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Multi-Objective Optimization of Tubular Composite Trusses: Analysis of CO_2 Emission and Load Bearing Capacity

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Abstract. The use of steel-concrete composite systems has been increasing over the past decades. Among the existing systems, steel-concrete tubular composite trusses stand out for their ability to span longer distances with reduced mass compared to full-web beams. The aim of this study is to present a multi-objective formulation for the topological optimization of steel-concrete tubular trussed beams, considering the possibility of filling the upper chord with concrete. The problem was modeled using bar elements with two degrees of freedom per node. The objective functions considered were CO_2 emissions, energy of fabrication process, and the load-bearing capacity of the truss, while the constraints were based on the requirements of Brazilian standards for laminated and tubular profiles. To solve the optimization problem, Multi-Objective Particle Swarm Optimization (MOPSO) was employed to generate Pareto fronts. The formulation was validated and compared with examples from the literature in which single-objective optimization of CO_2 emissions in beams was performed. Preliminary results indicate that the algorithm was effective in determining solutions when compared to the single-objective approach and led to more efficient structural systems, with increased load-bearing capacity and minimal CO_2 emissions and energy.

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

1 Introduction

The world is changing under human demands for space, resources, and survival. Technological advances have enhanced quality of life, but also generate environmental impacts that are often overlooked. The planet cannot indefinitely sustain our current consumption patterns and built environment. Recent heat-wave events, attributed to climate change, demonstrate that the consequences of uncontrolled resource exploitation are already manifesting and will only intensify. Accordingly, sustainability has become an imperative to secure resources for future generations. Governments and corporations have devised targets and action plans to curb these impacts, underscoring the need for research that integrates sustainable practices, especially in high-impact sectors. According to the United Nations Environment Programme (UNEP) [1], the construction industry, particularly cement and steel production accounted for 37 % of global CO_2 emissions in 2022, highlighting the urgency of solutions that optimize material use and mitigate environmental harm.

A comprehensive life-cycle analysis must assess a structural solution's performance. Tools such as Life Cycle Assessment (LCA) are employed to quantify emissions and energy consumption associated with a given design. Optimization studies on steel–concrete mixed truss beams have been reported by Erlacher

et al. [2] , Silva *et al.* [3], and Amorin *et al*. [4]. These authors demonstrate that truss beams with a concrete-filled upper chord outperform solid-web and cellular-beam alternatives. However, each study focused on a single objective: minimizing CO_2 emissions (Erlacher *et al.* [2]) or reducing structural cost (Silva *et al.* [3]; Amorin *et al.* [4]). To date, multi-objective optimization of tubular steel and concrete composite truss beams has not been addressed in the literature.

In view of the foregoing, this paper aims to formulate a multi-objective topological optimization of tubular steel and concrete composite truss beams with a concrete-filled upper chord, seeking simultaneously to: (i) minimize CO_2 emissions, (ii) minimize energy consumption in production, and (iii) maximize load-carrying capacity. Design constraints will comply with NBR 8800:2004 and NBR 16239:2013 [5]. In addition to selecting profiles for the upper chord, lower chord, diagonals, and verticals, design variables will include the concrete compressive strength of the slab, the compressive strength of the concrete in the upper chord, the truss height, and the number of panels composing the final truss. The multi-objective particle swarm optimization algorithm (MOPSO) will solve the problem and generate the Pareto front.

2 The Optimization Problem Formulation

In the multi-objective formulation for the design of composite steel and concrete tubular truss beams, 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:

$$Min[CO_2\ EE] = [CO_2\ EE]_{(truss)} + [CO_2\ EE]_{(fill_conc)} + [CO_2\ EE]_{(slab)} + [CO_2\ EE]_{(steel_deck,total)} + [CO_2\ EE]_{(connector,total)} + [CO_2\ EE]_{(mesh)} \quad (1)$$

$$Max\ Load\ Bearing\ capacity = Q \quad (2)$$

In Equation (1), CO_2 e EE denote the CO_2 emissions and the energy expended for each component of the steel and concrete composite tubular truss, given respectively by the truss itself, the concrete infill of the tube, the slab concrete, the steel deck formwork, the shear connectors, and the crack control mesh. Each term of the objective function is defined as follows:

