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Multi-Objective Optimization of Steel and Concrete Tubular Composite Columns

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Abstract. With the increasing trend of building verticalization, the demand for more efficient cross-sections of structural elements has become essential. Within this context, the use of concrete-filled steel tubular composite columns emerges as a promising alternative, as they provide reduced cross-sectional dimensions while offering high load-bearing capacity, and they eliminate the need for formwork compared to reinforced concrete sections or concrete-encased composite sections. The objective of the present study is to develop a multi-objective optimization formulation for concrete-filled composite columns, considering both the minimization of CO_2 emissions, the maximization of the column's load-bearing capacity across different cross-sectional geometries and minimizing energy consumption during the construction process. The constraints adopted in the optimization process comply with the specifications of the Brazilian standard for tubular structural profiles. The optimization problem was solved using the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. The resulting Pareto fronts are compared with those from single-objective optimization problems found in the literature, where CO_2 emissions were considered as the objective function to be minimized.

Keywords: Composite Tubular Truss, Multi-Objective Optimization, Multi-Objective Particle Swarm Optimization

1 Introduction

Steel–concrete composite columns composed of circular hollow sections (CHS) are prominent in civil construction due to advantages such as increased load-bearing capacity, high strength, stiffness, and construction efficiency (e.g., eliminating the need for wooden formwork during construction). The Brazilian standard ABNT NBR 16239:2013 [1] establishes specific design procedures for concrete-filled tubular sections, ensuring enhanced structural performance, better material optimization, and compliance with modern technical requirements, serving as a solid reference for vertical and large-scale structures.

Previous single-objective optimization studies conducted by Lourenção et al. [2] and by Guimarães et al. [3] addressed methodologies aimed at minimizing costs and improving the structural efficiency of concrete-filled composite columns, with and without reinforcement, for different tube geometries. These works provided the initial mathematical modeling guidelines and performance criteria used as a starting point for extending the multi-objective context.

Among the algorithms developed for multi-objective optimization, the MOPSO (Multi-Objective Particle Swarm Optimization) algorithm, initially proposed by Coello [4], is used to solve multi-objective optimization problems, dealing with multiple objectives simultaneously. This algorithm is an extension of the PSO (Particle Swarm Optimization) algorithm proposed by Kennedy and Eberhart [5]. Multi-objective optimization studies on concrete structures and steel structures with different algorithms can be found. For example, in the works of Garcia-Segura and Yepes [6] (Concrete Road Bridges), Trés Junior et al. [7] (Steel

Pedestrian Bridges), Trés Junior et al. [8] (Steel Foot Bridges), Alves et al. [9] (Prestressed steel-concrete beams), and Silva et al. [10] (steel-concrete slab).

Given the above, this study aims to propose a multi-objective formulation for steel–concrete composite tubular columns, considering the minimization of CO_2 emissions and the energy consumed in the production process, as well as the maximization of the column's load-bearing capacity. The constraints are based on the provisions established by ABNT NBR 16239:2013 [1]. The Multi-Objective Particle Swarm Optimization (MOPSO) algorithm will solve the problem and generate the Pareto fronts.

2 The Optimization Problem Formulation

In the multi-objective formulation for the design of composite steel and concrete tubular columns, the objectives of minimizing CO_2 emissions and energy consumption during the construction process, and maximizing the beam's load-carrying capacity, are considered as follows:

$$Min\ CO_2(kgCO_2) = CO_{2,steel\ section} + CO_{2,reinforcement} + CO_{2,concrete} \tag{1}$$

$$Min\ EE(kWh) = EE_{steel\ section} + EE_{reinforcement} + EE_{concrete} \tag{2}$$

$$Max\ Load\ Capacity\ (kN) = N_{Rd} = A_c f_{cd} + A_p f_{yd} + A_s f_{sd} \tag{3}$$

Where $CO_{2,steel\ section}$, $CO_{2,reinforcement}$ and $CO_{2,concrete}$ represent the CO_2 emissions attributed to the steel section, reinforcement bars, and concrete, respectively, all expressed in $kgCO_2/kg$. $EE_{steel\ section}$, $EE_{reinforcement}$ and $EE_{concrete}$ denote the energy consumed per unit volume of concrete during the production of the steel section, reinforcement bars, and concrete, respectively. N_{Rd} is the maximum load-bearing capacity of the composite column, in *kN*, where $A_c f_{cd}$ is the contribution from the compressive strength of concrete, $A_p f_{yd}$ is the contribution from the steel section strength, and $A_s f_{sd}$ is the contribution from the reinforcement bars.

