures. The examples analyzed will be compared with those from the literature to evaluate solutions from economic and environmental perspectives and to identify the factors influencing these solutions.

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

1 Introduction

Civil construction has been advancing over the last few decades with new proposals for solutions for flooring systems, but studies that analyze the economic and environmental predictions of these new systems are scarce in the literature. In this context, the use of optimization techniques applied to the topology of floors can help define parameters that serve as choice criteria for designers.

Topology optimization research with metaheuristic algorithms is considered a procedure aiming to improve the performance of the structure through the search for the optimal topology of structural systems. For its application in the field of optimization, several algorithms are available in the literature, such as the Particle Swarm Algorithm (PSO) proposed by Eberhart and Kennedy [1]. This algorithm stands out for its easy computational implementation and for providing robust results in the search for the optimal solution.

Among the new optimization algorithms proposed, the Bonobo Algorithm (BO) developed by Das and Pratihar [2] also presents itself as a robust algorithm in the search for solutions to optimization problems with discrete variables and several restrictions. Recent studies such as those presented by Silva, Kripka, and Alves [3] for composite floors with cellular beams, Goodarzimehr et al. [4] applied to the optimization of trusses and Das, Sahoo and Pratihar [5] for the application of the BO algorithm in the area of medicine for the development of orthopedic devices, point out that the BO algorithm was efficient in obtaining different solutions for different problems facing to other optimization algorithms.

Studies involving the optimization of composite tubular-floor trusses are scarce in the literature, with only a study by Silva et al. [6] where CO_2 emissions from the materials used on the floor were analyzed.

Within this context, the objective of this work is to propose the formulation of the optimization problem of composite tubular-floor trusses with the upper flange filled or not with concrete to minimize the costs and CO_2 emissions of the materials for execution of the floor individually and compare the solutions. The solutions to the problem were obtained via the Bonobo algorithm (BO) and were compared with the results proposed in the literature.

2 Optimization Formulation Problem

2.1 Objective Function

The goal is to minimize CO_2 emissions or floor system costs. The objective functions to be optimized are described in eq. (1) (in $kgCO_2$) and in eq. (2) (in R$):

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

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

Where: $CO_{2(formwork)}$ and $COST_{(formwork)}$ represent CO_2 emissions and the cost, respectively, generated by the steel deck formwork; $CO_{2(conc.slab)}$ and $COST_{(conc.slab)}$ represent the CO_2 emission and the cost, respectively, generated by the concrete in the slab; $CO_{2(conc.filled)}$ and $COST_{(conc.filled)}$ represent the total CO_2 emission and the cost respectively generated by the concrete to fill the upper chords of the trusses for the cases adopted, otherwise their index is zero, $CO_{2(mesh)}$ and $COST_{(mesh)}$ correspond to the CO_2 emission and the cost respectively generated by the reinforcement mesh, $CO_{2(conectors)}$ and $COST_{(conectors)}$ correspond to the CO_2 emission and the cost respectively generated by all shear connectors used and, $CO_{2(trusses)}$ and $COST_{(trusses)}$ correspond to the total CO_2 emission and the cost respectively generated by the profiles of the girder and secondary trusses (internal and edge). The Table 1 presents the CO_2 emissions and costs of the components that compose the objective function.

Table 1. CO_2 emission and material costs

MATERIAL	**CHARACTERISTICS**	**CO_2 EMISSION** ($kgCO_2/m^3$)	**SOURCE**	**COSTS** (R$)	**SOURCE**
Concrete	20 MPa	140.05	Santoro and Kripka [7]	463.14	SINAPI (2023)
	25 MPa	149.26		474.87	
	30 MPa	157.65		491.01	
	35 MPa	171.64		504.22	
	40 MPa	182.14		518.15	
	45 MPa	194.70		532.09	
	50 MPa	225.78		546.02	
Tubular Steel	VMB350	1.12 ($kgCO_2/kg$)	World Steel Association [8]	4.50	Guimarães et al. [9]
Steel Deck Formwork (280 MPa)	MF50/0.80 mm	2.64 ($kgCO_2/kg$)		90.5	Local supplier (2024)
	MF50/0.95 mm			107.64	
	MF50/1.25 mm			141.64	
	MF75/0.80 mm			99.00	
	MF75/0.95 mm			117.00	
	MF75/1.25 mm			154.48	
Reinforcement Mesh	600 MPa	1.92 ($kgCO_2/kg$)		10.48	SINAPI (2023)
Stud Bolt	(ø19mm, 105mm)	0.23 $kgCO_2/m^3$		11.40	Cordeiro [10]

2.2 Design Variables

The design variables of the optimization problem of the composite tubular-floor trusses are presented in Figure 1.

