Multiobjective Optimization of prestressed composite steel and concrete beam via Multi-Objective Particle Swarm Optimization (MOPSO)

Élcio Cassimiro Alves[1], Abner Endrye Pimentel de Almeida[1], Sayonara Maria de Moraes Pinheiro[1], Adenilcia Fernanda Grobério Calenzani[1]

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

Abstract. The use of prestressing in steel and composite steel and concrete beams is still underexplored in the design of structures with large spans due to the lack of specific normative codes for this type of structural element. Studies involving optimization techniques for these types of structures are scarce in the literature, thus opening up a vast field of research to be explored. This study aims to propose the formulation of a multi-objective optimization problem for composite steel and concrete beams with external prestressing. The final cost of the beams, CO_2 emissions from the materials used in their fabrication, and the maximization of the live load that the beam can support are considered minimization objectives. Constraints include the requirements for composite steel and concrete elements from NBR 8800:2008 and the prestressing provisions from NBR 6118:2021. The Multi-Objective Particle Swarm Optimization implemented in the Matlab package will be used to solve the optimization problem. Examples demonstrating the solution's effectiveness were compared with examples from the literature, and Pareto Frontiers shows that for the same load, different solutions are found, and the best solutions were obtained when using concrete with compressive strength over 45 MPa.

Keywords: Multiobjective Optimization, Prestressed Steel and Concrete Composite Beam, Cost, CO_2 emission and maximum load

1 Introduction

The use of prestressing in steel and composite steel-concrete beams is still not widely explored in the design of large-span structures due to the lack of specific normative codes for this type of structural element. Among the recent studies on the optimization of prestressed steel beams, the works of Netto et al. [1] (2023) and Fiorotti et al. [2] stand out. In the study by Netto et al. [1] (2023), the costs of prestressed steel beams with straight cables were analyzed and compared with problems from the literature, and the authors concluded that the application of optimization techniques could reduce the final cost of the beam by up to 23%. Fiorotti et al.[2] analyzed the costs and CO_2 emissions of steel beams with straight and polygonal cables and concluded that for these beams, the solution with straight cables was not different from the solution for polygonal cables. However, the studies by Netto et al. [1] and Fiorotti et al.][2] analyzed either the cost or CO_2 emissions separately, thus motivating the proposed study in this work.

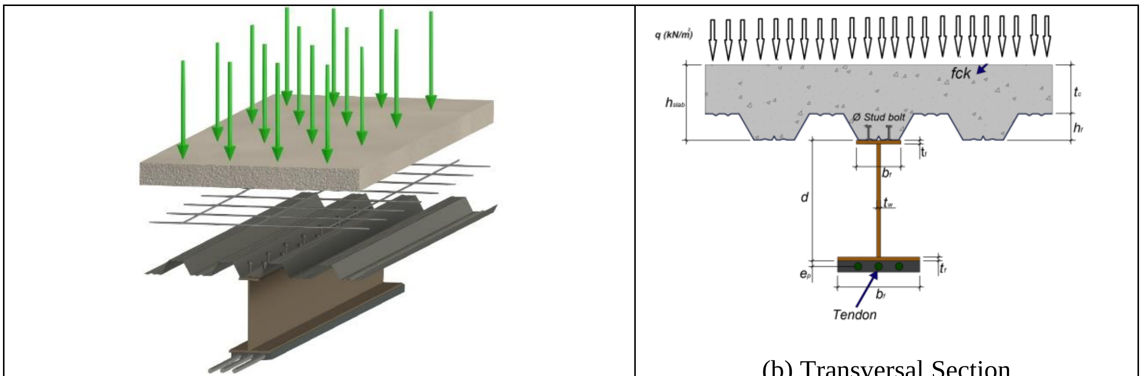
Among the algorithms developed for multi-objective optimization, the MOPSO (Multi-Objective Particle Swarm Optimization) algorithm, initially proposed by Coello[3], is an extension of the PSO (Particle Swarm Optimization) algorithm to solve multi-objective optimization problems, dealing with multiple objectives simultaneously. Multi-objective optimization studies applying MOPSO can be found, for example, in the works of Baei and Terzic [4] (Dampers in Seismic), Xu et al. [5] (Tubes and Shells), and Malashin et al. [6] (Neural Network in Polymer), among others.