The design variables were defined as a function of the choice of profile in a commercial tubular profile table (x_1), the concrete strength (x_2), the amount of reinforcement (x_3), and the selected steel yield strength (x_4), as shown in Fig. 1.

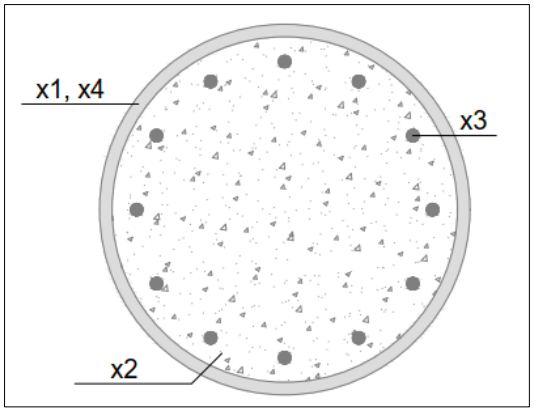


Figure 1 – Set of steel section parameters that comprise the design variables.

Negrin et al. (2025) [11] present values for estimating CO_2 emissions and energy consumption associated with different materials in their study unit, as shown in Table 1. However, in the authors' work, the emission and energy parameters related to concrete were limited to values corresponding to strengths ranging from 25 MPa to 40 MPa. Based on these values, an extrapolation was made for strengths of 20 MPa, 45 MPa, and 50 MPa. These values were necessary because, according to the results of Erlacher et al. [12] and Amorin et al. [13] , trusses with concrete-filled top chords provided solutions using concrete with strength exceeding 40 MPa.

Table 1 – CO_2 Emissions and Energy Consumption Values for Each Material.

Material	Unit	CO_2 emissions ($kgCO_2$)	Source	Energy (kWh)	Source
20 MPa Concrete	m³	140.05	Santoro e Kripka [14]	433.97	Extrapolation
25 MPa Concrete	m³	149.26		468.39	Negrin et al. [11]
30 MPa Concrete	m³	157.65		502.79	
35 MPa Concrete	m³	171.64		537.22	
40 MPa Concrete	m³	182.14		571.61	Extrapolation
45 MPa Concrete	m³	194.70		606.03	
50 MPa Concrete	m³	225.78		640.43	
CA60 Steel mesh	kg	1.204*	Negrin et al. [11]	10.39	Negrin et al. [11]
ASTM A572 Gr. 50 Steel	kg	2.04		4.98	
ASTM A572 Gr. 60 Steel	kg	2.07		5.05	
ASTM A572 Gr. 65 Steel	kg	2.09		5.10	
ASTM A913 Gr. 65 Steel	kg	2.10		5.13	
ASTM A913 Gr. 70 Steel	kg	2.13		5.20	

*World Steel Association

3 Numerical Results

To demonstrate the applicability of the proposed formulation, three case studies presented by Guimarães *et al.* [3] were analyzed with different load combinations (Fig. 2). For each case, circular hollow section (CHS) columns were optimized, as they exhibit superior structural performance compared to rectangular or square sections. The comparative analysis included: (i) evaluation of the results from Guimarães *et al.* [3] against the results obtained in this study, considering the steel yield strength (f_y) as a design variable; (ii) analysis of the solutions obtained using MOPSO for the same load level and comparison with the results from PSO; (iii) analysis of the Pareto fronts for the maximum load achieved. For the PSO optimization, a population of 70 individuals, 50 iterations, and 10 runs were considered. For MOPSO, 100 individuals, 50 iterations, and 10 runs were used. These parameter values were selected based on convergence criteria established through preliminary tests to ensure stability and consistency of the optimization process.