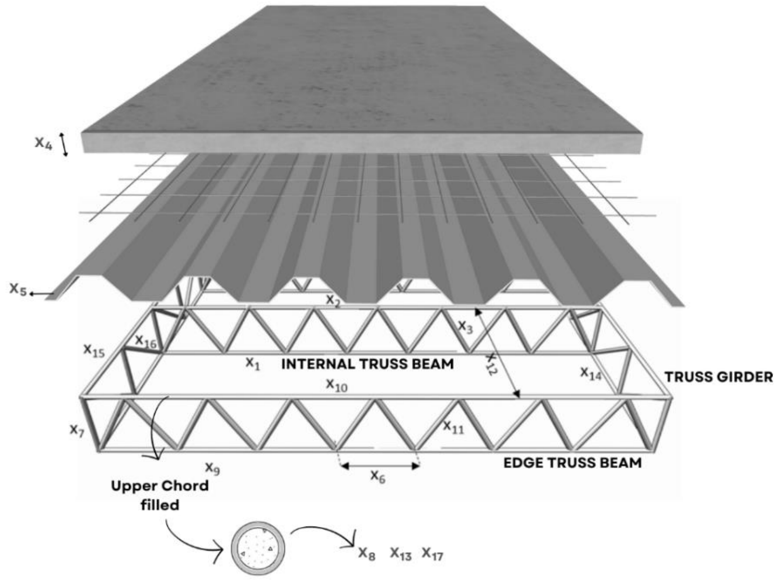


Figure 1. Design variables of the composite tubular-floor trusses

Where: x_1, x_2, x_3: refer to the circular profile of the lower and upper chords and web members of the internal trusses; x_4: refers to the f_{ck} of the slab concrete; x_5: refers to the thickness of the steel deck formwork; x_6: refers to the number of panels; x_7: refers to the height of the trusses; $x_8,\ x_{13},\ x_{17}$: refers to the f_{ck} of the concrete filling the upper chord of the internal, edge and girder truss, respectively; x_9, x_{10}, x_{11}: refer to the circular profile of the lower and upper chords and web members of the edge trusses; x_{12}: is the span between internal trusses; x_{14}, x_{15}, x_{16}: refer to the circular profile of the lower and upper chords and web members of the girder truss.

2.3 Constraints

For the topological optimization, the Ultimate Limit States and the Serviceability Limit State are described in eq. (3) to eq. (7) in the Table 2 that were considered according to ABNT NBR 8800:2008 [11] and ABNT NBR 16239:2013 [12].

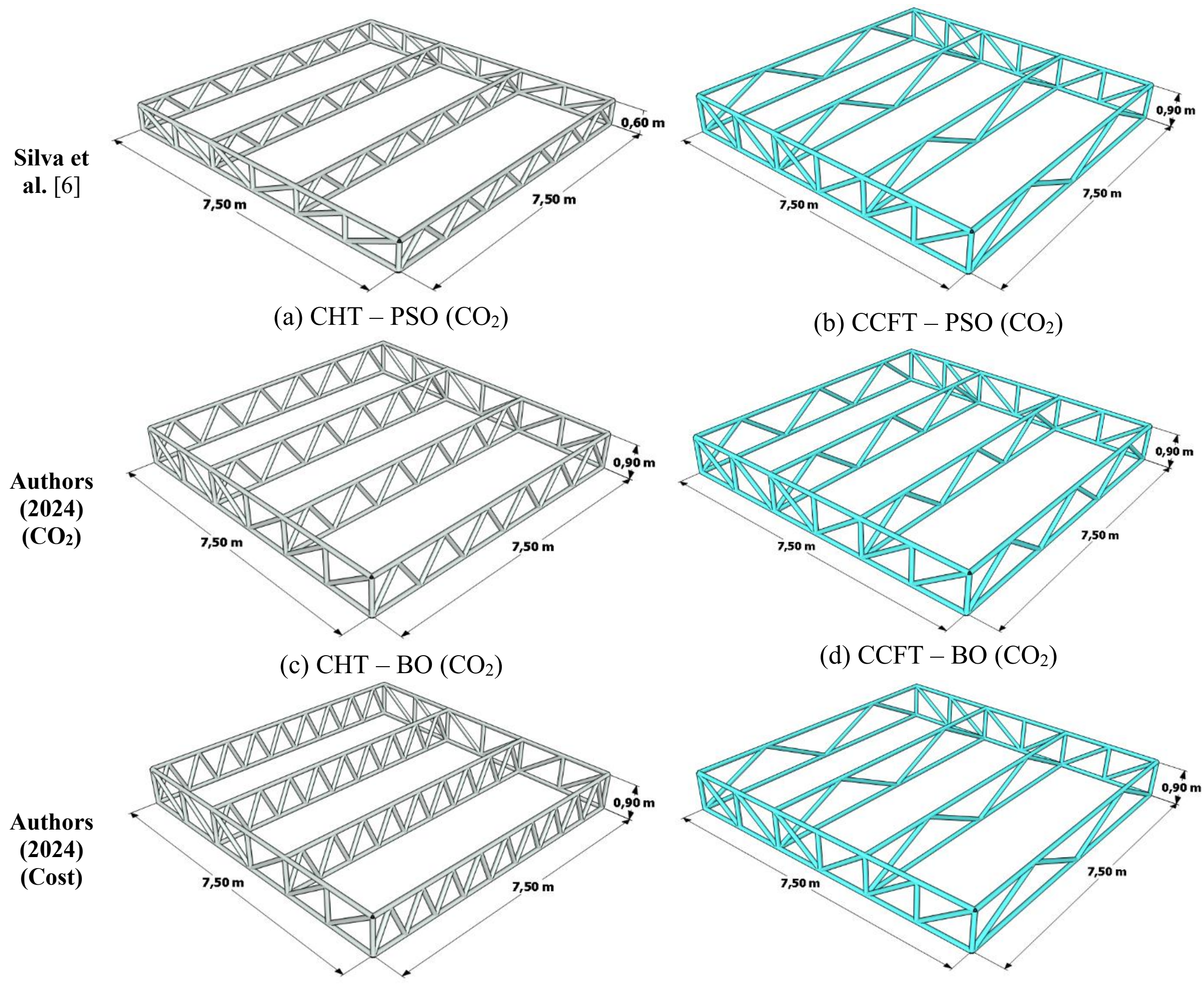
Table 2. Restrictions imposed on the design of composite tubular-floor trusses

