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Optimization of CO_2 Emission of the Composite Floor System via Metaheuristics Algorithm

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Abstract

Due to the growing demand from the civil construction sector around the world, actions minimizing greenhouse gas emissions from this sector have become necessary. Within this scenario, composite steel, and concrete structures have shown to be a good alternative, considering the recyclability of steel and the reduction in the use of concrete. Our study aims to present the formulation of the optimization problem, as well as its application for the composite steel and concrete system with steel deck slabs, aiming at minimizing the CO2 emission of the structure production. To solve the optimization problem, the Genetic Algorithm (GA) and the Particle Swarm Optimization (PSO) were used to verify the convergence of the solutions. Our models were compared with models from the literature to verify the effectiveness of the proposed solution, as well as the impact of the solutions for different classes of concrete strength. The results show that the best solution from the environmental point of view will not always be the best solution from the economic point of view and that the algorithms were efficient in determining the optimal solutions.

Keywords: Steel-Concrete composite structures; Optimization; CO_2 emission; Genetic Algorithm, Particle Swarm Optimization.

1. Introduction

Since the Industrial Revolution, global warming has intensified, leading to constantly rising temperatures. Global warming is the process in which the terrestrial oceans and atmosphere increase in temperature, the main reason for this increase is the burning of fossil fuels and the release of CO_2 (carbon dioxide) and CH_4 (methane).

In recent years, the need to reduce CO_2 emissions on Earth has become clear, leading several countries to sign the Paris Agreement[1] , in which serious measures were indicated to reduce greenhouse gas emissions. In this sustainability scenario, civil construction has a crucial role due to its area of influence; thus, an algorithm/routine that optimizes parameters measuring the sustainability of a construction is shown to be of great environmental and economic importance.

After water, concrete is the second most used material in the world. The emission of CO_2 from the concrete production cycle is responsible for 5% of all CO_2 generated by humans on Earth (WBCSD [2]). Flower et al. [3] also mention that the consumption of concrete is of the order of one ton per year for each living human being. In other words, the large consumption of concrete worldwide, the high emission per m^3 produced, and the low rate of reuse make concrete the main obstacle for reducing global warming gases in civil construction. The composite structures of steel and concrete appear to reduce the amount of concrete used. Additionally, the steel recycling capacity, without loss of quality, also favors the reduction of emission. This constant recycling of steel can be understood as a concept called circular economy. This concept proposes to eliminate the notion of waste, keeping materials in use for as long as possible.

To investigate the environmental impact of a given product, life cycle assessment (LCA) is used, which is a compilation and assessment of inputs, outputs, and potential environmental impacts of a product system throughout its life cycle (NBR ISO 14040 (2009) [4]). Anderson et al. [5] conducted a study on the environmental impacts related to steel manufacturing based on the LCA from Swedish steel mills. Figure 1 shows which steps, from the production process to recycling, are considered in an LCA. In this way, the coefficients regarding the emission from an LCA represent the emission of the entire life of the material.

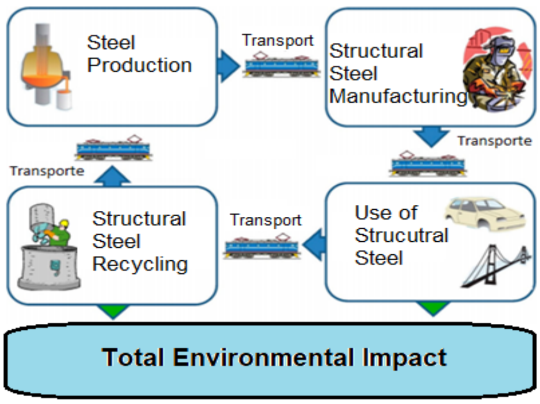

Fig. 1. Summary of environmental impact from steel production to recycling

The optimization of structures, through metaheuristic algorithms, plays an important role in minimizing cost in computational mechanics problems. Genetic algorithms have

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proven to be very effective in these optimizations. Among different works using GA, we can mention: Breda, Pietralonga, and Alves [6] composite floor system; Lourenção et al. [7] Tubular composite columns filled with concrete; Liu, Hammad, and Itoh [8] and Cho, Min, and Lee [9] who proposed the optimization for recovery and life cycle assessment of bridges, respectively, to reduce structural recovery costs and minimize the degree of deterioration of the work; Kuan-Chen Fu, Zhai, and Zhou [10]; Kociecki and Adeli [11] , Prendes-Gero et al. [12] and Kripakaran, Hall, and Grupta [13] spatial steel frames; Papavasileiou and Charmpis[14] optimized the cost of composite steel and concrete beams and columns intended for multi-story buildings built in regions prone to earthquakes.

In addition to GA, another evolutionary algorithm that stands out is the Particle Swarm Optimization (PSO), initially proposed by Kennedy and Eberhart [15], with variable applications in structural engineering, as can be highlighted in the works of the following authors:

Ratnaweera et al.[16] proposed a new automation parameter for strategies searches to improve the performance of the algorithm after a pre-defined number of generations. This proposed modification of the method showed a significant improvement in the speed rate at which the solutions converged to global minimum. Barbosa and Lemonge [17] proposed a penalty method for non-feasible solutions called the Adaptive Penalty Method (APM), aimed at improving the search criteria and convergence of the algorithm to the optimal solution. The method is based on penalizing the non-feasible solutions of the optimization problem recursively in each generation of the process. Carvalho et al. [18] proposed a variation of the PSO called Craziness Based Particle Swarm Optimization (CRPSO). In this variation, the authors demonstrated an improvement in the convergence process and results by varying the coefficients used to calculate the new particle positions and velocities in each iteration of the process. In line with the structural optimization of the PSO algorithm, the work of Poitras, Cormier, and Nabolle [19] sought to establish a relationship between the optimal solutions of composite floor systems with steel and concrete beams and the degree of interaction between steel and concrete. The results showed that the PSO can find the ideal floor configuration while minimizing the total mass or cost while satisfying all constraint criteria. Some other applications of PSO in structural optimization can be seen in several works in the literature, such as Perez and Behdinan [20], Plevris and Papadrakakis [21], and Kaveh and Zolghadr [22] with flat and spatial trusses; and Li et al. [23] with concrete dams.

Bringing to light the optimization of sustainability parameters in structures, Paya-Zaforteza et al. [24] carried out a work in which the cost and CO_2 emissions of six reinforced flat concrete frames are optimized with the Simulated Annealing algorithm, which is analogous to a metallurgy cooling process. In this study, we found that the best environmental solution was only 2.77% more expensive than the best economic solution, whereas the best economic solution represents an increase of 3.80% in CO_2 emissions.

Camp and Huq [25] carried out a study in which the objective was to reduce CO_2 emitted by concrete in reinforced concrete frames. For this, a hybrid optimization algorithm called Big Bang-Big Crunch (BB-BC) was used. Primarily proposed by Erol and Eksin **Error! Reference source not found.**, this algorithm is based on the theory of evolution and expansion of the universe starting at the Big Bang and its eventual collapse called the Big Crunch. In all models, BB-BC proved to be more efficient, reducing CO_2 emissions by up to 5.2% when compared with the Genetic Algorithm.

Lanikova, Štěpánek, and Simůnek [26] used the Monte Carlo method to optimize the emission of CO_2 and SO_2 by modifying the shape of the section of concrete structures. For the validation of the method and results analysis, a concrete column was designed, and the results were that the method used was able to reduce the emissions of the gases by up to 11% compared to the conventional production form.

Yeo and Potra [27] also carried out optimization tests of reinforced concrete structures. The results found showed that the optimization of the environmental impact occurs due to the addition of the relative amount of steel within the cross sections of the members. Another important result is that the use of the proposed optimization model for small structures shows a difference between emissions of about 10%, this number increases with the dimensions of the structures.

García-Segura and Yepes [28] presented the optimization of costs and CO_2 emissions of post-tensioned prestressed concrete road bridges, for which a formulation of the problem was carried out in a finite element analysis. The results showed that the optimization of costs and environmental impact were similar and an average reduction of 2.34 kg of CO_2 was found for every €1 saved.

Also regarding the optimization of costs Kaveh, Izadifard, and Mottaghi (, Kaveh, Izadifard, and Mottaghi (2014 [29] conducted a study in which they investigated the relationship between the optimal cost and the lowest amount of CO_2 emitted for reinforced concrete frames. The Enhanced Colliding Bodies Optimization (ECBO), Enhanced Vibrating Particles System (EVPS), and Particle Swarm Optimization (PSO) algorithms were used to compare the optimal solutions. The results showed that ECBO presented a greater research capacity and, consequently, resulted in better solutions for the proposed models. Along the same lines, Lagaros (2018) [30] discusses in his work whether, from an economic and environmental point of view, studies searching for structural optimization are worthwhile. He highlights that the discussion on the use of materials with lower environmental impacts should be the basis in the training of future generations of structural engineers.

