Multi-Objective Optimization of Steel–Concrete Composite Slabs Using MOPSO: Structural, Energy, and Environmental Assessment

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Abstract. This study proposes a multiobjective optimization methodology for steel–concrete composite slabs, aiming to enhance structural and environmental performance. Variants of the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm were implemented in MATLAB to solve an optimization problem defined by three conflicting objective functions: minimizing CO_2 emissions, minimizing total energy consumption, and maximizing load-bearing capacity. The computational model focuses on the post-curing phase of the concrete and includes reinforcement detailing. The structural capacity of each solution was evaluated with MOPSO implemented in the Matlab software, and a set of Pareto optimal solutions was obtained. The best-performing solution was selected from the Pareto front and used to generate a constructive model based on the geometric patterns of the Metform steel decking catalogue. A comparative analysis was conducted by applying the optimized values to the commercial slab configurations, validating the practical applicability of the proposed approach. The results demonstrate the effectiveness of MOPSO in producing balanced structural designs that also contribute to reducing environmental impact.

Keywords: Composite slabs; Multiobjective optimization; MOPSO; CO_2 emissions; Structural sustainability.

1 Introduction

The demand for more sustainable and efficient construction solutions has increased the use of steel–concrete composite slabs in structural systems. These elements offer advantages such as reduced use of concrete and steel, faster construction, and elimination of traditional formwork. However, conventional design approaches often prioritize structural performance and cost, without fully integrating environmental criteria into the decision-making process. In response to this challenge, this study proposes a computational methodology to assist in the structural design of composite slabs using multiobjective optimization techniques. The objective is simultaneously minimizing equivalent carbon dioxide ($CO_{2,e}$) emissions and total energy consumption, while maximizing the slab's load-bearing capacity. The optimization model is based on the post-curing phase of concrete, incorporating reinforcement detailing to ensure realistic and applicable solutions.

The methodology was implemented in MATLAB [1] using the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm proposed by Coelho [2]. The structural capacity of each candidate solution was evaluated, and a Pareto front was generated to identify optimal trade-offs between the objectives. The best-performing solutions were then selected and geometrically modeled following the Metform [3] steel decking catalog, allowing a practical comparison with commercially available configurations.

The results demonstrate the potential of multiobjective optimization to support more sustainable structural design, providing technically viable solutions that reduce environmental impacts.

2 Methodology

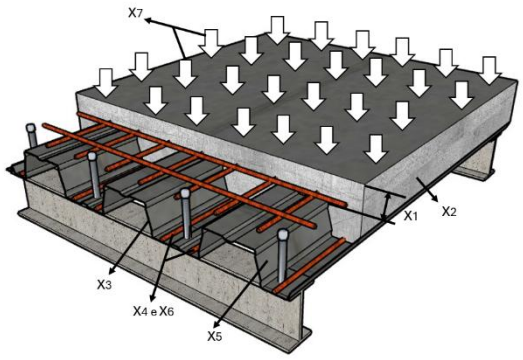
This work employs a computational approach based on multi-objective optimization for the design of steel–

concrete composite slabs. The algorithm used is the Multi-Objective Particle Swarm Optimization (MOPSO), implemented in MATLAB. The model structure considers three conflicting objectives: (i) maximizing the structural capacity of the slab, (ii) minimizing embodied energy consumption, and (iii) minimizing total CO_2 emissions.

2.1 Optimization Problem Formulation

The problem was formulated with seven discrete decision variables representing the slab's geometric properties and material characteristics, as presented in Figure 1 and Table 1.

Figure 1 – Design Variables



Source: Silva et al. (2025)

Table 1. Definition of decision variables

Variable	Description	Bounds
x_1	Thickness of the concrete topping	[50:1:110] (mm)
x_2	Type of concrete	[20:5:50] (MPa)
x_3	Type of steel decking	[MF50; MF75]
x_4	Positive reinforcement ratio	[0.04:0.001:0.5] (%)
x_5	Steel Deck Thickness	[0.8, 0.95, 1.25] (mm)
x_6	Reinforcement bar diameter	[5.0, 6.3,8.0] (mm)
x_7	Load-bearing capacity	[1.5:0.1:20] (kN/m^2)

2.2 Objective Functions

The model addresses a multi-objective optimization problem with three conflicting goals, which are computed as:

***Maximize the slab's load-bearing capacity*.** This objective uses the ultimate load obtained from the software. To follow a minimization approach, the function is expressed as:

$$f_1(x) = q \tag{1}$$

where q stores the load values and x_7 is the selected index.