	DESCRIPTION	RESTRICTION	
ELU	Normal force in the upper and lower chords and web members of the secondary trusses and girder	$C(1) = \frac{N_{Sd}}{N_{Rd}} - 1 \leq 0$	(3)
	Combined bending in the upper chord of the secondary trusses and girder	$C(2) = \begin{cases} if\ \frac{N_{Sd}}{N_{Rd}} \geq 0.2 \Rightarrow \frac{N_{Sd}}{N_{Rd}} + \frac{8}{9}\frac{M_{Sd}}{M_{Rd}} - 1 \leq 0 \\ if\ \frac{N_{Sd}}{N_{Rd}} < 0.2 \Rightarrow \frac{N_{Sd}}{2\,N_{Rd}} + \frac{M_{Sd}}{M_{Rd}} - 1 \leq 0 \end{cases}$	(4)
	Shear Connectors	$C(3) = \frac{n_{total,cs}}{n_{máx,cs}} - 1 \leq 0$	(5)
	Bending in the composite section	$C(4) = \frac{M_{Sd,composite}}{M_{Rd}} - 1 \leq 0$	(6)
ELS	Deflection	$C(5) = \frac{\delta_{Total}}{\delta_{Adm}} - 1 \leq 0$	(7)

The constraint $C(1)$ represents the analysis of the upper chord, lower chord, and web members, respectively before and after concrete curing of the girder and secondary trusses (internal and edge); the constraint $C(2)$ concerns the combined verification regarding the normal forces and the load-bearing and resistant bending moments, before and after curing of the concrete for the upper chords of the secondary trusses (internal and edge); the constraint $C(3)$ refers to the number of stud bolt of the girder and secondary trusses (internal and edge); the constraint $C(4)$ represents the composite section analysis of the trusses before and after curing of the concrete and $C(5)$ represents the analysis of limit total deflection.

3 Results and Discussions

In the study proposed by Arpini et al. [13] the optimization of the composite floor system measuring 7.5 m x 7.5 m was performed using full web beams via Genetic Algorithm (GA). Silva et al. [6] analyzed the same floor using tubular trusses with the solution obtained via PSO. In the study proposed by Silva et al. [6] only parameters were raised regarding the CO_2 emission of the floor system, with gains above 20% in reducing the final emission of the floor when using concrete-filled tubes when compared to full web beams. The authors considered ASTM GR 42 steel with f_y of 345MPa for the profiles of the beams and steel deck formwork from the Metform catalog [14] produced with galvanized steel ASTM A653 and f_y of 280 MPa. The loading included the self-weight of the slab and the steel structure, in addition to a live load of 5 kN/m². Figure 2 presents the topological configuration of the floor system obtained in the optimal solution for both, CO_2 emissions and cost, via the BO algorithm and compared with the solution proposed by Silva et al. [6].