Kripka and De Medeiros [31] emphasize the environmental damage caused by the transport and manufacture of reinforced concrete inputs. Thus, a study was carried out to optimize the monetary and environmental costs of rectangular reinforced concrete columns subjected to compressive and combined bending through the Harmony Search Algorithm (HS). Environmental emissions were determined by analyzing the concrete life cycle.

Tormen et al. [32] conducted a study on the formulation for the optimization with the use of HS of the CO_2 emission in composite steel and concrete beams. The study is carried out on optimized solutions for different spans with a minimum interaction of 40%. The conclusions pointed out that the increase in the thickness and width of the steel profiles' tables provided an increase in inertia and, consequently, an improvement in the resistance capacity and material savings. Regarding the degree of interaction and the number of connectors, it was found that, in general, the cost did not change in this variation.

Santoro and Kripka [33] presented the formulation of the optimization problem for reinforced concrete beams as well as the prediction of CO_2 emission for different concrete compositions with compressive strength ranging from 20 to 50 MPa. In this study, they pointed out that, in relation to CO_2 emission, there is a reduction in costs for solutions with less resistant concrete. Additionally, they concluded that any reductions in the dimensions of the cross section of the beams based on a greater strength of the concrete may not show satisfactory results in relation to environmental impact and financial cost.

Although the reduction of greenhouse gas emissions is quite relevant, there are few works that seek the minimization of these gases by metaheuristic algorithms.

In recent years, environmental problems have proved to be an alarming factor in society, the combination of an optimization that considers the CO_2 emissions minimization and not just the costs involved, proves to be very relevant. In view of this scenario, our work aims to present the formulation of the optimization problem as well as its application for composite steel and concrete floor systems. Our main objective is to minimize CO_2 emissions in the production of floorings, considering the main and secondary beams, columns, and steel deck slabs. The optimization problem solution was obtained with GA and PSO algorithms.

2. Optimization problem formulation

For the implementation of the optimization problem, an application called Composite Frame was developed within the Matlab platform. The program considers the design and optimization routines for composite steel and concrete floor systems – with composite beams, steel deck incorporated into the concrete slab, and steel columns – with the objective function of minimizing CO_2 emissions. Steel deck slab are defined based on the Metform® catalog [34] , steel profiles for beams and columns that can be laminated, from the Gerdau® company catalog [35] . Figure 2 shows the detail of the connection between the beams of the floor system proposed in this work.

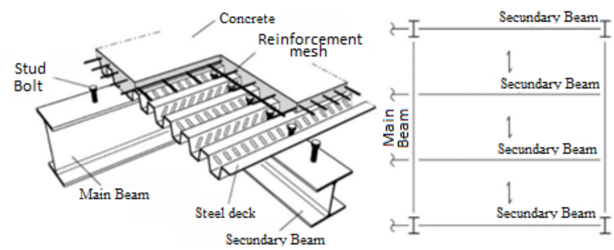

Fig. 2. Composite floor system with steel deck slab

Design loads are calculated according to NBR 6120 [36] . The procedures of these technical standards serve as the basis for the design of the constraint function, responsible for validating or not the final solution obtained. The amount of CO_2 in kg per kilogram of steel used in profiles, reinforcements, and shear connectors will be adopted based on the World Steel Association steel products life cycle assessment (LCA) database [37] .

2.1 Objective function

The objective function is composed of the sum of CO_2 emissions from each element of the structure (beams, columns, steel deck form, concrete, steel mesh, connectors, seam reinforcement, and profile weld). The objective function for optimizing the environmental impact, measured in kg of CO_2 emissions, is presented in Equation (1).

$$Minimize\ CO_2 = CO_{2(beams)} + CO_{2(steel\ deck)} + CO_{2(concrete)} + CO_{2(mesh)} + CO_{2(columns)} \tag{1}$$

in which $CO_{2(beams)}$ corresponds to the CO_2 emission value of the steel profile, the seam reinforcement, and the shear connectors of the secondary and main composite beams given by the sum of Equations (2) and (3)

$$CO_{2(beams)VS} = (2 + n_{beams}).[(\rho_{steel}.A_a.L.E_{steel}) + (n.\rho_{steel}.V_c.E_{steel}) + (A_s.l_b.\rho_{steel}.E_{steel})] \tag{2}$$

in which the first part of the function is the sum of secondary beams, represented by n_{beams}, and two parallel external beams; while ρ_{steel} is the specific mass of the steel of the beam profile in kg/m^3, A_a is the cross-sectional area of the beam profile (m^2), L is the length (m) of the beam , E_{steel} is CO_2 emissions from steel (kgCO_2/kg), n is the number of stud bolt connectors of the secondary beams , V_c is the volume of the stud bolt connector (m^3), A_s is the steel area of the seam reinforcement (m^2), and l_b is the anchorage length of the seam reinforcement in meters (m).

$$CO_{2(beams)VP} = (V_{steel}.E_{steel}.\rho_{steel}) + (n_p.V_c.\rho_{steel}.E_{steel}) + (A_{sp}.l_{bp}.\rho_{steel}.E_{steel}) \tag{3}$$

in which V_{steel} is related to the volume of the main beam profile perpendicular to the secondary beam (m^3), n_p is the quantity of main beam stud bolt connector, A_{sp} is the steel area of the main beam seam reinforcement (m^2), and l_{bp} is the anchorage length of the main beam seam reinforcement (m).

$CO_{2(concrete)}$, represents the CO_2 emission from the concrete shown in Equation (4).

$$CO_{2(concrete)} = E_{conc}.\ A_{slab}.v_{conc} \tag{4}$$

in which E_{conc} corresponds to the CO_2 emission of the concrete of the slab (kgCO_2/m^3), A_{slab} is the rectangular area of the slab to be covered with the built-in formwork (m^2), and v_{conc} is the consumption of concrete (m^3/m^2).

$CO_{2(steeldeck)}$ is the emission of the steel deck form shown in Equation (5) (5).

$$CO_{2(steeldeck)} = A_{slab}\ .\ p_{steeldeck}\ .E_{sd} \tag{5}$$

in which $p_{steeldeck}$ represents the weight of the steel deck formwork (kg/m²) and E_{sd} is the CO_2 emission of the steel deck formwork (kgCO_2/kg).

$CO_{2(columns)}$ represents the emission from the steel columns shown in Equation (6).

$$CO_{2(columns)} = 4.(\rho_{steel}.A_{columns}.E_{steel}.L_{columns} \tag{6}$$

in which $A_{columns}$ is the cross-sectional area of the column and $L_{columns}$ is the length of the columns (m).

The concrete CO_2 emission used were proposed by Santoro and Kripka 0. The emission of steel was found in the steel life cycle report carried out by the World Steel Association [39] and the CO_2 emission related to the weld that is necessary for the formation of the welded profiles was based on the study by Sproesser et al. 0. After assembling the emissions from the traces, Tables 1 and 2 were devised, in which the values of the CO_2 emission rate of the materials considered in the modeling of the objective function are presented.

Table 1. CO_2 emission in concrete production.

Concrete (Mpa)	***Emissions*** ($kgCO_2/m^3$)
20	129.85
25	142.71
30	153.68
35	163.25
40	171.73
45	189.60
50	199.72

Source: Santoro e Kripka 0[33]

Table 2. CO_2 emission in steel production.

Material	**Unity**	**Emissions** ($kgCO_2$)
Steel deck formwork	kg	2.6380
Steel Profile		
Stud bolt Connector	kg	1.1160
Reinforcement Steel		
Steel CA-50, ø 8 mm	kg	1.9240
Weld	kg/m	$0.02 \cdot A_{wl}$

Source: World steel Association 0 and Sproesser et al. 0

2.2 Design variables

Overall, eight design variables were preliminarily considered: two for the main beams, two for the secondary beams, seven for the choice of steel deck characteristics, and one for the choice of columns.

$x(1)$: Profile of secondary beams;
$x(2)$: Interaction degree of the secondary beams;
$x(3)$: Slab height and formwork thickness according to Metform ® 0;
$x(4)$: Maximum slab span according to Metform ® 0;
$x(5)$: The type of form according to Metform ® 0;
$x(6)$: Profile of the main beams;
$x(7)$: Degree of interaction of the main beams;
$x(8)$: Columns profiles.