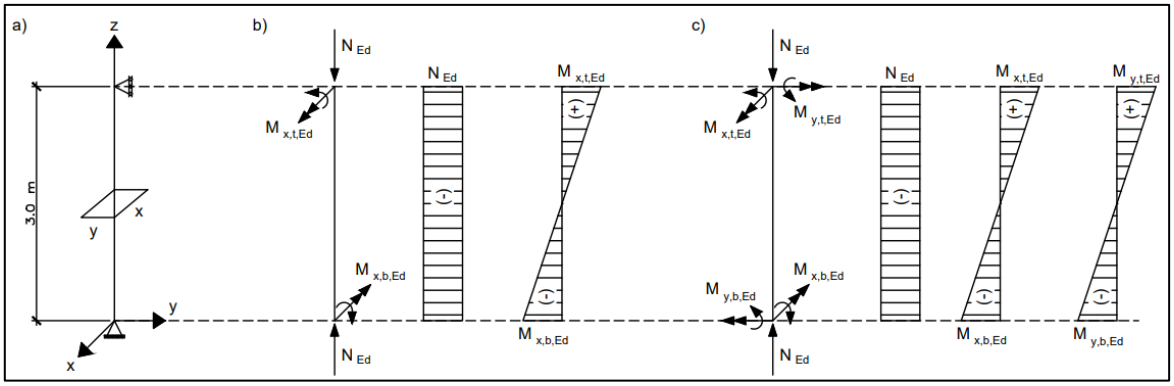


Figure 2 – Analyzed cases with the respective forces and bending moments applied to a 3.0 m long column: (a) Column; (b) Combined Compression and Uniaxial Bending; (c) Combined Bending (x and y axes) and Compression.

Source: Guimarães et al. [3].

Table 2 presents the results obtained for the final emissions and energy, while Table 3 shows the resulting geometries and the final steel and concrete for each solution.

Table 2 – Results Analysis

Without Reinforcement

Column (m)	Nsd (kN)	Msd_x/ Msd_y (kNm)	Guimarães et al. [3] (PSO) ($kgCO_2$)	Authors. PSO (fy Optimized) $kgCO_2$	Authors PSO (fy Optimized) Energy kW	Ratio Authors /Guimarães et al. [3] CO_2	Authors MOPSO Load kN	Authors MOPSO $kgCO_2$	Authors MOPSO Energy kW
3.00	2700	30/0	240.04	233.30	578.27	0.97	2729.16	252.92	625.88
3.00	3000	270/0	394.72	286.44	717.66	0.73	3058.75	283.30	700.00
3.00	1500	27/27	202.99	153.90	380.74	0.76	1534.06	170.01	422.23

Column (m)	Authors MOPSO Max Load kN	Msd_x/ Msd_y (kNm)	Authors MOPSO Max Load $kgCO_2$	Authors MOPSO Max Load Energy kW
3.00	13018.33	30/0	1329.39	3263.65
3.00	13018.33	270/0	1329.39	3263.65
3.00	13018.33	27/27	1329.39	3263.65

With Reinforcement

Column (m)	Nsd (kN)	Msd_x/ Msd_y (kNm)	Guimarães et al. [3] (PSO) ($kgCO_2$)	Authors. PSO (fy Optimized) $kgCO_2$	Authors PSO (fy Optimized) Energy kW	Ratio Authors /Guimarães et al. [3] CO_2	Authors MOPSO Load kN	Authors MOPSO $kgCO_2$	Authors MOPSO Energy kW
3.00	2700	30/0	259.76	254.97	810.45	0.98	2725.43	254.13	807.00
3.00	3000	270/0	413.94	264.39	870.00	0.64	3091.63	263.13	866.55
3.00	1500	27/27	184.83	151.99	485.47	0.82	1524.37	149.81	469.68