(a) CHT – PSO (CO_2)

(b) CCFT – PSO (CO_2)

(c) CHT – BO (CO_2)

(d) CCFT – BO (CO_2)

(e) CHT – BO (Cost)

(f) CCFT – BO (Cost)

Figure 2. Finals Topologies

The final topology of the trusses found by the BO algorithm optimizing CO_2 emissions, described as BO (CO_2), for the hollow circular tube (CHT) presents the same configuration obtained by Silva et al. [6] applying the PSO (CO_2) algorithm, with four secondary trusses and six panels, showing an increase only in the final height of the trusses, from 60 cm to 90 cm. For the concrete-filled circular tube (CCFT), it was observed that there was only an increase in the number of secondary truss panels, from two to three. For optimization considering the reduction of system costs, described as BO (Cost), note that for the CHT there was also an increase in the height of the truss (60 cm to 90 cm) as well as an increase in the number of secondary truss panels (6 to 9). For the CCFT it is observed that the BO (Cost) obtained the same configurations found by PSO (CO_2). The BO algorithm in all solutions found also maintained the reduction of 1 secondary beam (5 to 4). Furthermore, all solutions for slab configuration were the same as those obtained by Silva et al. [6], the form being MF 50 with a thickness of 0.95mm, a concrete layer of 6 cm, f_{ck} of 25 MPa, and a reinforcement mesh of Q-75 (ø3.8-150 × 150). For the secondary trusses (internal and edge) 16 connectors were needed each and 8 connectors for the girder truss. Table 3 presents the steel profiles obtained in the optimal truss solution via BO (CO_2) and BO (Cost), compared with the solution by Silva et al. [6].

Table 3. Steel profiles comparative solutions

Shape of profile	Alg.	Edge Truss Profile(mm)	Internal Truss Profile (mm)	Girder Profile (mm)	Height (cm)	Nº Panels
CHT Silva et al. [6]	PSO (CO_2)	LC:TC38.1x4.0	LC: TC88.9x3.6	LC:TC60.3x3.6	60	6
		UC:TC73.0x3.6	UC: TC88.9x5.0	UC:TC88.9x5.0		
		WM:TC33.4x3.2	WM:TC38.1x3.6	WM:TC33.4x3.6		
CHT Authors (2024)	BO (CO_2)	LC: TC38.1x3.6	LC: TC48.3x4.5	LC: TC48.3x3.6	90	6
		UC: TC73.0x3.6	UC: TC48.3x3.6	UC: TC88.9x4.0		
		WM:TC33.4x3.2	WM:TC48.3x4.0	WM:TC33.4x3.6		
	BO (Cost)	LC: TC38.1x4.0	LC: TC60.3x4.5	LC: TC48.3x3.6	90	9
		UC: TC48.3x4.5	UC: TC101.6x4.0	UC: TC88.9x4.0		
		WM: TC33.4x3.2	WM: TC38.1x3.2	WM: TC33.4 x3.6		
CCFT Silva et al. [6]	PSO (CO_2)	LC:TC33.4x3.2	LC:TC42.2x5.0	LC:TC38.1x4.0	90	2
		UC:TC33.4x3.2	UC:TC48.3x3.6	UC:TC60.3x3.6		
		WM:TC33.4x3.2	WM:TC42.2x4.5	WM:TC33.4x3.6		
		f_{ck}: 25 MPa	f_{ck}: 35MPa	f_{ck}: 40 MPa		
CCFT Authors (2024)	BO (CO_2)	LC: TC33.4x3.2	LC: TC48.3x4.5	LC: TC42.2x4.0	90	3
		UC: TC33.4x3.2	UC: TC48.3x3.6	UC: TC60.3x4.0		
		WM:TC33.4x3.2	WM:TC48.3x4.0	WM:TC38.1x3.6		
		f_{ck}: 50 MPa	f_{ck}:30 MPa	f_{ck}: 25 MPa		
	BO (Cost)	LC: TC33.4x3.2	LC: TC48.3x4.5	LC: TC42.2x3.6	90	2
		UC: TC33.4x3.2	UC: TC48.3x3.6	UC: TC60.3x3.6		
		WM: TC33.4x3.2	WM: TC 48.3x4.0	WM: TC 33.4x3.6		
		f_{ck}:25MPa	f_{ck}:30MPa	f_{ck}:50		

As can be seen in Table 3, the BO algorithm found different solutions for the profiles of hollow and concrete-filled tubes when compared to the results of Silva et al. [6], as well as the f_{ck} of the filling concrete. It is also verified that the solutions obtained from the point of view of cost and emissions were different for the final profiles found.