The vector l_b (lower bonds) represents the minimum values, and u_b (upper bonds) the maximum values:

$$\boldsymbol{l_b} = [1, 40, 1, 1, 1, 1, 40, 1] \tag{8}$$

$$\boldsymbol{u_b} = [541, 100, 24, 16, 4, 541, 100, 541]. \tag{9}$$

Equations 8 and 9 show that the limits corresponding to $\boldsymbol{x(1)}$, $\boldsymbol{x(6)}$, and $\boldsymbol{x(8)}$ are equal since these variables are obtained through the same table. The profiles used in the optimization are laminated and welded, thus totaling 541 profiles with different characteristics. The variables $\boldsymbol{x(2)}$ and $\boldsymbol{x(7)}$ represent the degrees of interaction of the secondary and main beams, respectively, and the minimum degree of interaction is 40%. Variables $\boldsymbol{x(3)}$ and $\boldsymbol{x(4)}$ are values obtained directly from the table of the steel deck company Metform, in which the variable $\boldsymbol{x(3)}$ represents the thickness of the concrete slab and steel deck formwork, and variable $\boldsymbol{x(4)}$ indicates the maximum spans that can be adopted in the optimization. As 16 different values are adopted for the maximum spans for each type of formwork (MF-50: 1.8 to 3.2 m and MF-75: 2 to 4 m), this is the maximum number that this variable assumes. The variable $\boldsymbol{x(5)}$ determines whether the form to be used will be the MF-50 or MF-75 and which direction the steel column will be adopted, thus presenting four elements in its domain.

2.5 Constraints problem

Within the problem, 21 inequalities are considered as constraints. The technical limitations imposed on the structural design are given by Brazilian standards 0 which is responsible for regulating the design of steel and the structures of composite steel and concrete. Equations 10 to 30 represent the constraints of the problems.

$$C(1):\ \frac{\frac{h_{w,s}}{t_{w,s}}}{5.7\sqrt{\frac{E_a}{f_y}}} - 1 \le 0 \tag{10}$$

$$C(2):\ \frac{\alpha_{min,s}}{\alpha_{int,s}} - 1 \le 0 \tag{11}$$

$$C(3):\ \frac{M_{Sd,s}}{M_{Rd,s}} - 1 \le 0 \tag{12}$$

$$C(4):\ \frac{V_{Sd,s}}{V_{Rd,s}} - 1 \le 0 \tag{13}$$

$$C(5):\ \frac{\delta_{t,s}}{\delta_{adm,s}} - 1 \le 0 \tag{14}$$

$$C(6):\ \frac{\frac{h_{w,p}}{t_{w,p}}}{5.7\sqrt{\frac{E_a}{f_{yk}}}} - 1 \le 0 \tag{15}$$

$$C(7):\ \frac{\alpha_{min,p}}{\alpha_{int,p}} - 1 \le 0 \tag{16}$$

$$C(8):\ \frac{M_{Sd,p}}{M_{Rd,p}} - 1 \le 0 \tag{17}$$

$$C(9):\ \frac{V_{Sd,p}}{V_{Rd,p}} - 1 \le 0 \tag{18}$$

$$C(10):\ \frac{\delta_{t,p}}{\delta_{adm,p}} - 1 \le 0 \tag{19}$$

$$C(11):\frac{Q_{Rd}}{Q_{Sd}} - 1 \le 0 \tag{20}$$

$$C(12)\ \ \frac{M_{Sd,0,s}}{M_{Rd,0,s}} - 1 \le 0 \tag{21}$$

$$C(13):\frac{M_{Sd,0,p}}{M_{Rd,0,p}} - 1 \le 0 \tag{22}$$

$$C(14)\ \ \frac{H_{v,Sd,s}}{H_{v,Rd,s}} - 1 \le 0 \tag{23}$$

$$C(15):\frac{H_{v,Sd,p}}{H_{v,Rd,p}} - 1 \le 0 \tag{24}$$

$$C(16)\ \ \frac{N_{Sd}}{N_{Rd}} - 1 \le 0 \tag{25}$$

$$C(17):\begin{cases} \frac{N_{Sd}}{2N_{Rd}} + \frac{8}{9}\frac{M_{Sd,Pi}}{M_{Rd,Pi}} \\ ou \\ \frac{N_{Sd}}{2N_{Rd}} + \frac{8}{9}\frac{M_{Sd,Pi}}{M_{Rd,Pi}} \end{cases} \tag{26}$$

$$C(18)\ \frac{\frac{b_{f,p}}{t_{f,p}}}{0.38\sqrt{\frac{E_a}{f_{yk}}}}-1\ \leq\ 0 \tag{27}$$

$$C(19):\frac{\frac{2t_{w,p}-2R}{t_{w,p}}}{3.76\sqrt{\frac{E_a}{f_{yk}}}}-1\ \leq\ 0 \tag{28}$$

$$C(20):\begin{cases}\frac{1.05\cdot b_{f,p}}{b_{f,Pi}}\\ ou\\ \frac{1.05\cdot b_{f,p}}{h_{w,Pi}}\end{cases} \tag{29}$$

$$C(21):\begin{cases}\frac{1.05\cdot b_{f,s}}{h_{w,Pi}}\\ ou\\ \frac{1.05\cdot b_{f,s}}{b_{f,Pi}}\end{cases} \tag{30}$$

The constraint group $G_1 = \{C(1), C(2), C(3), C(4), C(5)\}$, formed by equations 10 to 14 has a very similar form to the group $G_2 = \{C(6), C(7), C(8), C(9), C(10)\}$, formed by equations 15 to 18. The constraints of these groups represent, respectively: the web slenderness limitation, the degree of interaction, the ultimate limit state (ULS) for bending, ULS for shear, ELS of permissible deflection. G_1 represents the variables of the secondary beams, and G_2 represents the characteristics of the main beams. $C(11)$ is the maximum load (kN/m²) that the steel deck supports, $C(12)$ and $C(13)$ are the ULS related to the bending moment before the curing of the concrete, that is, in an unsupported construction. The constraints $C(14)$ and $C(15)$ represent the constraints regarding the seam reinforcement, $C(16)$ and $C(17)$ represent the ULS related to the compression of the columns and the verification of the combined compression and bending stress at the top of the column, respectively. The last four constraints are related to the geometric constraints of the problem. $C(18)$ and $C(19)$ are normative requirements related to the main beam and the negative moment that it may be subjected to if there is a rigid connection between beam and column. $C(20)$ and $C(21)$ are defined according to the variable $\boldsymbol{x}(\mathbf{5})$, which defines, in addition to the steel deck formwork, the way in which the edge beams will be connected to the columns. Figure 3 shows the two configurations that can happen in the connections of the edge beams with the columns.

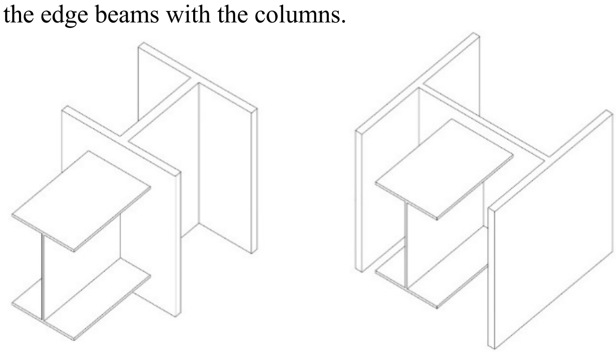

Fig. 3. Forms of connection Beams-Columns

The properties of the materials used and the weighting factors common to the analyzed models are:

- Steel modulus of elasticity E_a = 200 GPa;
- Specific mass of steel: 78.50 kN/m³;
- Shear connector steel tensile strength f_{ucs} = 415MPa;
- Coefficient of actuation effect of groups of connectors: R_g= 1;
- Coefficient for considering connector position R_P = 0.6;
- Shear Connector Strength Weighting Factor γ_{cs} = 1.25;
- Concrete strength weighting factor γ_c = 1.4;
- Steel profile strength weighting factor γ_a = 1.1;

To determine the optimal solutions and compare them, the GA and PSO will be used. The GA used was the native toolbox of the MATrix LABoratory software – MATLAB® [40]. The PSO was also implemented on the same platform (MATLAB) so that the optimization results could be compared and analyzed in terms of solution efficiency. For GA, the maximum number of generations adopted was 100; the crossover factor, which is the fraction of the current population that will be present in the next generation, was equal to 0.8; and the population size was equal to 200 individuals. In PSO the maximum number of iterations was set at 100 and the population size to 100 individuals.

3. Numerical simulations and results analysis

3.1 Algorithm efficiency analysis

The first model was proposed by Poitras, Cormier, and Nabolle [41], in which a composite floor system with dimensions of 8 m and 6 m was analyzed. For the original optimization, a new metaheuristic algorithm called Peloton Dynamics Optimization (PDO) was proposed, which is based on the behavior of platoons of cyclists during races. The loads used in this work followed the same intensities as those proposed by the original 2018 article. The dead and live loads were of 4.8 kN/m² and 2.4 kN/m², respectively. Additionally, the edge beams were also requested: the secondary beams by 16 kN/m and the main beams by 25.6 kN/m.

