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Cost and CO_2 Emissions Analysis in the Multi-Objective Optimization of Steel-Concrete Composite Slabs Using the MOPSO Algorithm

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Abstract. The use of steel-concrete composite slabs has expanded in recent years due to their fast construction, the elimination of formwork in most cases, and the reduction in the use of concrete and steel—materials that most significantly contribute to greenhouse gas emissions in the construction industry. In this context, the present study aims to formulate a multi-objective optimization problem for steel-concrete composite slabs, focusing on minimizing CO_2 emissions and final costs, as well as increasing their load-bearing capacity. The design constraints prescribed by Brazilian standards were considered for both the construction and service stages, using the Effective Width Method (EWM), as defined by ABNT NBR 14762:2010 for the construction stage, and ABNT NBR 8800:2024 for the service stage. To solve the problem, the Multi-Objective Particle Swarm Optimization (MOPSO) method was employed, and Pareto fronts were generated and analyzed based on the algorithm's output. An equation was proposed to relate CO_2 emissions to cost. The optimization results show that MOPSO was effective in identifying optimal solutions for simply supported composite slabs using MF-75 steel decking. The manufacturer's catalog was studied with the aim of proposing a new span and load table as a product of the applied multi-objective optimization, presenting composite slab solutions with a load capacity increased by more than 275% compared to the manufacturer's solutions, while also reducing CO_2 emissions and final structure costs due to the use of additional reinforcement. According to the results, the governing constraints in the optimization problem were the verification of the steel decking under bending moments before concrete curing, and the verification of the composite section under longitudinal shear after curing.

Keywords: Steel-Concrete Composite Slab; Multi-objective Optimization; CO_2 Emissions; Cost; Load Capacity.

1 Introduction

Steel-concrete composite slabs have been used in civil construction as a structural solution offering significant environmental and economic advantages, considering their potential to reduce or eliminate the need for shoring and formwork, thereby contributing to material waste reduction. Both experimental and computational analyses have been carried out to assess how steel decking and the addition of tensile reinforcement influence the longitudinal shear resistance of composite slabs, as demonstrated in the research by Grossi et al. [1] and Celis-Imbajoa et al. [2]. In this context, research has been conducted applying optimization techniques in the search for optimal structural solutions, aiming to minimize CO_2 emissions and cost, as seen in the works of Santoro and Kripka [3], Guimarães et al. [4], Erlacher et al. [5], Loureiro et al. [6], and Teixeira et al. [7]. Specifically regarding simply supported composite slabs, Silva et al. [8] contributed to the topic by applying a multi-objective formulation using NSGA, considering only the service phase of the slabs.

Regarding the optimization technique, recent studies have shown that MOPSO has become a sufficiently robust alternative for solving structural optimization problems, offering advantages in terms of efficiency—especially in multi-objective problems involving the optimization of environmental and economic impacts of

structures (Trentini et al. [9])—when compared to other algorithms such as NSGA-II. Studies involving the minimization of costs and CO_2 emissions along with the maximization of loads for prestressed composite beams and steel-concrete composite slabs, considering the service phase, can be found in the works of Alves et al. [10] and Silva et al. [8], respectively. Silva et al. [11] proposed a comprehensive analysis of the construction and service phases of steel-concrete composite slabs. In that study, solutions obtained through multi-objective formulations were compared to those provided by the manufacturer for slabs using MF50 steel decking, and a new span and load table was proposed for the analyzed form.

Although there are numerous studies in the literature focusing on both single-objective and multi-objective optimization of structures aimed at reducing CO_2 emissions, few have applied MOPSO or other multi-objective algorithms specifically to steel-concrete composite slabs. Thus, the objective of this study is to present a multi-objective optimization applied to steel-concrete composite slabs, considering the minimization of CO_2 emissions and final costs, while simultaneously maximizing the design load, with the goal of proposing an optimized loading table for these slabs. To solve the optimization problem, the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm was implemented on the MATLAB platform [12], aiming to obtain the Pareto fronts corresponding to the problem under study. For the construction phase, the Effective Width Method was used to analyze the steel decking, as prescribed by NBR 14762 [13], and for the service phase, the guidelines established by NBR 8800 [14] were adopted. The results were compared to the MF75 decking table proposed by the manufacturer Metform [15].