Figure 3 presents a comparison of the final emissions and costs of the solutions obtained and Figure 4 presents the convergence graph of the solutions.

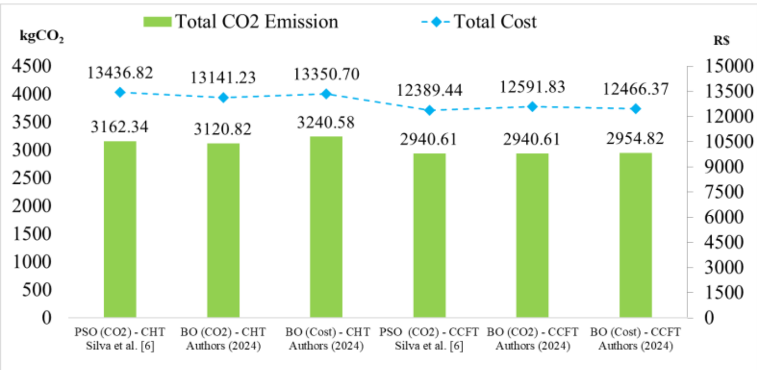
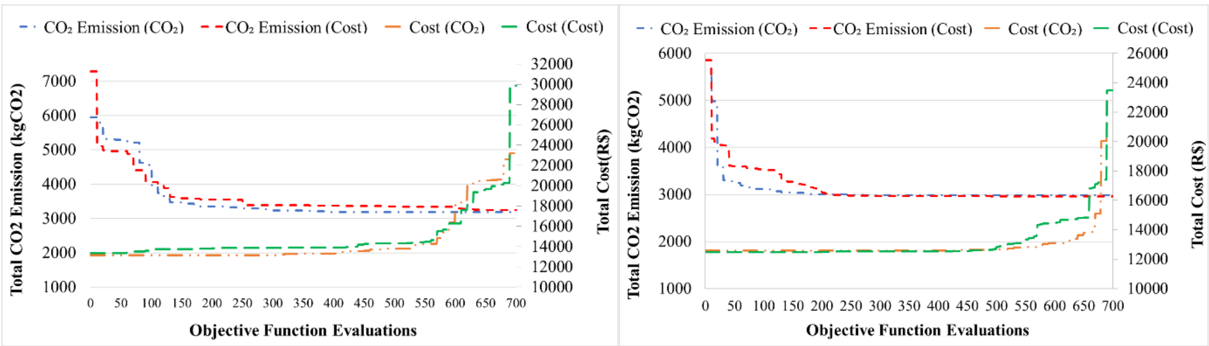


Figure 3. Comparative analyses of the solutions to the total CO_2 emission



(a) CHT BO (b) CCFT BO

Figure 4. Evolution of the optimization problem

According to Figure 3, the total CO_2 emission showed a reduction of around 1.30% for the CHT profiles in the BO (CO_2) optimization, and for the BO (Cost) optimization, it showed an increase of less than 2.50%. For the CCHT profiles, the solution found for the BO (CO_2) optimization presented the same emission as Silva et al. [6]. Although the solution obtained for both algorithms is the same, the BO algorithm presented a lower standard deviation of 1.2%, while the PSO presented a standard deviation of 4%. In the BO (Cost) optimization for CCHT profiles, there was an increase in emissions of less than 0.50%. Regarding costs, it can be observed that for the CHT profiles, there was a reduction for both BO (CO_2) and BO (Cost) optimization, around 2.20% and 0.70%, respectively. However, for the CCFT profiles, a non-significant increase is observed, around 1.70% and 0.70%, respectively, for the BO (CO2) and BO (Cost) optimization. Regarding the behavior of the problem for analyzing costs and emissions, it can be seen in the convergence graph that the curves are parallel, opening a field of study on multi-objective optimization by adding to the problem some function that competes with the two studied in this work.

4 Conclusions

From the results obtained, it can be seen that cost optimization and CO_2 emissions are not competing functions, presenting the same behavior in the trajectory of the objective function. Furthermore, it is observed that the cost optimization of the composite tubular-floor trusses, when compared to the optimization of CO_2 emissions, did not result in significant savings and that although the geometric solutions of the profiles are different, the solutions found were practically the same when comparing the final values of the solutions from an economic and environmental point of view. The BO algorithm had great behavior with values similar to or better than the PSO, presenting a smaller standard deviation in the solutions, thus demonstrating effectiveness in the search for a solution to the problem.

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