To perform the convergence test, we verified whether the solutions of the model converged to the same global minimum starting from random locations within the sample space of the variables. The strength of the concrete used was 30 MPa, and the composite floor system and the columns with a ceiling height of 3 m were executed. The algorithms were run 50 times and the results were analyzed. Figures 4 and 5 represent the convergence of the optimal solutions of the Genetic Algorithm and the Particle Swarm Optimization, respectively.

Fig. 4. GA Convergence

In the GA there was a convergence to the optimized solution in 94% of the results, in the PSO there was a convergence to the optimal result in 88% of the results. The PSO showed a variety in the proposed solutions, finding a total of 6 beyond the optimal solution, the Genetic Algorithm on the other hand found only one solution beyond the optimal one. Although the PSO found a greater variety of solutions, the result of the best optimized solution of the PSO was 6% lower than the solution found by the GA.

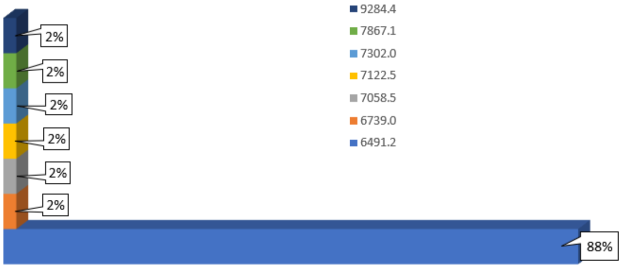

Fig. 5. PSO Convergence

In addition to the convergence test, the model was developed in the optimization routine and the results compared with those found by the authors. Figure 6 presents the constructive arrangement for the frame proposed by the authors.

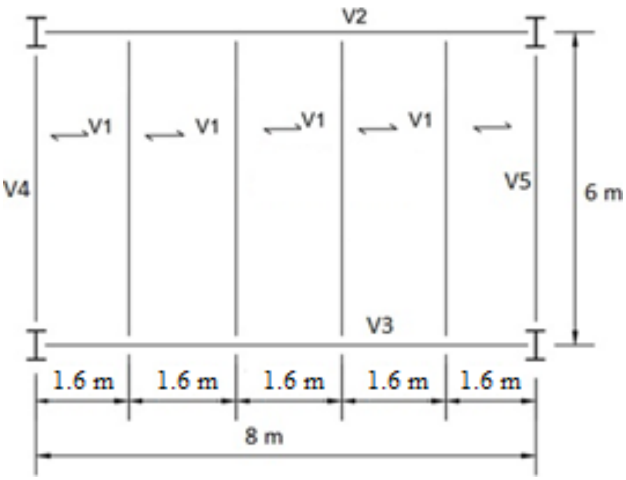

Fig. 6. Propose Geometry

The sample space of steel deck slabs is formed by two different thicknesses (0.76 and 0.91 mm). The result of the model for the dimensions of a 6m long by 8m wide floor showed 4 interior beams (V1) with the profile of W 310 × 24; 2 main beams, V2 and V3, with W 530 × 74 and W 460 × 52, respectively; and 2 edge beams, V4 and V5, parallel to V1, with W 310 × 24 and W 310 × 21 profiles. According to the company catalog **Canam® [42]** the concrete needs to have a characteristic of compressive strength (f_{ck}) of at least 20 MPa for the steel deck characteristics, so this was the value initially considered in the optimization.
After the optimization, the optimal solution configuration obtained by the algorithms (GA and PSO) was with the same number of interior beams. This configuration is represented in Figure 7.

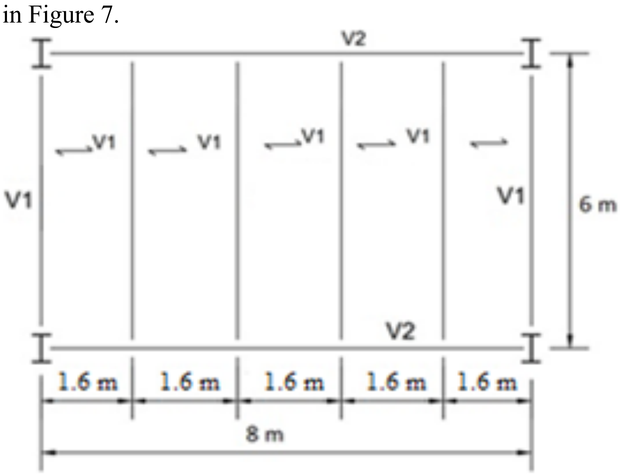

Fig. 7. Geometry found by the algorithms (GA and PSO)

Table 3 shows the profiles selected for the main and secondary beams by the genetic algorithm and the particle swarm optimization for the f_{ck} 20 MPa.

Table 3. Profiles selected by the algorithms

	GA	*PSO*
Secondary Beams (V1)	W 410 × 38.8	W 360 × 39.0
Girder (V2)	W 200 × 22.5	W 250 × 22.3

Table 4 shows the comparison between the constructive characteristics of the optimized solution found by the GA and PSO used in this work and the solution found by Poitras, Cormier, and Nabolle (2018) [43].

Table 4. Constructive characteristics with f_{ck} 20 Mpa.

Information	*Un.*	*Poitras, Cormier, and Nabolle 0*	*GA Authors (2022)*	*PSO Authors (2022)*
Nº of Secondary Beams	un	6	5	5
Steel Deck	--	PC-3615	MF-75	MF-75
Formwork thickness	mm	0.76	0.8	0.80
Maximum spam of slab	m	1.69	210	220
Slab total height	cm	9.00	16.00	16
Concrete thickness	cm	5.20	12.00	11
Reinforcement mesh	--	Q-75 (ø3.8-150x150)	Q-113 (ø3.8-100x100)	Q-113 (ø3.8 x ø3.8 – 100x100)
Secondary Profile Beams	--	5 de W 310 x 24 1 de W 310 x 21	W 410 x 38.8	W 360 x 39.0
Iteration Degree of Secondary Beams	--	---	0.95	0.95
Stud Bolt Secondary Beams	un	---	264	264
Girder Profiles	--	W 530 x 74 e W 460 x 52	W 250 x 22.5	W 250 x 22.3
Iteration Degree of Girder	un	---	0.67	0.62
Stud Bolt of Girder	--	---	44	40

With the results presented in Table 4, the CO_2 emissions of the proposed structures were calculated, and these values were compared. Table 5 shows this comparison of the emission in kg of CO_2 of the solutions.

Table 5. CO_2 emission from model 01 for f_{ck} 20 Mpa.

Elements	*Poitras, Cormier, and Nabolle 0*	*GA Authors (2022)*	*PSO Authors (2022)*
Secondary Beams	1044.14	2076.38	1940.03
Girders	1824.93	562.59	560.98
Steel deck	1776.30	1770.62	1770.63
Slab Concrete	1064.54	1102.38	1102.38
Reinforcement Mesh	111.75	277.05	277.06
TOTAL	5821.66	5789.04	5651.07

As can be seen, the optimal solutions were those with a greater thickness of the concrete cover, but by selecting the smallest steel deck formwork (MF-50), the reason for this choice can be seen in the reduction of the number of secondary beams and the profiles referring to the main and secondary beams compared with the proposed problem. Both algorithms showed better solutions than the one proposed by the PDO, the Genetic Algorithm showed a small improvement of the order of 1%, while the PSO managed to improve the emissions result by just over 3%.

As can be seen in Table 5, the elements that performed worse in relation to the problem proposed in model 01 were the number of secondary beams and the thickness of the concrete cover. A probable reason for the increase in the thickness of the concrete and the emission of the secondary beams is the reduced compressive strength of the concrete adopted (20 Mpa), which represents the lowest of the values used in this study. To verify this justification, the composite slab was modeled with f_{ck} ranging from 20 to 50 MPa with a step of 5 MPa, to verify any improvement in the optimization results. For this verification, the optimal dimensioning of the columns was carried out considering a ceiling height of 3m for the complete analysis of the frame. Table 6 shows the constructive information for each concrete strength of the proposed model for the Genetic Algorithm, and Table 7 presents the information for the PSO.