Minimize total embodied energy. The total embodied energy is the sum of the energy associated with the concrete, steel decking, positive reinforcement, and shrinkage control mesh. The function is defined as:

$$f_2(x) = EE_{concrete} + EE_{deck} + EE_{reinf} + EE_{crack\ mesh} \tag{2}$$

In Equation (2) $EE_{concrete}$, EE_{deck}, EE_{reinf}, $EE_{crack\ mesh}$, represents the energy of concrete, steel deck,

reinforcement mesh and cracking mesh of the production process, respectively.

Minimize total CO_2 emissions. The third objective function aims to reduce the carbon footprint of the slab system. Emissions are calculated for each material component:

$$f_3(x) = CO_{2\ concrete} + CO_{2\ deck} + CO_{2\ reinf} + CO_{2\ mesh} \tag{3}$$

Where each term of Eq. (2) and Eq. (3) is obtained by multiplying the quantity (volume or mass) by the respective emission factor.

3 Numerical Results

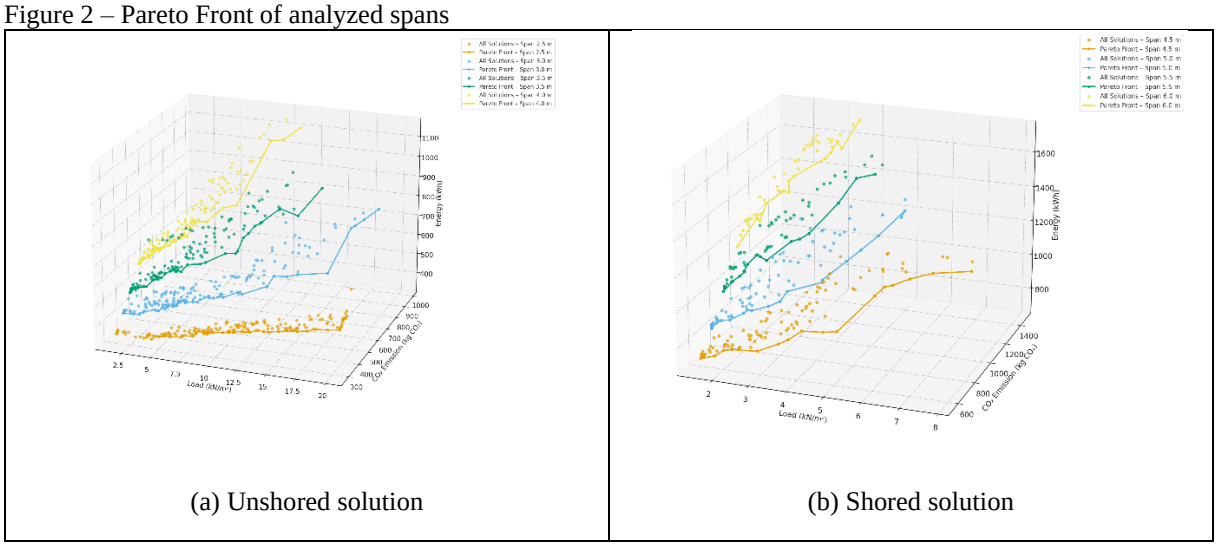
To implement the optimization problem, the unit values of CO_2 emissions and energy are presented by Negrin et al.[4] (2025) and presented in Table 2 were used. The constraints proposed by Silva et al. (2025) [5] for after cure phase of concrete were adopted as problem constraints. For the MOPSO algorithm, a population of 100 individuals, 200 iterations, and 10 runs were considered for each case study.