$$[CO_2\ EE]_{(truss)} = W_{(truss)} \times [CO_2\ \ EE]_{(steel,\ profile)} \quad (3)$$

$$[CO_2\ EE]_{(fill_conc)} = A_{(int,tube,upper)} \times L_{(truss)} \times [CO_2\ EE]_{(conc)} \quad (4)$$

$$[CO_2\ EE]_{(slab)} = Vol_{(conc,slab)} \times [CO_2\ EE]_{(conc)} \quad (5)$$

$$[CO_2\ EE]_{(steel_deck,\ total)} = W_{(steel_deck)} \times [CO_2\ EE]_{(steel_deck)} \quad (6)$$

$$[CO_2\ EE]_{(connector,\ total)} = W_{(connector)} \times [CO_2\ EE]_{(connector)} \quad (7)$$

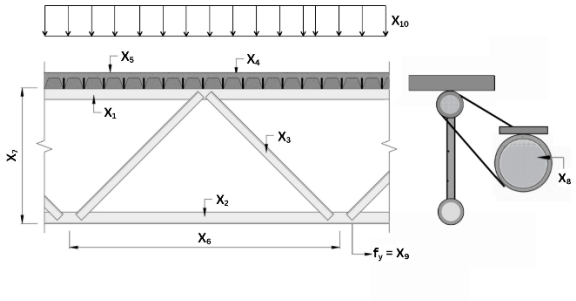
$$[CO_2\ EE]_{(mesh)} = W_{(mesh)} \times [CO_2\ EE]_{(steel,\ mesh)} \quad (8)$$

where W_{truss}, W_{steel_deck}, $W_{connector}$, W_{mesh} denote the total mass (in kg) of the truss, the steel-deck formwork, the shear connectors and the crack-control mesh used in the slab, respectively; $A_{int,tube,upper}$ is

the internal cross-sectional area of the upper-chord tube available for concrete infill; L_{truss} is the span of the truss.

As design variables, in addition to the selection of the upper-chord profile (x_1), lower-chord profile (x_2) and diagonal/vertical member profiles (x_3), the formulation also includes: the choice of steel-deck slab type (x_4); the compressive strength of the slab concrete (x_5); the number of panels composing the final truss (x_6); the truss height (x_7); the compressive strength of the concrete infill in the upper chord (x_8); (x_9) the yield stress of steel; and (x_{10}) the load capacity of the truss, as illustrated in Figure 1. The design variables' bounds are defined in Table 1.

Figure 1 – Design Variables for Composite Steel and Concrete Tubular Truss Beams



Source: Adapted from Erlacher et al [2].

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

Design Variables	Space Search
x_1, x_2, x_3	[1:1:142]
x_4 (m)	[1.8:0.1:4.0]
x_5 (MPa)	[20:5:50]
x_6	[1:1:50]
x_7 (m)	[L/15:0.5:L/8]
x_8 (MPa)	[20:5:50]
x_9 (MPa)	[345, 415….]
x_{10}(kN/m^2)	[1.5:0.1:20]

Negrin *et al.* [6] present values for estimating CO_2 emissions and energy consumption associated with different materials in their study unit, as shown in Table 2. 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.* [2] and Silva *et al.* [3], trusses with concrete-filled top chords provided solutions using concrete with strength exceeding 40 MPa.

Table 2 – 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		433.97	Extrapolation
25 MPa Concrete	m³	149.26		468.39	
30 MPa Concrete	m³	157.65	Santoro and Kripka [7]	502.79	Negrin *et al.* [6]
35 MPa Concrete	m³	171.64		537.22	
40 MPa Concrete	m³	182.14		571.61	
45 MPa Concrete	m³	194.70		606.03	Extrapolation

50 MPa Concrete	m³	225.78	World Steel Association [8]	640.43	Negrin *et al.* [6]
Steel deck	m²	2.638		8.70	
CA60 Steel mesh	kg	3.01	Negrin *et al.*[6]	10.39	
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	

The design constraints considered in this work were those proposed by Erlacher *et al.* [2].