Table 6. GA Results

Information	*Un.*	*20 MPa*	*25 MPa*	*30 MPa*	*35 MPa*	*40 MPa*	*45 MPa*	*50 MPa*
Nº of Secondary Beams	un	5	6	6	6	6	6	6
Steel Deck	--	MF-75	MF-75	MF-50	MF-50	MF-50	MF-50	MF-50
Formwork thickness	mm	0.8	0.8	0.8	0.8	0.95	0.8	0.8
Maximum spam of slab	m	210	250	210	200	200	200	200
Slab total height	cm	16	15	15	13	11	13	14
Concrete thickness	cm	12	9.5	10	8	6	8	9
Reinforcement mesh	--	Q-113 (ø3.8 × ø3.8 – 100x100)	Q-92 (ø4.2 × ø4.2 – 150x150)	Q-113 (ø3.8 × ø3.8 – 100x100)	Q-92 (ø4.2 × ø4.2 – 150x150)	Q-75 (ø3.8 × ø3.8 – 150x150)	Q-92 (ø4.2 × ø4.2 – 150x150)	Q-92 (ø4.2 × ø4.2 – 150x150)
Secondary Profile Beams	--	W 410 × 38.8	W 410 × 46.1	W 250 × 38.5	W 360 × 39.0	W 250 × 38.5	W 360 × 39.0	W 360 × 39.0
Iteration Degree of Secondary Beams	--	0.95	0.88	0.96	0.94	0.94	0.95	0.95
Stud Bolt Secondary Beams	un	264	220	264	264	264	264	264
Girder Profiles	--	W 200 × 22.5	W 310 × 28.3	W 250 × 22.3	W 250 × 25.3	W 310 × 21.0	W 250 × 22.3	W 200 × 22.5
Iteration Degree of Girder	--	0.67	0.63	0.61	0.84	0.92	0.78	0.81
Stud Bolt of Girder	un	44	52	40	60	56	52	52
Columns Profile	un	W 360 × 44.6	W 360 × 44.6	W 460 × 52.0	W 310 × 38.7	W 460 × 52.0	W 360 × 44.6	W 360 × 44.6
Total Cost	R$	40758.77	42115.51	41333.04	40014.05	40685.94	40543.97	41521.98
Total CO_2 Emission	kg	6382.50	7053.86	6895.26	6583.21	6742.03	6817.53	7063.94

In analyzing Table 6 we notice the reduction of CO_2 emission even with the increase of the concrete strength. This behavior shows that the Genetic Algorithm makes use of certain parameters deemed more important (those that emit more CO_2) and reduces them while increasing factors that are less significant in CO_2 emission. The secondary beams do not show a significant amount of difference, with 6 beams in all models except for the 20 MPa solution. This same solution presented the greatest thickness of the concrete slab and the largest steel deck formwork. The optimal solution was shown in the f_{ck} of 20 MPa; the lowest financial cost was also found in this same solution.

Table 7 presents a wider range of solutions with 5 secondary beams. The solutions with 6 beams presented the smallest steel deck formwork and the smallest concrete slab heights. Reducing the secondary beams from 6 to 5 requires an increase in the linear mass of the profiles to support the imposed load. The optimal solution of the PSO algorithm was shown in the f_{ck} of 30 MPa. The lowest financial cost was presented in the 20 MPa solution. Notably, the results of the 20 MPa solutions, in both algorithms, presented higher values when compared with those presented in Tables 7 and 9, this is because, in the study carried out by Poitras, Cormier, and Nabolle 0, the columns were not considered. The emission increase represents the emission of the columns.

Table 7. PSO Results

Information	*Un.*	*20 Mpa*	*25 MPa*	*30 MPa*	*35 MPa*	*40 MPa*	*45 MPa*	*50 MPa*
Nº of Secondary Beams	un	5	6	6	6	5	5	6
Steel Deck	--	MF-75	MF-50	MF-50	MF-50	MF-75	MF-75	MF-50
Formwork thickness	mm	0.8	0.8	0.8	0.95	0.8	0.8	0.8
Maximum spam of slab	m	220	200	200	220	250	260	200
Slab total height	cm	16	13	13	14	17	19	14
Concrete thickness	cm	11	8	8	9	9,5	11,5	9
Reinforcement mesh	--	Q-113 (ø3.8 × ø3.8 – 100×100)	Q-92 (ø4.2 × ø4.2 – 150×150)	Q-92 (ø4.2 × ø4.2 – 150×150)	Q-92 (ø4.2 × ø4.2 – 150×150)	Q-92 (ø4.2 × ø.4.2 – 150×150)	Q-113 (ø3.8 × ø3.8 – 100×100)	Q-92 (ø4.2 × ø4.2 – 150×150)
Secondary Profile Beams	--	W 360 × 39.0	W 410 × 38.8	W 410 × 38.8	W 360 × 39.0	W 310 × 44.5	W 460 × 52.0	W 200 × 41.7 (H)
Iteration Degree of Secondary Beams	--	0.95	0.93	0.95	0.71	0.91	0.79	0.89
Stud Bolt Secondary Beams	un	264	264	264	264	220	220	264
Girder Profiles	--	W 250 × 22.3	W 310 × 23.8	W 310 × 21.0	W 360 × 32.9	W 360 × 32.9	W 250 × 22.3	W 250 × 22.3
Iteration Degree of Girder	--	0.62	0.65	0.77	0.57	0.71	0.63	0.63
Stud Bolt of Girder	un	40	44	48	52	68	40	40
Columns Profile	un	W 310 × 38.7	W 460 × 52.0	W 360 × 44.6	W 310 × 52.0	W 460 × 52.0	W 360 × 44.6	W 460 × 52.0
Total Cost	R$	40031.27	40965.34	39737.77	49025.82	43654.72	44718.36	43388.71
Total CO_2 Emission	kg	6164.77	6553.97	6491.21	8001.98	7490.1	8027.83	7293.61

The optimal solutions presented by the PSO showed a small advantage in relation to the optimization of the GA, especially in the lower strengths of concrete. In the optimal solution of the algorithms, the CO_2 emission was very similar to the PSO, presenting a value 3% lower than the optimal solution of GA. Regarding the financial cost, a 2% reduction in the cost of the optimal PSO solution was observed in relation to the Genetic Algorithm. Figure 8 shows the comparison between cost and emission.

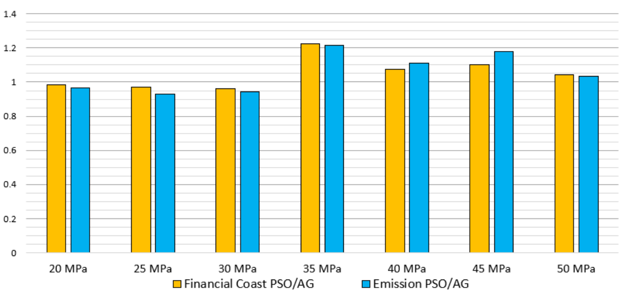

Fig. 8. Total Cost and Emission Analysis

The solutions up to 30 MPa show a better optimization of emissions and costs (ratio bars smaller than 1), from 35 MPa the genetic algorithm presented better solutions than those found by the PSO. The financial cost presented a behavior like the issuance, with the structure becoming financially advantageous for the genetic algorithm in the solutions with the highest f_{ck}. Figures 9 and 10 details each structural element and how much each one represents in the total emission of the Genetic Algorithm structure and the Particle Swarm Optimization, respectively.

From Figure 11 it is possible to notice that, in the optimization performed by GA, for all the f_{ck}, the secondary beams represented the highest CO_2 emission among all the materials of the structure. we can also conclude that the steel profiles, that is, the columns and beams, represent around 40% of all the emission from the solutions. If we consider the steel deck formwork, we arrive at a value of more than 70% of emission from steel materials. In relation to concrete, the emission from this element represents, on average, 20% of all the emission of the solutions. The f_{ck} of 20 MPa was the one that presented the lowest emissions, with the lowest concrete emission among all the solutions.

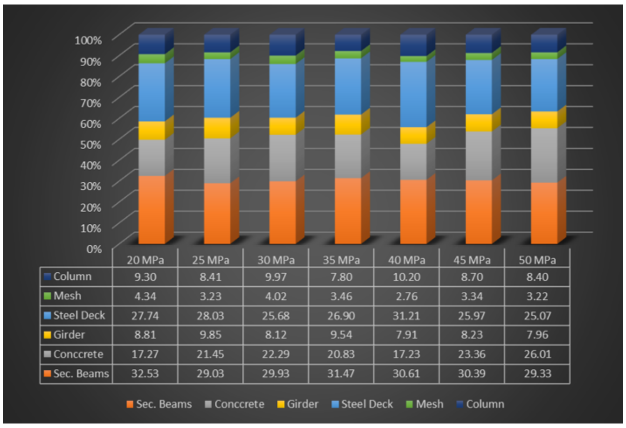

Fig. 9. CO_2 Emission for each f_{ck} – GA

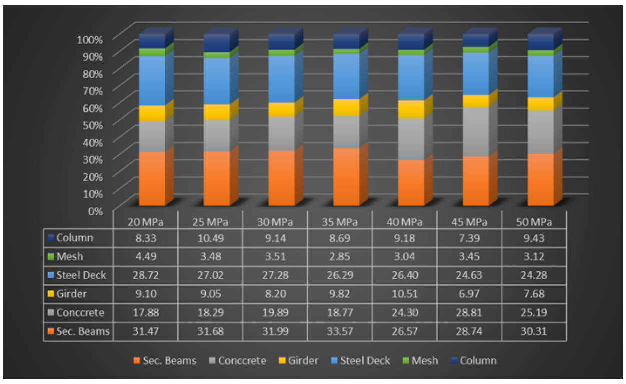

Fig. 10. CO_2 Emission for each f_{ck} – *PSO*

Figure 10 shows a similar behavior of the PSO in relation to GA. Again, the secondary beams represented the highest emission among all the elements and soon after, the steel deck was the element that most emitted CO_2. The exception is the 45 MPa solution, which presented the greatest thickness of the concrete slab (Table 11), with this the emission of the concrete exceeded the emission of the steel deck. The optimal solution occurred at 20 MPa, and, as in the genetic algorithm, this solution represented the lowest emission from the concrete slab. Similar to the genetic algorithm, the PSO presented the sum of emissions from steel elements greater than 70% of all the emission of the optimal solutions.