2 Formulation and Implementation of the Multi-Objective Optimization Problem

2.1 Objective function

The application of the multi-objective formulation for steel-concrete composite slabs considered three objective functions, which are presented as follows:

$$Min\ CO_2 = CO_{2(formwork)} + CO_{2(concrete)} + CO_{2(add.pos.reinf)} + CO_{2(mesh)} \tag{1}$$

$$Min\ Cost = Cost_{(formwork)} + Cost_{(concrete)} + Cost_{(add.pos.reinf)} + Cost_{(mesh)} \tag{2}$$

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

In Eq. (1), Eq. (2), and Eq. (3), Eq. (1) refers to the total CO_2 emissions, Eq. (2) represents the cost of the composite slab, and Eq. (3) refers to the maximum design load that the composite slab can withstand. $CO_{2(formwork)}$, $CO_{2(concrete)}$, $CO_{2(add.pos.reinf)}$ and $CO_{2(mesh)}$ refer respectively to the CO_2 emissions rates (in $kgCO_2$) of the steel formwork, concrete, additional positive reinforcement and mesh. $Cost_{(formwork)}$, $Cost_{(concrete)}$, $Cost_{(add.pos.reinf)}$ and $Cost_{(mesh)}$, refer respectively to the cost of the steel formwork, concrete, additional positive reinforcement, and welded mesh. Tables 1 and 2 present the unit costs and CO_2 emissions used in this study.

Table 1. Costs and Emissions- Concrete

Material		CO2 Emissions ($kgCO2/m^3$)	Source	Costs ($R\$/m^3$)	Source
Concrete (MPa)	20	129.85	Santoro and Kripka [3]	463.14	SINAPI [14]
	25	142.71		474.87	
	30	153.68		491.01	
	35	163.25		504.22	
	40	171.73		518.15	

45	189.6	532.09
50	199.72	546.02

Table 2. Costs and Emissions – Steel

Material			CO_2 Emissions ($kgCO_2/m^3$)	Source	Costs (R$/m²)	Source
Steeldeck formwork (280MPa)	MF50	esp.0.8mm	2.638	Worldsteel Association [17]	90.5	Local Supplier (2024)
		esp.0.95mm			107.64	
		esp.1.25mm			141.64	
	MF75	esp.0.8mm			99	
		esp.0.95mm			117	
		esp.1.25mm			154	
Reinforcement mesh (CA60)			1.924 ($kgCO_2/kg$)		10.48 R$/kg	SINAPI [14]
Welded Mesh (CA60)						

2.2 Design variables

For the presented multi-objective optimization problem, three design variables were considered, as can be seen in Figure 1. Only discrete variables were used in this formulation, where x_1 refers to the thickness of the concrete layer (t_c), x_2, is the characteristic compressive strength of the concrete (f_{ck}), x_3 is the thickness of the steel formwork (t_f), x_4 is the positive additional reinforcement ratio (ρ_R), x_5 is the diameter of the positive additional reinforcement ($\emptyset_R$) and x_6 refers to the design load of the composite steel-concrete slab.

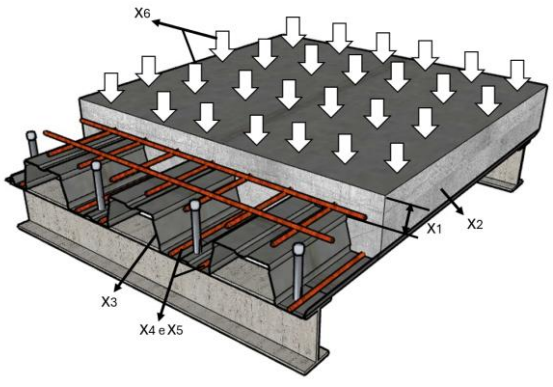


Figure 1. Design variables for composite steel-concrete slabs: Adapted from Silva et al. [8]

Table 3 presents the search intervals adopted for the design variables considered in this study.