Column (m)	Authors MOPSO Max Load kN	Msd_x/ Msd_y (kNm)	Authors MOPSO Max Load $kgCO_2$	Authors MOPSO Max Load Energy kW
3.00	14703.57	30/0	1397.87	3820.10
3.00	14703.57	270/0	1397.87	3820.10
3.00	14703.57	27/27	1397.87	3820.10

As shown in Table 2, the solution was improved for the three analyzed examples when performing a single-objective optimization using PSO and considering the steel yield strength as a design variable, with reductions in CO_2 emissions ranging from 3% to 24%. When comparing the solutions obtained using MOPSO for a level of applied load similar to that proposed in the problems, the algorithm yielded results comparable to PSO, showing an increase in load capacity of up to 3% and differences in emissions of 8% and 9% for CO_2 and energy, respectively. The best results using MOPSO were for the second example without reinforcement, where the load increased by 2% the total energy reduced by 2%.

The environmental reductions regarding the maximum load in the scenario with higher applied stresses were more significant. MOPSO stood out for identifying solutions with maximum load capacity, enabling a more favorable balance between environmental impact and structural performance. Table 3 presents the final geometries resulting from analyzing the different examples.

Table 3 – Final Geometries

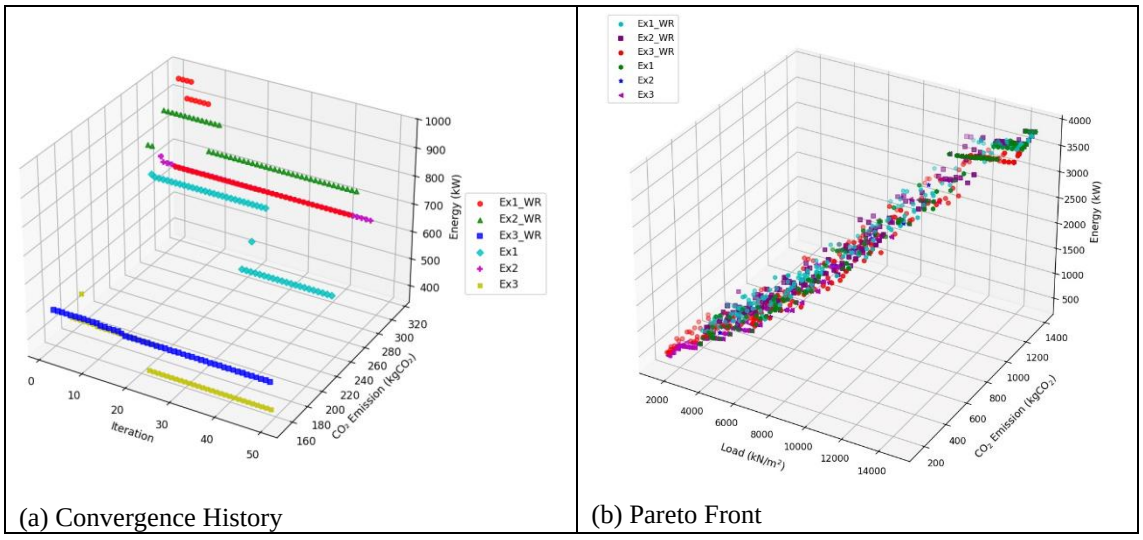
Without Reinforcement

	Nsd(KN)	Steel	D : t (mm)	f_{ck} (MPa)	φ (mm)	n		Steel	D : t (mm)	fck (MPa)	ϕ (mm)	n
Authors PSO	2700	ASTM A572 Gr. 65	219.1:6.4	50	-	-	Authors MOPSO	ASTM A572 Gr. 60	219.1:7.1	50	-	-
	3000	ASTM A572 Gr. 60	273.0:6.4	30	-	-		ASTM A572 Gr. 65	219.1:8.0	50	-	-
	1500	ASTM A572 Gr. 65	168.3:5.6	50	-	-		ASTM A572 Gr. 60	168.3:6.4	45	-	-
Guimarães et al. [3]	2700	ASTM A572 Gr. 50	273.0:5.0	50	-	-						
	3000	ASTM A572 Gr. 50	355.6:6.3	50	-	-						
	1500	ASTM A572 Gr. 50	244.5:5.0	35	-	-						