Among the various constraints imposed on the problem, the main and most important ones for the analysis are those that refer to the ultimate limit states (ULS) of the beams and columns. The beams are dimensioned to the bending moment and shear force, and the columns are dimensioned to the normal compression force. The analysis of these characteristics is done in relation to the optimization percentage, that is, the ratio between the requesting efforts and the resisting ones. Figures 11 and 12 present an analysis of the constraints that govern the optimization problem for the ULS of the structural elements of different f_{ck} for the genetic algorithm and PSO, respectively.

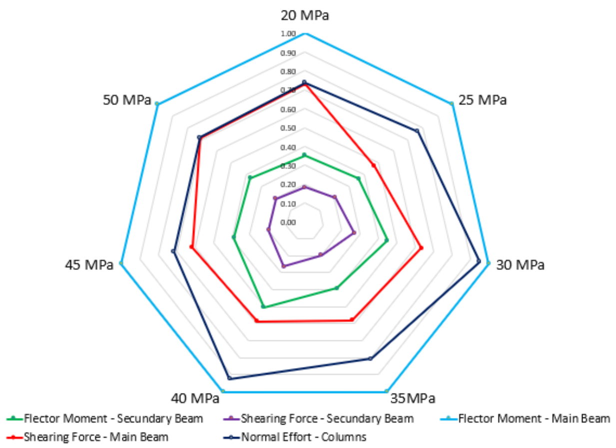

Fig. 11. Constraints Analysis – GA

Fig. 12. Constraints Analysis – *PSO*

The constraints analysis of the solutions proposed by GA (Figure 11) clearly demonstrates that the constraints closest to being active were those related to the bending moments of the main beams that represent the limit states with greater optimization reaching 100% in virtually all f_{ck}. The normal effort to which the columns are subjected proved to be the second largest ULS optimization of the genetic algorithm. In the 30 and 40 MPa solutions, the optimization of this effort was above 95%. The limit states to which the secondary beams are subjected (bending moment and shear force) were shown to be the smallest optimizations, being below 50% in all solutions. Overall, the 30 MPa solution showed the best percentage of optimization considering the five ultimate limit states.

The PSO (Figure 12) showed a lower optimization of the bending moment of the main beams, but it was always above 80% and was the highest optimization among the ULS in all concrete strengths. The normal stress to which the column is subjected was the lowest among the limit states analyzed. The optimization of the bending moment of the secondary beams proved to be the second major optimization. Additionally, the bending moment of the secondary beams was more apparent in the PSO than in the Genetic Algorithm, another point to be highlighted was the optimization of the columns in the GA, presenting as the second greatest optimization while the PSO presented a performance substantially inferior to the one found by the GA, limited to a maximum of 25% in the 25 MPa solution and being the smallest among all the analyzed elements.

3.2 Example 2 – Composite frame analysis

The second model presented was proposed by Poitras, Lefrançois and Cormier [19]. The original optimization was carried out through PSO and with an objective function defined as the sum of the masses of each structural component and subjected to Ultimate Limit State constraints by bending moment and shear force and Service Limit State composed of excessive deflection and vibration. In this second example, the permanent loads were 2.08 kN/m² and 4.8 kN/m² were the accidental loads. The loads on the edge beams were 8 kN/m on the secondary beams and 32 kN/m on the main beams. The secondary beams found by the authors of the study were of the laminated type and with a W 610 x 82 profile, the main beams were even heavier, formed by the W 610 x 140 profiles, the resulting steel deck was the PC-2432 with 0.91 mm of thickness and concrete slab equal 19 cm. Figure 13 shows the layout of the secondary and main beams proposed by Poitras, Lefrançois and Cormier (2011).

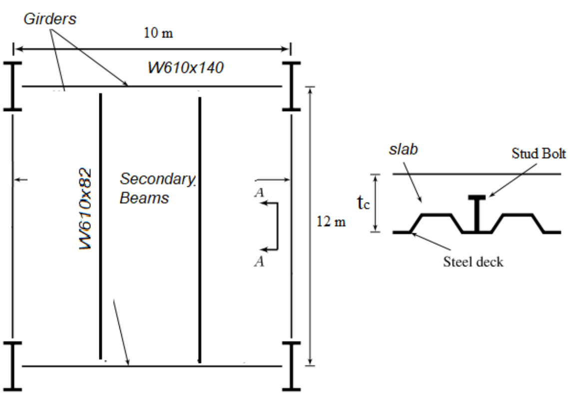

Fig. 13. Adapted from Geometry proposed by Poitras, Françoise e Cormier (2011)

After the execution of the optimization routine, the characteristics of the optimized solution were found as shown in the Figure 14 with the layout of the beams characteristics of the optimized solution. Table 8 presents the constructive characteristics found by the genetic algorithm and the particle swarm optimization, against the proposal by Poitras, Lefrançois and Cormier [19].

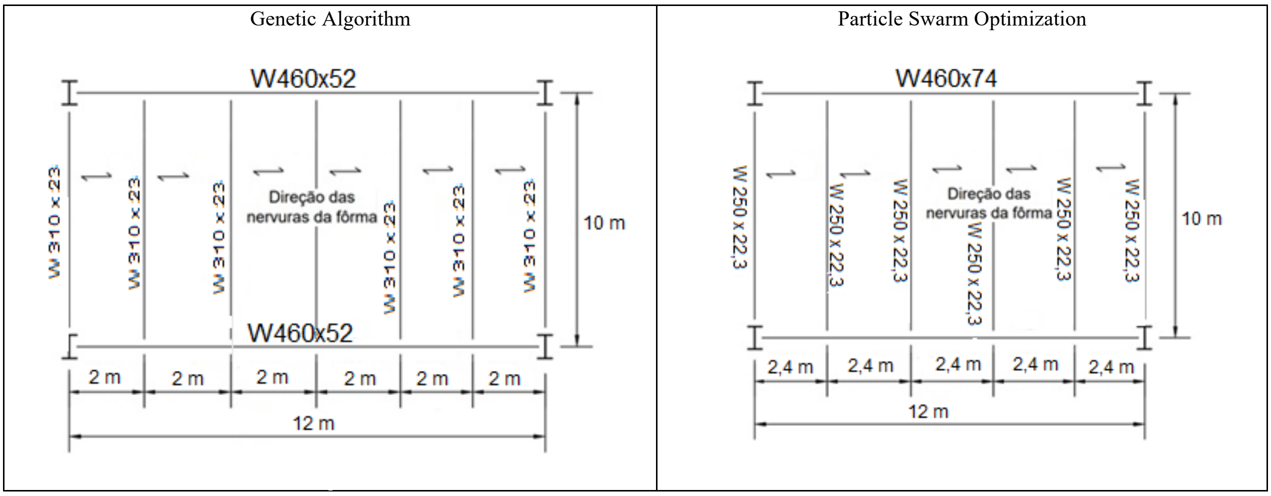

Fig. 14. Optimum Solution

Table 8. Construction characteristics with 20 MPa f_{ck}

Information	*Un.*	*Poitras, Lefrançois and Cormier [19]*	*GA Authors*	*PSO Authors*
Nº secondary beams	un	4	7	6
Steel deck	--	PC-2432	MF-50	MF-75
Steel deck thickness	mm	0.90	0.80	0.95
Maximum spam	m	12,00	200	280
Total height slab	cm	19.00	15.00	15.00
Concrete thickness	cm	11.40	10.00	7.50
Reinforcement Mesh	--	Q-75 (ø3.8-150x150)	Q-113 (ø3.8-100x100)	Q-75 (ø3.8-150x150)
Secondary beams profile	--	W 610 x 82	W 310 x 23	W 250 x 22.3
Iteration degree second. beams	--	0,75	0,97	0,90
Stud bolt second. beams	un	128	308	264
Girder Profile	--	W 610 x 140	W 460 x 52	W 460 x 74
Iteration degree Girder	un	0.75	0.70	0.40
Stud bolt Girder	--	114	48	30

As can be seen in Table 8, the number of secondary beams was different to the optimal solution considering the solution initially proposed by Poitras, Lefrançois and Cormier [19]. The reduction in the total thickness of the concrete slab and the type of steel deck formwork are structural consequences from the extra secondary beam. Moreover, the genetic algorithm showed a reduction in the linear mass of the structural profiles used in the solution. In the secondary beams, for example, the linear mass was reduced by more than 60%. In the main beams, the reduction was about 50% of the original solution proposed by Poitras, Lefrançois and Cormier [19]. The large difference in the results can be explained by the non-use of the floor vibration constraint considered by Poitras, Lefrançois and Cormier [19]. Probably this constraint should have governed the problem during the optimization phase. Table 8 also shows the characteristics proposed by the Particle Swarm Optimization, this algorithm showed a solution with characteristics similar to those presented by the Genetic Algorithm. The steel deck formwork used was also reduced, however the thickness of the concrete layer and the reinforcement mesh increased; these increases caused a reduction in the linear mass of the profiles in the secondary and main beams in addition to adopting a greater interaction between the slab of concrete and the steel profiles in these structural elements. Table 9 shows the comparison of CO_2 emissions for each member of the optimization.