Table 3. Space of search design variables (MF-75)

	Variables	Intervals
x_1	Thickness of concrete layer (mm)	55 to 125, with an interval of 10
x_2	Characteristic compressive strength of concrete (MPa)	20 to 50, an increase of 5
x_3	Thickness of steel formwork (mm)	0.8, 0.95, and 1.25
x_4	Additional reinforcement rate (%)	0 to 0.5 with increase of 0.05
x_5	Additional reinforcement diameter (mm)	5.0; 6.3, and 8.0
x_6	Design load (kN/m²)	1.5 to 60 with an increase of 0.1

2.3 Design constraints

The design constraints adopted include verifications at the ultimate limit state (ULS), related to bending moment and shear force, and at the serviceability limit state (SLS), emphasizing limiting excessive deflections and checking construction detailing requirements. The verification of the composite slab considers both the construction phase, in which steel and concrete act independently, and the service phase, in which the steel decking and concrete work together to resist the applied loads. The constraints adopted for the construction phase are presented in Eq. (4) to Eq. (9) shown below.

$$C(1): \frac{M^{+}_{sd_{ac}}}{M^{+}_{Rd_{ac}}} - 1 \leq 0 \tag{4}$$

$$C(2): \frac{M^{-}_{sd_{ac}}}{M^{-}_{Rd_{ac}}} - 1 \leq 0 \tag{5}$$

$$C(3): \frac{V_{sd_{ac}}}{V_{Rd_{ac}}} - 1 \leq 0 \tag{6}$$

$$C(4): \frac{R_{sd_{ac}}}{P_{nd}} - 1 \leq 0 \tag{7}$$

$$C(5): \left(\frac{M_{sd_{ac}}}{M_{Rd_{ac}}}\right)^2 + \left(\frac{V_{sd_{ac}}}{V_{Rd_{ac}}}\right)^2 - 1 \leq 0 \tag{8}$$

$$C(6): \frac{\delta_{ac}}{\delta_{máx_{ac}} = mín \begin{cases} \frac{L_F}{180} \\ 20 \end{cases}} - 1 \leq 0 \tag{9}$$

Where C(1) and C(2) represent the limit state verifications related to the positive and negative bending moments acting on the steel decking. C(3) corresponds to the shear verification, and C(4) addresses the web crippling check. C(5) corresponds to the combined action verification between the positive bending moment and shear force, and finally, C(6) represents the serviceability limit state verification regarding excessive deflection during the construction phase.

The design constraints for the service phase can be seen in the following Eq. (10) to Eq. (15).

$$C(7): \frac{M^{+}_{sd_{dc}}}{M_{Rd_{dc}}} - 1 \leq 0 \tag{10}$$

$$C(8): \frac{V_{sd_{dc}}}{V_{l_{Rd_{dc}}}} - 1 \leq 0 \tag{11}$$

$$C(9): \frac{V_{sd_{dc}}}{V_{v_{Rd_{dc}}}} - 1 \leq 0 \tag{12}$$

$$C(10): \frac{\delta_{dc}}{\delta_{máx} = \frac{L}{350}} - 1 \leq 0 \tag{13}$$

$$C(11): 1 - ns_{nerv} \leq 0 \tag{14}$$

$$C(12): \frac{ns_{nerv}}{2} - 1 \leq 0 \tag{15}$$

Where C(7) represents the verification of the positive bending moment for the analyzed simply supported slab. C(8) and C(9) correspond, respectively, to the verifications of the longitudinal and vertical shear limit states. C(10) refers to verifying the excessive deflection limit state during the service phase. Finally, C(11) and C(12) are the constraints related to the construction provisions that limit the number of bars placed within the rib of the deck, which should be limited to two bars per rib according to best design practices.