With Reinforcement

		Steel	D : t (mm)	f_{ck} (MPa)	φ (mm)	n		Steel	D : t (mm)	fck (MPa)	ϕ (mm)	n
Authors PSO	2700	ASTM A572 Gr. 65	219.1:6.4	30	16.0	10	Authors MOPSO	ASTM A913 Gr. 70	219.1:6.4	25	16.0	6
	3000	ASTM A913 Gr. 65	219.1:6.4	40	16.0	11		ASTM A913 Gr. 70	219.1:6.4	40	16.0	6
	1500	ASTM A572 Gr. 65	168.3:5.0	30	12.5	10		ASTM A913 Gr. 65	168.3:5.0	40	10.0	7
Guimarães et al. [3]	2700	ASTM A572 Gr. 50	273.0:5.0	40	12.5	8						
	3000	ASTM A572 Gr. 50	355.6:6.3	40	12.5	9						
	1500	ASTM A572 Gr. 50	219.1:4.5	50	10.0	7						

As shown in Table 3, the solutions obtained in this study prioritized the use of higher-strength concrete and profiles with smaller diameters compared to those reported by Guimarães et al. [3]. In the reinforced scenarios, the reinforcement was used more efficiently, whereas in the unreinforced cases, the geometry was adjusted to compensate for the absence of reinforcement. Figure 3 presents the convergence history (Figure (a)) as well as the Pareto Fronts for the analyzed examples.



(a) Convergence History (b) Pareto Front

Figure 3 – (a) Convergence History and (b) Pareto Front.

As shown in Fig. 3, the graphs indicate that the MOPSO algorithm reached convergence, stabilizing CO_2 emissions and energy consumption within the first iterations. In this context, the notation Ex1, Ex2 and Ex3 refers to the different loading scenarios analyzed without reinforcement, while Ex1_WR, Ex2_WR and Ex3_WR refers the respective reinforced cases. In the reinforced cases, particularly in Example 2 (with higher loads and moments), more pronounced reductions were observed, highlighting a greater optimization potential. Conversely, the unreinforced cases exhibited lower initial values and smoother adjustments. The trajectory of the solutions reveals that each scenario presents a distinct relationship between environmental and structural performance, confirming that higher applied loads offer greater efficiency gains.

4 Concluding Remarks

This study presented a multi-objective optimization formulation for circular composite columns filled with concrete, in compliance with the requirements of ABNT NBR 16239:2013, focusing on

maximizing load-bearing capacity while simultaneously minimizing CO_2 emissions and energy consumption. Different combinations of applied loads were evaluated, considering solutions both with and without longitudinal reinforcement, using optimized PSO and MOPSO algorithms.

Comparison with previous studies revealed significant environmental reductions, particularly in scenarios involving higher loads and bending moments, where geometric and material optimizations had a greater influence on overall performance. In these situations, CO_2 emissions were substantially reduced while maintaining or increasing load-bearing capacity. For lower applied loads, environmental gains were more moderate yet still relevant, reinforcing the potential applicability of the proposed methodology.

Reinforcement-free solutions proved advantageous from an environmental perspective when the structural demand allowed, due to reduced steel volume and the prioritization of high-strength concrete. In scenarios with higher demands, longitudinal reinforcement enabled lower-strength concrete and dimensional adjustments that preserved compact and efficient sections, balancing performance and sustainability.

The results demonstrate that applying multi-criteria optimization techniques is an effective strategy for designing composite tubular columns. This strategy enables designers to explore different combinations of materials and geometries to balance structural efficiency, environmental impact, and construction feasibility.

Suggestions for future research include expanding the optimization of concrete-filled steel tubular columns by incorporating additional sustainability metrics, such as life-cycle assessment, considering dynamic loads like wind, and exploring non-circular sections and multi-span systems to extend applicability.

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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.

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