Despite several studies in the literature on multi-objective optimization, whether applying MOPSO or another optimization algorithm, no studies were found in the literature on the multi-objective formulation of prestressed steel and concrete composite beams focusing on minimizing CO_2 emissions and cost while considering the beam's load capacity.

Given the absence of works addressing the multi-objective optimization of prestressed composite steel-concrete beams, this work aims to present the formulation of the multi-objective optimization problem for composite steel-concrete beams with external prestressing and straight cables. The minimization functions will consider the final cost of the beams and the CO_2 emissions from the materials used in their manufacture, in addition to maximizing the useful load the beam can support. To solve the problem, the MOPSO algorithm was implemented in MATLAB 2020[7].

2 Optimization Problem Formulation

For the definition of the multi-objective problem, the design variables presented in Figures 1(a) and 1(b) were defined, showing the longitudinal section and the beam cross-section, respectively, for monosymmetric welded steel profiles with steel deck slabs.



(a) Longitudinal Section

(b) Transversal Section

Figure 1 – Design Variables

Each variable had the following range in the Table 1.

Table 1 – Upper and lower bounds of design variables

Profile height (d): 50 mm ≤ d ≤ 1100 mm;	Lower flange thickness (t_f^{bot}): 4 mm ≤ t_f^{bot} ≤ 30 mm
Upper flange (b_f^{top}): 50 mm ≤ b_f^{top} ≤ 700 mm;	Web thickness (t_w): 4 mm ≤ t_w ≤ 30 mm
Lower flange (b_f^{bot}): 50 mm ≤ b_f^{bot} ≤ 700 mm	Slab concrete thickness (t_c) and steel deck formwork height (h_f) were selected from the options in the Metform steel formwork catalog [34]
Upper flange thickness (t_f^{top}): 4 mm ≤ t_f^{top} ≤ 30 mm	Slab concrete compressive strength (f_{ck}): 20 MPa ≤ f_{ck} ≤50 MPa, with a step of 5 MPa.
Lower flange thickness (t_f^{bot}): 4 mm ≤ t_f^{bot} ≤ 30 mm	Number of tendons: 0 ≤ $No.Tendons$ ≤ 20
Web thickness (t_w): 4 mm ≤ t_w ≤ 30 mm	Live Load: 3 kN/m² ≤ q ≤ 8 kN/m²

3.1. Objective Functions

The multiobjective problem is defined with three objective functions: CO2 emission minimization, Cost minimization, and maximization of the load capacity of the beam present in Eqs. (1) to (3).

$$Min\ CO_2 = CO_{2,S}V_S\rho_S + CO_{2,TR}V_{TR}\rho_S + CO_{2,Slab} + CO_{2,Studbolt} + L_W CO_{2,W} \tag{1}$$

$$Min\ COST = Cost\ \ V_S\rho_S + COST_{(tendons)} + COST_{(slab)} + COST_{(conectors)} \tag{2}$$

$$Max\ Load = q \tag{3}$$

The parts of Eq. (1) and (2) represent the CO_2 emissions and cost of each beam component. The first term refers to the steel profile, where $CO_{2,S}$ and $Cost$ is the CO_2 emission in $kgCO_2$ per kilogram and cost of steel profile, V_s is the volume of steel profile given by area A_s and beam span L, and ρ_S is the specific mass of steel. The second term represents the CO_2 emission and cost of the tendons, where $CO_{2,TR}$ and $COST_{(tendons)}$ is the emission in $kgCO_2$ per kilogram of tendon and tendon cost respectively, V_{TR} is the volume of the tendon given by the product of area A_{TR} and length of the tendons L, $CO_{2,CS}$ and $COST_{(conc.slab)}$ is the CO_2 emission and the cost of the composite slab consisting of the steel deck formwork emission and cost, reinforcement emission and cost, and concrete emission and cost, $CO_{2,Studbolt}$ is the stud bolt emission, and $L_W CO_{2,W}$ is the weld emission of the profile manufacturing.