According to Table 9, the CO_2 emission obtained by the formulation proposed in this work was minimized in most items, except for emissions from reinforcement mesh, which in both algorithms showed a same emission. In both algorithms used in this work, the item that showed the greatest reduction were the secondary beams, with about 22% reduction in the Genetic Algorithm and more than 10% in the Particle Swarm Optimization. In the global emission of structures, the PSO proved to be slightly better than the GA. The global emission reduction presented by the GA was 44% lower than that proposed by the authors, and the PSO showed a reduction of just under 38% when compared with the original solution.

In line with the previous models, the analysis of the optimized solution for different f_{ck} values was carried out to find the solution that emits less CO_2 to determine the influence on the results of the optimization of the environmental impact in different concrete strengths. In these analyses, the optimization of the steel column for a ceiling height of 3m was inserted, making it possible to find the best solution for financial cost and issuance of the complete gantry. Tables 10 and 11 present the constructive characteristics for each f_{ck} for the genetic algorithm and for the particle swarm optimization.

Table 9. CO_2 emission of the 25 MPa f_{ck}

Elements	*Poitras, Lefrançois and Cormier (2011) (kg)*	*GA Authors (kg)*	*PSO Authors (kg)*
Secondary Beams	4453,12	3456.80	4029.13
Girders	3155.07	670.20	711.87
Steel Deck	4444.50	2655.93	2655.93
Concrete slab	2960.58	1752.98	1947.75
TOTAL	15013.27	8535.91	9344.69

Table 10. Results found by GA.

Information	*Un.*	*20 MPa*	*25 MPa*	*30 MPa*	*35 MPa*	*40 MPa*	*45 MPa*	*50 MPa*
Nº of Secondary Beams	un	7	8	7	7	7	7	8
Steel Deck	--	MF-50	MF-50	MF-50	MF-50	MF-50	MF-50	MF-50
Formwork thickness	mm	0,8	0.8	0.8	0.8	0.8	0.8	0.8
Maximum spam of slab	m	200	180	200	200	200	200	180
Slab total height	cm	15	12	15	14	13	13	11
Concrete thickness	cm	7	10	9	9	9	9	6
Reinforcement mesh	--	Q-113 (ø3.8 x ø3.8 - 100x100)	Q-75 (ø3.8 x ø3.8 - 150x150)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-75 (ø3.8 x ø3.8 - 150x150)
Secondary Profile Beams	--	W 460 x 52.0	W 360 x 44.6	W 460 x 52.0	W 460 x 52.0	W 460 x 52.0	W 410 x 46.1	W 460 x 52.0
Iteration Degree of Secondary Beams	--	0.97	1	0.9	0.9	0.9	0.97	0.96
Stud Bolt Secondary Beams	un	308	352	308	308	308	308	352
Girder Profiles	--	W 310 x 23.8	W 310 x 23.8	W 460 x 52.0	W 310 x 23.8	W 310 x 21.0	W 250 x 25.3	W 310 x 23.8
Iteration Degree of Girder	--	0.7	0.75	0.63	0.78	0.97	0.75	0.87
Stud Bolt of Girder	un	48	52	92	52	60	56	60
Columns Profile	un	W 360 x 51.0	W 410 x 53.0	W 360 x 51.0	W 410 x 60.0	W 360 x 51.0	W 360 x 51.0	W 460 x 74.0
Total Cost	R$	66009.46	64438.55	71751.73	66151.73	64893.14	62392.76	73847.20
Total CO_2 Emission	kg	10428,49	9953,14	11275,67	10776,62	10702,01	10608,06	11269,98

Table 10 shows that, in the Genetic Algorithm, the increase in concrete strength initially causes an increase in CO_2 emissions. At 35 and 40 MPa, there is a further reduction in emission, getting close to the emission of 25 MPa. The solution that presented the lowest emission was the 20 MPa solution, corroborating the initial analysis of the increase in emission with the increase in concrete strength.

Table 11. Results found by *PSO*

Information	*Un.*	*20 MPa*	*25 MPa*	*30 MPa*	*35 MPa*	*40 MPa*	*45 MPa*	*50 MPa*
Nº of Secondary Beams	un	6	6	6	7	7	6	6
Steel Deck	--	MF-75	MF-75	MF-75	MF-75	MF-50	MF-75	MF-50
Formwork thickness	mm	0.95	0.8	1.25	0.95	0.8	0.95	1.25
Maximum spam of slab	m	280	250	240	210	210	240	290
Slab total height	cm	15.00	18	13	13	15	16	11
Concrete thickness	cm	7.50	10.5	8	8	10	8.5	6
Reinforcement mesh	--	Q-75 (ø3.8-150x150)	Q-113 (ø3.8 x ø3.8 - 100x100)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-113 (ø3.8 x ø3.8 - 100x100)	Q-92 (ø4.2 x ø4.2 - 150x150)	Q-75 (ø3.8 x ø3.8 - 150x150)
Secondary Profile Beams	--	W 460 x 74.0	W 360 x 51.0	HP 250 x 62.0 (H)	W 360 x 58.0	W 410 x 60.0	W 360 x 64.0	W 200 x 59.0 (H)
Iteration Degree of Secondary Beams	--	0.90	1	0.8	0.8	0.76	0.8	0.77
Stud Bolt Secondary Beams	un	264	264	264	308	308	264	264
Girder Profiles	--	W 250 x 22.3	W 250 x 28.4	W 250 x 38.5	W 360 x 32.9	W 310 x 23.8	W 310 x 23.8	W 530 x 85.0
Iteration Degree of Girder	--	0.40	0.78	0.69	0.7	0.75	0.88	0.73
Stud Bolt of Girder	un	30	64	76	64	52	60	176
Columns Profile	un	W 410 x 53.0	W 410 x 53.0	HP 310 x 79.0 (H)	W 360 x 51.0	W 410 x 53.0	HP 250 x 85.0 (H)	W 530 x 74.0
Total Cost	R$	70838.39	63677.09	65849.74	63991.62	61576.04	69139.32	63105.03
Total CO_2 Emission	kg	9445.37	10578.07	11145.56	11164.25	10524.29	11568.97	10973.06

Table 11, which shows the values found by the PSO, presents mostly lower emission values when compared with the results of the Genetic Algorithm. Moreover, the lowest emissions found for the problem were shown in the solutions of this algorithm (in the 20 and 40 MPa). However, the best financial solutions were obtained by concrete with 40 MPa. This solution is the smallest among all the solutions presented by the Genetic Algorithm.

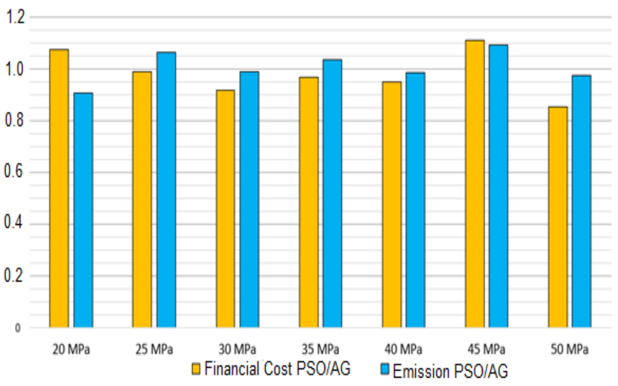

Fig. 15. Cost and Emission Analysis

Figure 15 shows that, except for the 25 and 40 MPa solutions that presented very similar values in both algorithms, in general the solutions presented by the PSO proved to be more advantageous in terms of the financial cost. The emission of structures was better in the GA; the optimal solution, however, was found by Particle Swarm Optimization at 30 MPa.