Table 2. CO_2 Emissions and Energy

Material	CO_2 Emission ($kgCO_{2,e}$)	Energy (kWh)
Concrete 20 MPa	263.00	433.98
Concrete 25 MPa	287.00	468.39
Concrete 30 MPa	311.00	502.79
Concrete 35 Mpa	357.00	537.22
Concrete 40 MPa	405.00	571.61
Steel formwork	2.53	8.70
Steel mesh (CA-60)	3.01	10.39
Reinforcement steel (ABNT 1020)	1.99	4.86

The Pareto fronts for the analyzed examples are shown in Figure 2, with Figure (a) corresponding to unshored spans and Figure (b) to spans that required shoring according to the formwork manufacturer Metform[3]. It is important to note that the manufacturer limits the spans to a maximum of 4.0 m when using the MF75 formwork. The spans of 4.5 m, 5.0 m, 5.5 m, and 6.0 m were analyzed in order to assess the algorithm's ability to propose new solutions.

Figure 2 – Pareto Front of analyzed spans



(a) Unshored solution

(b) Shored solution

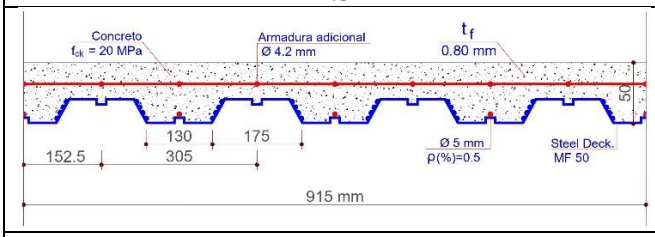
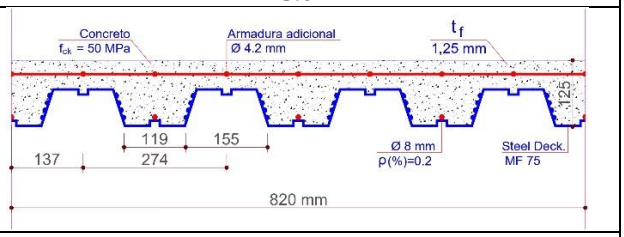
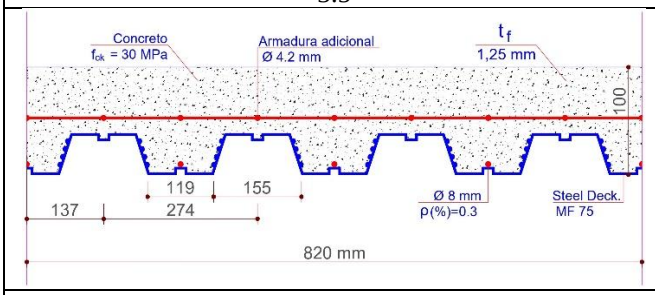
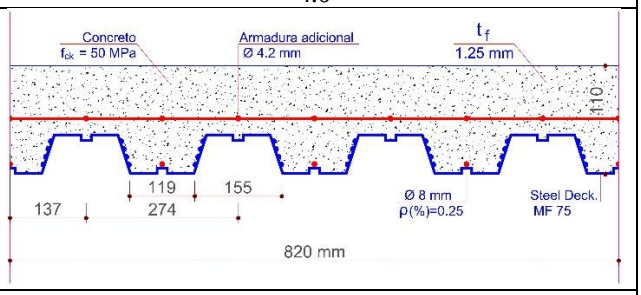
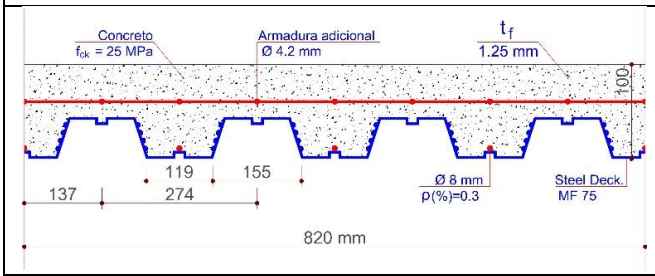
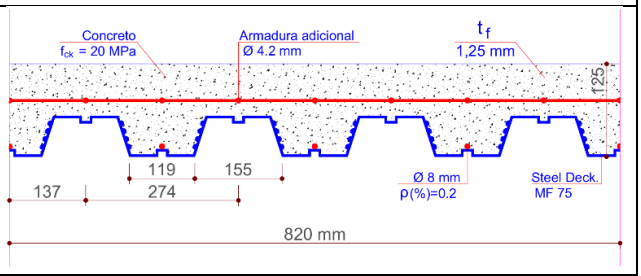
Table 3 summarizes the formwork manufacturer's proposed results and the results obtained for the analyzed problems.