To determine the potential contribution to global warming in $kgCO_2$, the weld emission value of 3.3 $kgCO_2$-Equiv./m was adopted, adjusted by the ratio between the actual cross-section of the weld chord (A_{wl}) and the reference cross-sectional area of the weld chord for the 20 mm plate, which is 158 mm² (Sproesser et al., 2015).

For emissions related to concrete, Santoro and Kripka [8] carried out a study considering the analysis of the beam cycle of materials from cradle to the gate for all materials that make up the concretes adopted in this study, and the material costs were used the values proposed by SINAP [9] (2023) and a local supplier in Espírito Santo. Furthermore, a transport radius of 100 km was considered for emissions due to concrete transport. Table 1 presents the CO_2 emissions for each material considered in Equation (18).

Table 1 – Units Costs and Emissions

Component	Strength	***CO_2 Emission (kgCO₂/m³)***	***Source***	***Cost (R$)***	***Source***
Concrete	20 MPa	129.85	Santoro e Kripka [8]	463.14	SINAPI [9]
	25 MPa	142.71		474.87	
	30 MPa	153.68		491.01	
	35 MPa	163.25		504.22	
	40 MPa	171.73		518.15	
	45 MPa	189.6		532.09	
	50 MPa	199.72		546.02	
Steeldeck formwork MF50 esp.0.8mm	280 MPa	2.638kg/kg	Worldsteel Association [10]	90.5/m²	Local Supplier(2024)
Steeldeck formwork MF50 esp.0.95mm				107.64 m²	
Steeldeck formwork MF50 esp.1.25mm				141.64 m²	
Steeldeck formwork MF75 esp.0.8mm				99.00 m²	
Steeldeck formwork MF75 esp.0.95mm				117.00 m²	
Steeldeck formwork MF75 esp.1.25mm				154.00 m²	
Steel Profile	AGR52	1.116kg/kg		12.0/kg	
Stud Bolt		1.924kg/kg		11.40/unit	
Tendons	CP190	1.924kg/kg		15.60/kg	
Reinforcement Mesh	CA60	1.924kg/kg		10.48/kg	SINAPI [9]

The constraints proposed by Fiorotti [11] for the different stages of execution of the prestressed composite beam were adopted for the problem as follows: Stage 1 – prestressed steel beam subjected to its own weight; Stage 2 – prestressed steel beam subjected to its own weight plus the weight of the slab and construction loads; Stage 3 – analysis of the prestressed composite steel and concrete section with live load; Stage 4 – verification of the serviceability limit state at infinite time. The MOPSO implemented on the MATLAB platform was used to determine the optimal solution to the problem.