Figures 16 and 17 present the detailed emission of each of the optimized elements that make up the composite frame.

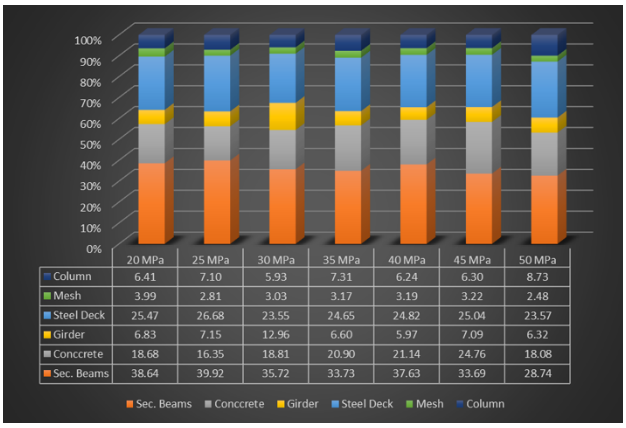

Fig. 16. CO_2 emission for each f_{ck} – GA

From the CO_2 emission graph in Figure 16, we can verify that the secondary beams represented the highest emission (on average of 33%) among all materials for all concrete strengths. The slab concrete showed an increase in emission as its characteristic strength increased. In the optimal solution presented by the Genetic Algorithm (20 MPa) the lowest emission of concrete was presented, being around 15% of the total and therefore presented the highest emission of materials formed by steel (beams, columns, and formwork) reaching a higher value than 80% in this solution.

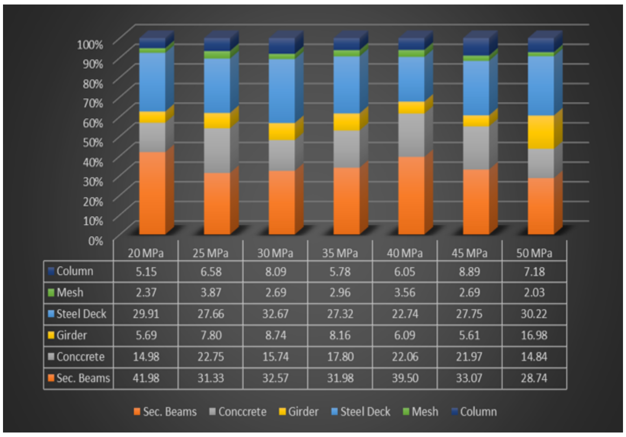

Fig. 17. CO_2 emission for each f_{ck} – *PSO*

Figure 17, which presents the emission of the solutions proposed by the PSO, shows some changes in relation to the Genetic Algorithm. First, the total concrete emissions were slightly higher than those presented by the Genetic Algorithm. In the optimal solution (20 MPa) the concrete showed the lowest emission among all the solutions, a behavior similar to the Genetic Algorithm. The secondary beams represented a large part of the total emission of the structure, always being above 26% in most solutions. The exceptions can be observed in the f_{ck} of 20 and 30 MPa, in which the steel deck formwork is the material that emits the most CO_2. Moreover, this behavior can also be seen in the 40 MPa solution (solution that obtained the highest emission among all) in which concrete proved to be the material that most emitted among all.

Figures 18 and 19 present the analysis of the constraints of the optimized solutions obtained for the different values of f_{ck} in relation to the ULS of the beams and columns for the GA and PSO, respectively.

Figure 19 shows that the bending moment of the main beam was the one that obtained the highest percentage of optimization among all the calculated limit states. Additionally, the normal stress in which the columns were submitted presented high optimizations, reaching almost 100% in 30, 45, and 50 MPa solutions. The loads on the secondary beams were substantially lower, with optimizations of around 60% and 40% for bending moment and shear, respectively, both in the 35 MPa solution.

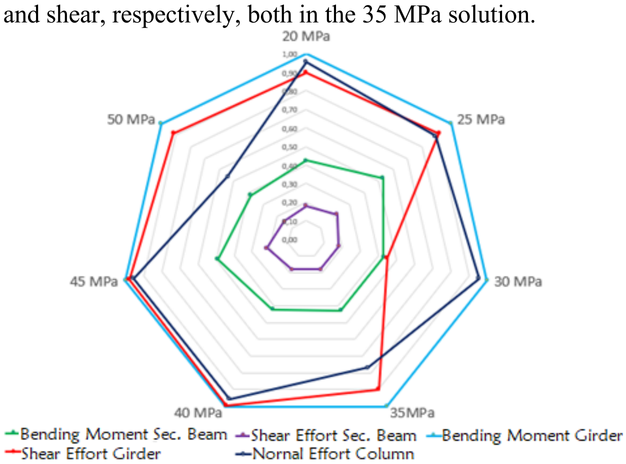

Fig. 18. Constraints Analysis Model 2 – GA

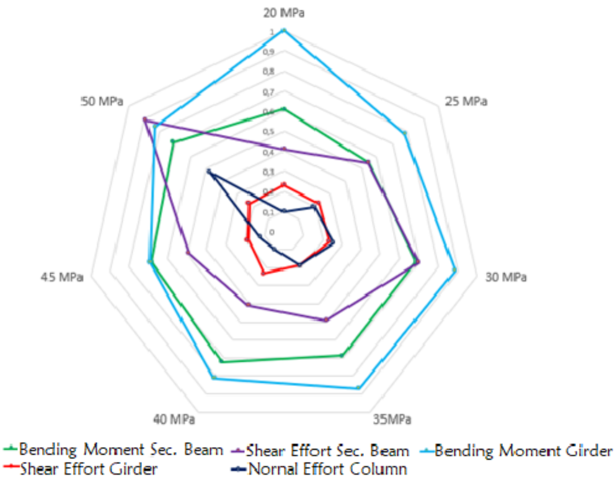

Fig. 19. Constraints Analysis Model 2 – PSO

Figure 19, which shows the optimization of constraints by Particle Swarm Optimization, shows the bending moment of the main beams as the ultimate limit state with greater optimization. None of the solutions, however, was fully optimized, reaching a maximum value of 91 % in the 45 MPa solution. The constraints related to the characteristics of the secondary beams presented, in general, a better optimization than the columns and the shearing force of the main beams. Moreover, in the 30 MPa solution, the optimization of the secondary beams was equal to the optimization of the bending moment of the main beam, and at 50 MPa the shearing force of the secondary beams also reached the maximum optimization value of the solution.

4. Conclusions

Our study aimed to present the formulation of the optimization problem involving the CO_2 emissions of a composite frame system of steel deck slabs. Two models were presented in addition to a convergence test to verify the ability of the algorithms to find the global minimum of the sample space of the solution starting from random locations. Regarding the analyses originally performed on the problems, both algorithms used in this work showed an improvement in the solution that considers the environmental impact. The main comparison that can be made is the efficiency of each algorithm in the "search" for the optimal solution. In this sense, the Particle Swarm Optimization presented solutions with less environmental impact than the Genetic Algorithm, thus the PSO proved to be more efficient than the GA in these composite frame models.

Regarding the convergence test, a high convergence (at least 88%) was observed for the optimal solution in both algorithms. The GA presented a greater convergence for the optimal solution, 94% against 88% presented by the PSO. Additionally, there was also a smaller number of solutions: GA presented 2 solutions and the PSO presented 7. The PSO, on the other hand, presented solutions with smaller emission than the GA 90% of the time, which increases the reliability of this algorithm. In summary, we noticed that the Genetic Algorithm presents a smaller variation in the solutions, converging quickly to the "absolute minimum," and that the PSO presents better and more economically and energetically efficient solutions.

From the initial analysis of the first numerical model, a small improvement was observed in the use of both algorithms in relation to the PDO proposed in the initial study. The optimal solutions always presented a greater thickness of the concrete slab than the one proposed by Poitras, Cormier, and Nabolle [41].

In the second model, the composite slab presented in the work Poitras, Lefrançois and Cormier [19] was used. In the original problem, the structural design was performed using the particle swarm optimization and considering floor vibration. When each optimization element in the genetic algorithm was analyzed separately, the secondary beams presented an almost constant increase in the representation of the total emission as the strength increased. This behavior was partially repeated in the PSO. In addition to the analyses already carried out, the optimization of the structural elements of this work clearly presented a substantially lower emission than that found by the authors.

In general terms, all the models presented the optimal solutions as the one in which the concrete represented the smallest portion of emission among all the analyzed resistances. Moreover, the steel deck formwork and the secondary beams were always the elements that emitted the most compared to the other optimized elements. In the ultimate limit states, the bending of the main beam almost always showed a maximum optimization. The optimization of the normal stress on the columns proved to be the second biggest optimization, especially in the solutions presented by the Particle Swarm Optimization whereas in the Genetic Algorithm, the shear stress on the main beams proved to be the second most optimized ULS.

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