3 Numerical Results

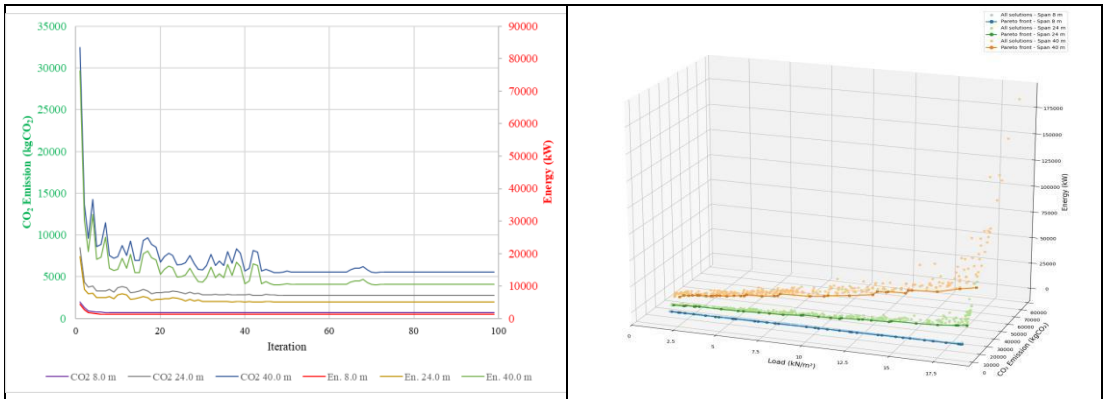
To demonstrate the application of the proposed formulation, the problem addressed by Erlacher *et al.* [2] was analyzed, in which the final CO_2 emissions of the truss were optimized. The authors proposed optimizing trusses with double-angle profiles and concrete-filled tubular profiles in the upper chord, combined with steel deck slabs. In addition to the structure's self-weight, a live load of 2.0 kN/m², a dead load of 0.15 kN/m² and an additional load of 1kN/m². In the first stage, using the PSO algorithm, a mono-objective optimization was performed considering steel f_y as a design variable. The Pareto fronts and the MOPSO ability to find optimal solutions under the same loading conditions proposed by Erlacher *et al.* [2] were analyzed in the second stage. Table 3 presents the comparative analysis. All simulations were implemented in MATLAB, considering 200 individuals, 80 iterations, and 15 rounds.

Table 3 – Comparative Analysis

Span (m)	Load (kN/m²)	Erlacher *et al.* [2] (PSO) ($kgCO_2$)	Authors PSO (f_y Optimized) $kgCO_2$	Authors PSO (f_y Optimized) Energy kW	Ratio Authors / Erlacher *et al.* [2]	Authors MOPSO $kgCO_2$	Authors MOPSO (f_y Optimized) Energy kW	Ratio (MOPSO/PSO) CO_2	Ratio (MOPSO /PSO) Energy
8	2	746,74	731,70	1217,29	0,98	731,6963725	1217,286743	1,00	1,00
24	2	3151,97	2537,90	4489,28	0,80	1385,555866	2201,181212	0,55	0,49
40	2	7122,50	5697,44	18722,89	0,80	5955,843569	11816,90787	1,05	0,63

As can be observed, when considering the steel yield strength as a variable and using PSO as the optimizer, the solutions for all spans were improved, with the most significant difference found for the 40 m span. When comparing the solutions obtained using MOPSO and PSO, it is evident that the algorithm found similar solutions in terms of cost and energy, being 4% worse for the 24 m span and 8% better for the 40 m span. Figure 2 presents the convergence history for the optimization considering the steel yield strength using PSO and the Pareto fronts for the different spans analyzed.