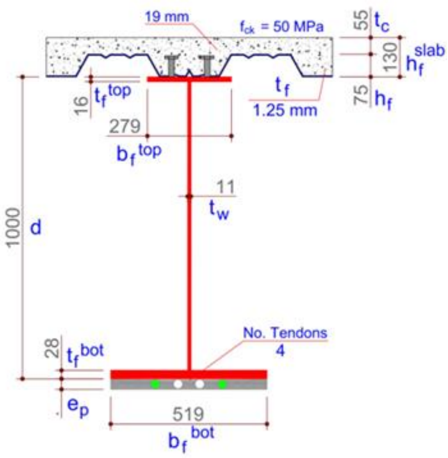
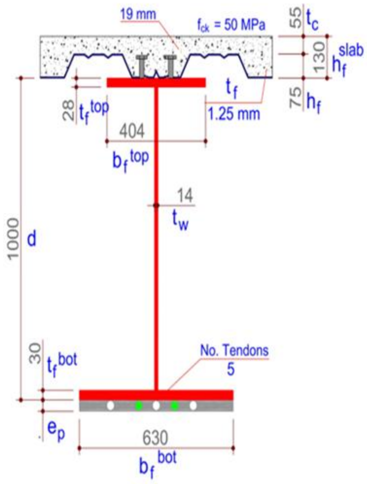
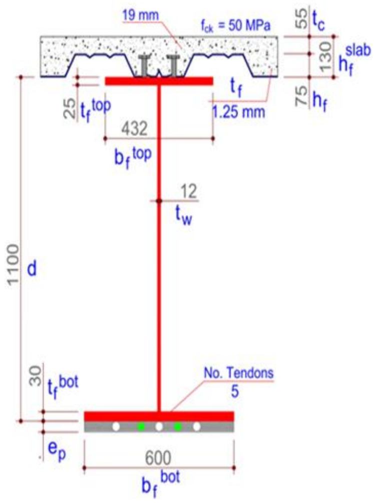
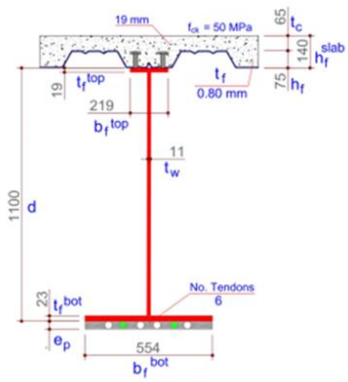
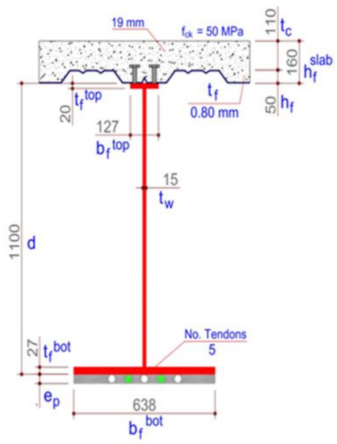
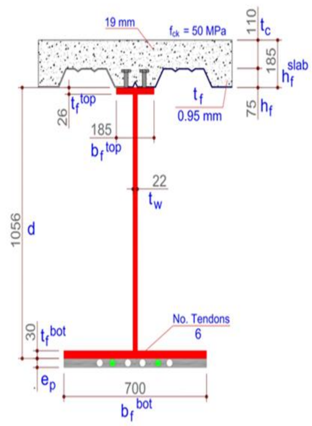
3 Numerical Results

To demonstrate the application of the proposed formulation beams with spans of 35m, 37.5m, and 40m analyzed by Fiorotti [11] were examined. This study analyzed the CO_2 emissions of prestressed composite steel beams with doubly symmetric and monosymmetric profiles, with the monosymmetric profiles providing the best solutions. This analysis considered a beam spacing of 3m, a steel yield strength (f_y) of 345MPa, and all design variables: composite slab thickness, concrete compressive strength, number of tendons, profile dimensions, and choice of steel deck slab. Besides the slab and beam self-weight, a dead load of 2kN/m² and a construction load of 1kN/m² were also considered. The tendons should be 50mm below the lower flange of the steel profile, and the steel CP190 should have a diameter of 15.2mm. For the multi-objective optimization, 10 rounds were performed for each example, with an initial population of 300 individuals and 100 iterations for each round. Table 2 presents the CO_2 emissions results obtained by Fiorotti [11] using the SABO algorithm for a live load of 5kN/m² and the values found by applying MOPSO, and Table 3 presents the profile geometries presented by Fiorotti [11] and the geometries proposed in this work.

Table 2 – Comparison of results between the Authors and Fiorotti [11].