To solve the optimization problem, the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm was implemented using the MATLAB 2020 platform [12]. A preliminary analysis was conducted to determine suitable parameters for population size and maximum number of iterations per run. As a result, a limit of 300 iterations was adopted, with an initial population of 300 individuals generated via the Latin Hypercube Sampling method. For each problem analyzed, 5 independent runs were performed.

3 Formulation of Multi-Objective Optimization Problems

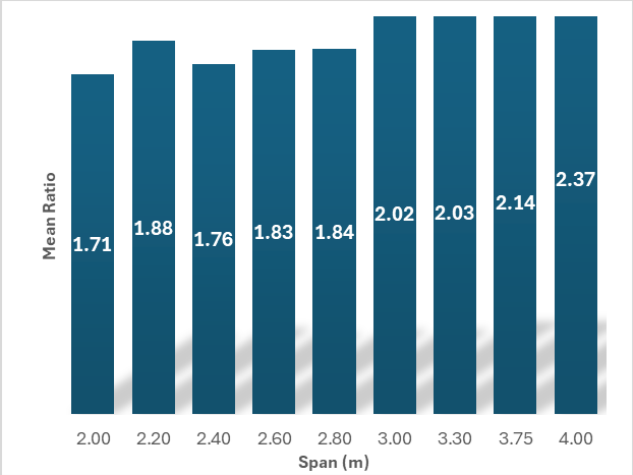
After verifying the efficiency of the multi-objective formulation via MOPSO, the study was based on the method to optimize the composite slabs presented in the manufacturer's catalog (Metform [15]), for the MF-75 steel deck profiles, considering alternating spans, ranging from the shortest span (2.0m) to the longest span (4.0 m).

Table 4 presents the analyzed spans with the optimized load values, and Figure 2 shows the average ratios between the maximum optimized load and the maximum load provided by the manufacturer corresponding to each span, from 2.00 m to 4.00 m.

Table 4**.** Optimized Maximum Loads for Spans from 2.00 m to 4.00 m

			2.00	2.20	2.40	2.60	2.80	3.00	3.30	3.75	4.00
Total height (mm)	Thickness of concrete layer (mm)	Thickness of steel formwork (mm)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)	Optimized Load (kN/m²)
130	55	0.80	30.20	25.70	22.80	13.40	14.90	13.50	10.10	5.80	3.60
130	55	0.95	24.90	21.70	21.20	19.30	13.40	13.90	10.60	5.50	4.30
130	55	1.25	35.20	26.50	16.30	18.30	16.50	15.40	12.20	7.40	6.70
140	65	0.80	31.40	20.40	23.10	9.80	15.20	12.60	7.80	5.40	5.40
140	65	0.95	29.80	25.30	18.60	16.60	13.00	10.90	12.10	5.50	4.70
140	65	1.25	24.40	28.80	21.20	22.40	16.50	13.80	11.20	9.50	6.10
150	75	0.80	24.00	27.10	14.20	14.30	12.50	13.70	7.70	6.80	5.30
150	75	0.95	27.50	27.00	23.80	14.20	14.50	11.60	7.50	6.40	7.00
150	75	1.25	28.70	31.50	30.00	15.10	15.60	13.60	13.00	7.40	6.30
160	85	0.80	27.40	28.10	15.30	16.00	12.60	11.90	7.10	7.50	4.80
160	85	0.95	32.10	27.30	25.40	20.40	12.30	14.30	9.70	8.00	6.20
160	85	1.25	29.60	28.70	20.40	18.30	18.90	17.50	12.10	8.30	9.30
170	95	0.80	25.50	26.80	15.90	14.20	13.20	15.10	9.60	5.60	6.50
170	95	0.95	30.30	26.10	23.60	17.20	15.10	15.60	12.10	9.40	6.90
170	95	1.25	32.80	34.80	29.60	25.50	18.10	13.40	14.80	10.50	8.30
180	105	0.80	24.30	27.60	19.00	19.80	13.60	12.60	9.10	6.20	6.20
180	105	0.95	40.50	27.10	23.70	22.80	18.00	15.40	12.40	6.80	7.60
180	105	1.25	40.80	35.00	25.10	35.60	21.30	15.50	15.10	10.70	10.30
190	115	0.80	31.60	29.90	24.80	21.30	16.00	15.50	10.70	7.00	7.30
190	115	0.95	31.10	34.80	26.10	25.00	16.90	17.80	13.90	10.30	7.60
190	115	1.25	40.00	38.30	28.20	27.70	25.40	16.70	16.50	10.60	8.90
200	125	0.80	26.10	31.40	19.40	19.30	17.80	13.60	11.40	6.90	5.60
200	125	0.95	33.60	31.50	27.10	22.40	17.20	16.80	11.90	7.80	5.90
200	125	1.25	33.50	41.00	31.20	37.60	17.50	17.50	13.00	11.70	10.10