Figure 2 – Convergence History and Pareto Fronts of the analyzed problems

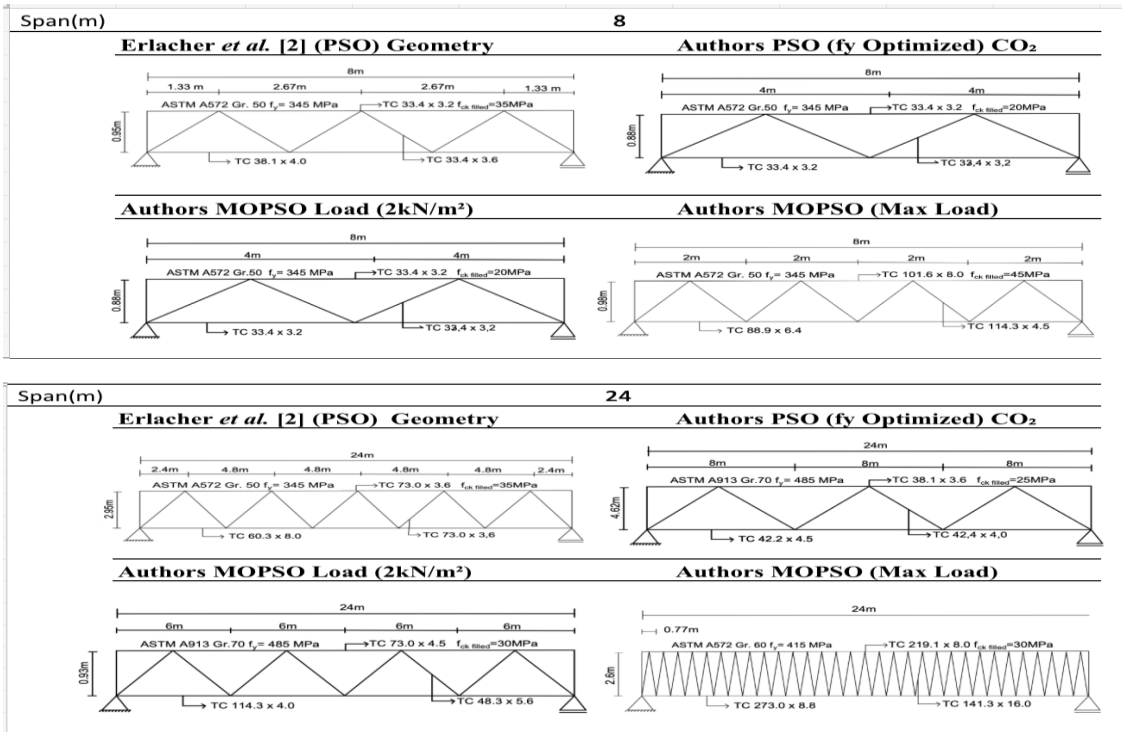


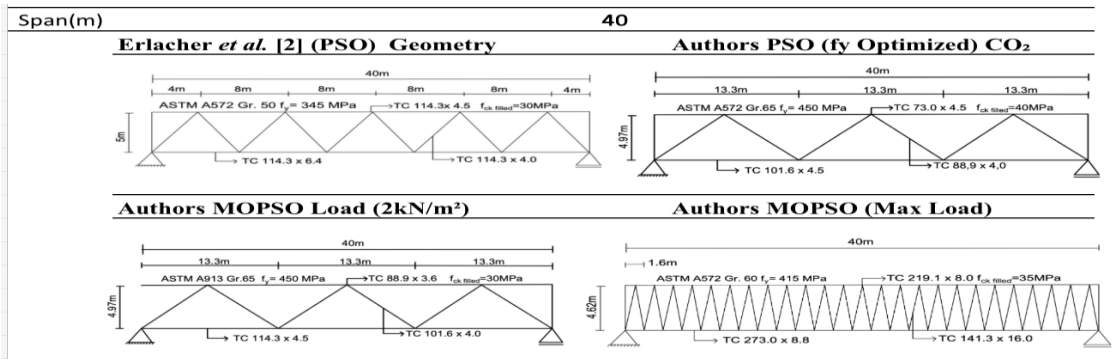
(a) PSO Convergence History

(b) Pareto Front

As can be seen in Figure 2(a), the convergence history indicates that the emission and energy functions exhibit parallel behavior for the analyzed problems, not generating a trade-off in the multi-objective problem. This makes it necessary to include the third objective function related to load. According to the Pareto Fronts, the maximum loads obtained for the analyzed spans were 18.8 kN/m², 18.1 kN/m², and 15.3 kN/m² respectively to the analyzed spans. Table 4 presents the final geometries of the solutions obtained using PSO with optimization of the steel's yield strength (fy) and the solutions found using MOPSO for a load of 2 kN/m² and for the maximum load of each analyzed span.