Span (m)	**CO_2 Emission (kg) Fiorotti [11]**	**CO_2 Emission(kg) Authors**	**Cost (R$) Authors**	**Ratio [%] CO_2 Authors/ CO_2 Fiorotti [11]**
35.0	16080.7	17099.50	132203.76	6.3
37.5	19146.7	19044.69	154370.22	-0.5
40.0	22738.0	21821.20	178434.29	-4

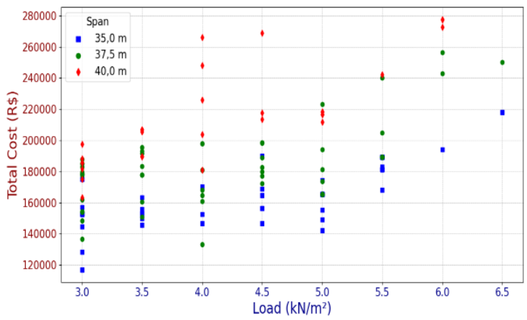
Table 3 – Geometries to load of 5kN/m².

	35.0m	37.5m	40.0m
Fiorotti. [11]			
Authors			

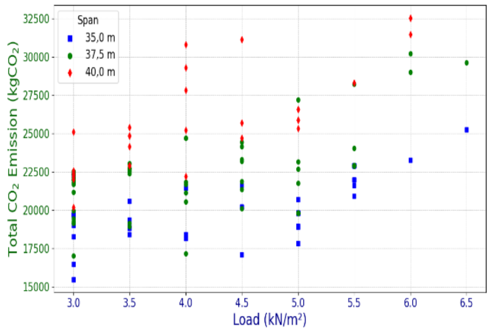
As shown in Table 2, although the results are different, the values for multi-objective optimization are close to those obtained by Fiorotti [11] when applied to multi-objective optimization, with the 37.5m span being the nearest. Despite these close values, it can be observed that the final geometry of the profiles and cables differed from those proposed by Fioroti [11], as presented in Table 3. For the three analyzed examples, the f_{ck} of the slab was the same for spans of 35m and 40m, but with different steel deck formwork and concrete thickness. Figures 3(a), 3(b), and 3(c) show the Pareto Fronts for Load versus Emission, Load versus Cost, and Emission versus Cost.

As can be observed in Figure 3, the lowest load obtained was 3kN/m², and the highest load was 6.5kN/m² for the 35m and 37.5m spans and 6kN/m² for the 40m span. It can also be noted that the algorithm obtained more than one solution when analyzing costs and CO2 emissions for different load conditions on the Pareto Frontiers. Figure 3(c) shows that the relationship between cost and CO2 emission for the different solutions is nearly linear. The best solutions for each span are presented in Table 3, and Figure 4 presents a graph of the evolution of cost and CO2 emission per beam meter.

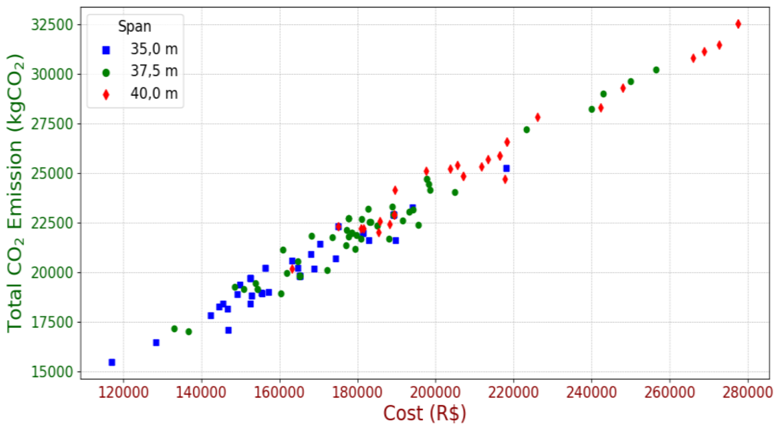
Figure 3 –Pareto Fronts



(a) Load *versus* Cost



(b) Load *versus* CO_2 Emission



(c) Cost *versus* CO_2 Emission

Table 3 – Best Solutions Analysis

Span (m)	**Load (kN/m²)**	**CO_2 Emission ($kgCO_2$)**	**Cost (R$)**
35.0	6.5	25248.20	218111.75
37.5	6.5	29644.83	250060.35
40.0	6.0	31479.14	272730.44