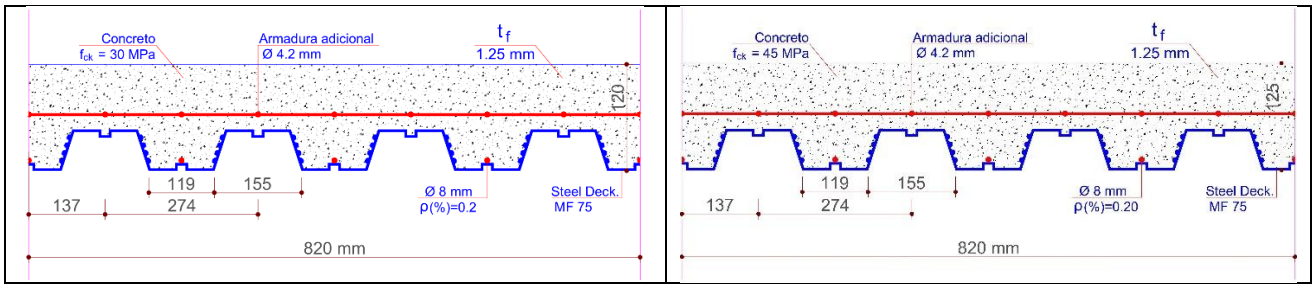
Table 3 – Comparative Analysis

Span (m)	Max Load (kN/m^2) Metform	Emission ($kgCO_{2,e}$) Metform	Energy (kW) Metform	Max Load (kN/m^2) (Authors)	Emission ($kgCO_{2,e}$) (Authors)	Energy (kW) (Authors)
2.5	14.00	127.08	385.40	20.0	395.93	509.63
3.0	13.25	174.71	534.10	20.0	754.89	859.38
3.5	8.94	191.51	603.91	15.0	758.34	928.16
4.0	6.12	208.31	673.72	11.2	967.99	1112.85
4.5	--	--	--	7.8	953.72	1183.36
5.0	--	--	--	5.6	1090.42	1364.96
5.5	--	--	--	4.5	1247.13	1512.86
6.0	--	--	--	3.5	1476.24	1705.18

The results in Table 3 show that, although the proposed solutions present higher energy consumption and CO_2 emissions compared to Metform's values for spans between 2.5 m and 4.0 m, this increase is not significant when considering the gain in load capacity. For these same spans, the maximum loads of the proposed model are considerably higher than those of Metform, which justifies and makes the observed increase a positive outcome. These increases reflect a more robust structural design, capable of supporting greater loads and accommodating longer spans without compromising construction feasibility. In addition, the developed model demonstrated a remarkable advantage: the ability to design for spans between 4.5 m and 6.0 m, which are not included in Metform's commercial table. This expands the scope of application and highlights the efficiency and versatility of the proposed approach. Finally, the final geometries of the optimized slabs, based on Metform [3] profiles, and the parameters generated by the algorithm are presented in Table 4.

Table 4 – Final Geometries

2.5	3.0
	
3.5	4.0
	
4.5 m	5.0
	
5.5	6.0



4 Concluding Remarks

This study presented a computational methodology for the design of steel–concrete composite slabs based on multi-objective optimization. Using the MOPSO algorithm implemented in MATLAB enabled the identification of solutions balancing structural performance, energy consumption, and CO_2 emissions. The problem formulation was structured using discrete variables representing the main geometric and material parameters of the slabs, with constraints that ensure constructability and compliance with commercial profiles.

The analysis of results, through Pareto fronts, allowed for the selection of optimized configurations for different slab spans, with the best performance of the proposed solution by the manufacturer's deck and new solutions proposed.

The results highlight the potential of multi-objective optimization as a decision-support tool for structural design. It enables the integrated exploration of alternative solutions, which improve technical performance and environmental sustainability.

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