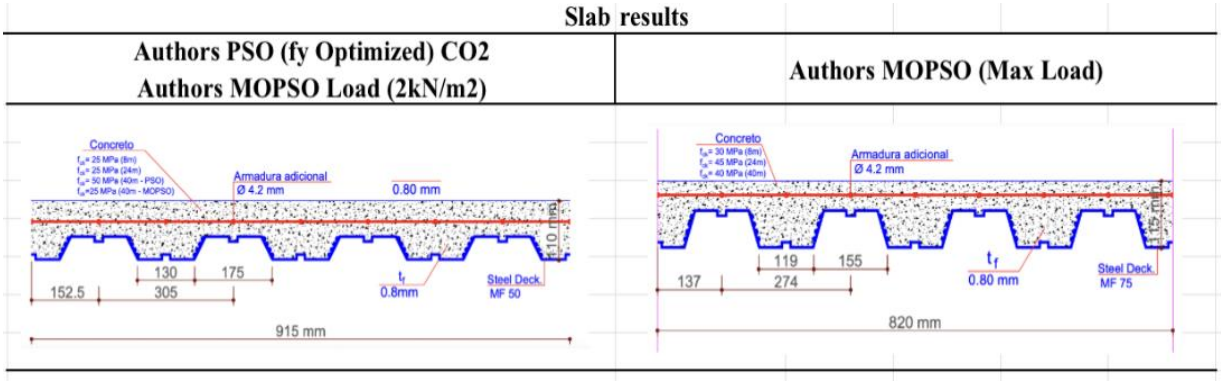
Table 4 – Final Geometries





As shown in Table 4, the final solutions obtained by optimizing the steel yield strength using both PSO and MOPSO for the 2 kN/m² load were similar, although with different values for the emission and energy functions, as already indicated in Table 3. For these solutions, the formwork used was an MF50 with a thickness of 0.8 mm, a 6 cm concrete topping, and a slab concrete strength (f_{ck}) of 25 MPa. For the solutions with the maximum load, the formwork used was an MF75 with a thickness of 1.25 mm, a 6.5 cm concrete topping, and a slab concrete strength (f_{ck}) of 30, 45, and 40 MPa as indicated in Figure 3.

Figure 3 – Final Slab Geometry



4 Concluding Remarks

The objective of this study was to present the multi-objective formulation of tubular truss concrete beams with infill in the top chord. The formulation considers the minimization of CO_2 emissions and the energy consumed during the truss manufacturing process, as well as the maximization of the truss load-bearing capacity, with the type of steel considered as a design variable. According to the results, and considering a single-objective optimization, there was a 22% reduction when the f_y was considered a design variable in CO_2 emissions for the 40 m span compared to the problem analyzed by Erlacher *et al.* [2].

Regarding the multi-objective optimization, the MOPSO algorithm effectively found solutions when considering the same load used in the single-objective optimization for all spans. The best result was obtained for the 40 m span, with a 6% reduction. Among the three analyzed problems, the maximum load was obtained for the 8 m span, reaching the maximum limit of 18.8 kN/m². This limit was imposed due to the upper bound defined by the manufacturer's formwork table.

Additionally, it was noted that the convergence curves in the single-objective optimization were parallel for both CO_2 emissions and energy consumption, highlighting the need for a third objective function to foster competition among solutions.

Finally, although the solutions obtained from single-objective and multi-objective approaches were close in performance, the resulting geometries were different, with distinct profile shapes.

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