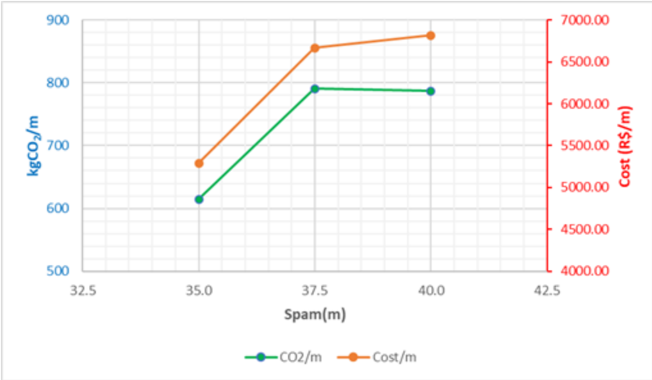
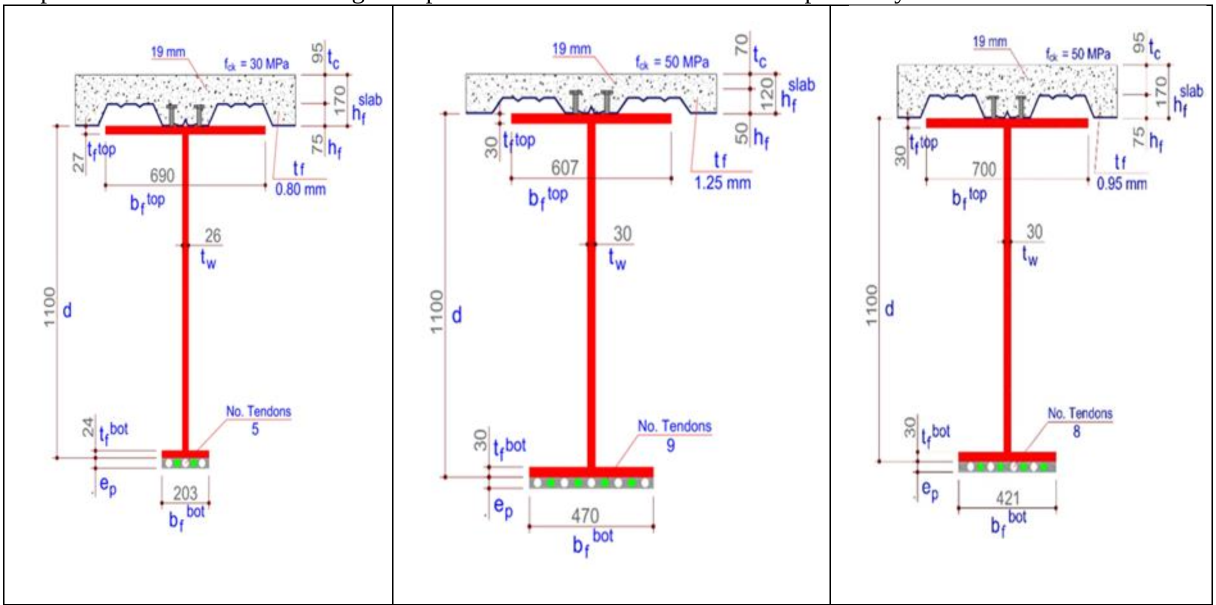


Figure 4 –Cost and CO_2 Evolution

As observed, the relationship between CO_2 emissions and beam costs follows a nearly linear trend as the span of the beam increases. Figure 5 presents the best solution for each span analyzed to the maximum load.