Figure 2. Average Ratios Between Maximum Loads MOPSO/Metform [15] – MF-75



As shown in Figure 2, all the spans analyzed yielded solutions superior to those presented in the catalog, due to the algorithm's use of additional positive reinforcement to enhance the composite slab's resistance to longitudinal shear forces—a mandatory limit state in composite slabs with medium to long spans. Furthermore, the highest average values were concentrated in longer spans, ranging from 3.0 to 4.0 meters, reaching a peak average of 3.46 for a composite slab with a 4.0-meter span and a steel decking thickness of 0.80 mm.

It is noteworthy that in cases with longer spans, shoring was needed at mid-span. The mean ratio also drops starting from the 2.0 m span, followed by a gradual increase beginning at 1.71 m, reaching a maximum value of 2.37.

Table 5 presents two specific cases. Cases A and B correspond to the optimization solutions for composite slabs with a 4.0-meter span, representing the first and second highest increases in load capacity, respectively.

Table 5. Cases A and B – Slab with 4.0m

Span (m)	Case	Solution	Load (kN/m²)	h_t (mm)	h_f (mm)	t_c (mm)	e (mm)	f_{ck} (MPa)	ρ_R(%)	CO_2 Emission ($kgCO_2$)	Cost (R$)
4.00	A	Manufac.	1.44	140	MF75	65	0.80	20	0.00	161.42	636.61
		MOPSO	5.40	140	MF75	65	0.80	50	0.40	208.29	769.84
		Ratio	3.75	-	-	-	-	-	-	1.29	1.21
	B	Manufac.	1.88	170	MF75	95	0.80	20	0.00	181.55	716.92
		MOPSO	6.50	170	MF75	95	0.80	20	0.30	199.76	816.17
		Ratio	3.46	-	-	-	-	-	-	1.10	1.14

In Case A, the slab's design load capacity increases by 275%, while CO_2 emissions rise by 29% and costs by 21%. Case B shows a slightly lower gain in terms of maximum superimposed load—an increase of 246%—but results in lower emissions and costs compared to Case A, with only a 10% increase in emissions and a 14% increase in costs.

4 Conclusions

The analysis demonstrated satisfactory results regarding applying multi-objective optimization via MOPSO for MF-75 composite slabs from the Metform catalog [15]. For all cases studied, the optimization algorithm presented solutions with maximum loads greater than those provided by the manufacturer, reaching values up to 3.75 times higher in slabs with longer spans and reduced overall height. This improvement in the design load capacity of the slab highlights the influence of additional positive reinforcement on shear resistance, while

maintaining emissions and costs at reasonable levels, as shown in Case A and, in a better perspective, in Case B. Comparisons between the load capacities of the new table—generated from the optimization of the maximum superimposed load, cost minimization, and CO_2 emissions reduction— and the original table indicated that the highest ratios were concentrated in slabs with steel decking thickness of 0.80 mm and spans ranging from 3.00 m to 4.00 m."

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