(a) 35.0m | (b) 37.5m | (c) 40.0m

Figure 5 –Final geometries

As observed, different steel deck slabs were chosen for each span analyzed. However, it's important to note that concrete with compressive strength over 45MPa was used for the slab with similar solutions to the load of 5kN/m^2. Despite these concretes emitting a higher amount of CO_2, their use compensates for the final strength of the composite section.

4 Conclusions

The present study aimed to present a multi-objective formulation for prestressed steel and concrete composite beams, applying the MOPSO to obtain optimal solutions. According to the results, the algorithm was efficient in searching for solutions for different load stages and according to the results of the comparative analysis with the single-objective optimization algorithm presented by Fiorotti [11]. Although the results are similar, the geometries obtained for the MOPSO solutions differed from those proposed in Fiorotti's study [11].

The results indicated that for the same load situation, more than one solution was presented in the Pareto Fronts, thus allowing the design engineer to choose the best solution from the cost and environmental points of view. It can also be observed that for the analyzed spans, the maximum loads of the beams were 6.5kN/m^2 for the spans of 35m and 37.5m, and 6kN/m^2 for the span of 40m, with composite slabs with concrete above 45 MPa. These results highlight the importance of using higher-strength concrete in prestressed composite elements.

Acknowledgements. The authors 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 first and fourth authors.

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] Netto, P. M. ; Calenzani, A. F. G. ; Alves, É. C. . Optimum design of prestressed steel beams via genetic algorithm. REM - International Engineering Journal, v. 76, p. 29-37, 2023.
[2] Fiorotti, K. M. ; Silva, G. F. ; Calenzani, A. F. G. ; Alves, E. C. . Optimization of steel beams with external pretension, considering the environmental and financial impact. Asian Journal Of Civil Engineering (Building And Housing), p. 1, 2023
[3] Coello Coello, C. A., Van Veldhuizen, D. A., & Lamont, G. B. Evolutionary algorithms for solving multi-objective problems (Vol. 5). 1999, Springer Science & Business Media
[4] Baei, M., Terzic, V. Optimal design of dampers in seismic applications utilizing the MOPSO algorithm. Frontiers, p.1-13, 2022
[5] Xu, Z., Ning, X., Li. R., Wan, X., Zhao, C. Configuration Optimization of a Shell-and-Tube Heat Exchanger with Segmental Baffles Based on Combination of NSGAII and MOPSO Embedded Grouping Cooperative Coevolution Strategy. Process, p. 1-25, 2023.
[6] Malashin, I., Tynchenko, V., Gantimurov, A., Neylub, V., Borodulin, A., AMulti-Objective Optimization of Neural Networks for Predicting the Physical Properties of Textile Polymer CompositeMaterials, Polymers, p. 1.21, 2024.
[7] MATLAB version: 9.8.0 (R2020a), Natick, Massachusetts: The MathWorks Inc.; 2020.
[8] Santoro J F, Kripka M. Minimizing environmental impact from optimized sizing of reinforced concrete elements. Computers and Concrete 2020, 25: p. 111-118.
[9] SINAPI: Metodologias e Conceitos: Sistema Nacional de Pesquisa de Custos e Índices da Construção Civil / Caixa Econômica Federal. – 9ª Ed. – Brasília: CAIXA, 2023.
[10] World Steel Association. Life cycle inventory (LCI) study, 2020 data release [Internet]. 2020 [cited 2023 Nov 13]. Available from: https://worldsteel.org/wp-content/uploads/Life-cycle-inventory-LCI-study-2020-data-release.pdf
[11] Fiorotti, K.M. Redução da Emissão de CO2 de Vigas Mistas Protendidas de Aço e Concreto via Algoritmos Metaheurísticos. 2023. Dissertação (Mestrado em Engenharia Civil) - Universidade Federal do Espírito Santo