CO_2 emission and costs optimization of composite floor systems with cellular beams via Particle Swarm Optimization (PSO)

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Abstract. The use of composite floor systems has been increasing in recent years, primarily with full-web beams, while other beam topologies, such as cellular beams, remain underutilized. The objective of this study is to propose a formulation for the optimal design of composite floor systems composed of cellular beams. The objective function will analyze the floor's costs and final CO_2 emissions. Technical prescriptions proposed in the literature will serve as constraints, as Brazilian standards lack clear guidelines for designing cellular beams. Particle swarm optimization (PSO) will be employed to solve the optimization problem. A comparative analysis with solutions proposed in the literature for floors with solid beams will be conducted to assess the efficiency of the proposed solution for composite floors with cellular beams.

Keywords: Composite Floors, Cellular Beams, Particle Swarm Optimization, Cost, CO_2 Emission.

1 Introduction

Due to the significant increase in greenhouse gas emissions in Brazil and worldwide, searching for more efficient solutions within the construction sector is necessary. Within this context, the use of composite steel and concrete structural elements becomes interesting, as it reduces the use of concrete, one of the main contributors to greenhouse gas emissions. Consequently, the use of optimization techniques becomes a great ally, as through mathematical algorithms, the solution to engineering problems, which initially occurs according to the designer's experience or through trial-and-error techniques, can become automated. In this scenario, using composite floor systems with cellular beams is a good alternative to reduce the use of concrete and steel in the search for environmentally friendly solutions.

Research of optimization using composite castellated and composite cellular beams can be found in the jobs of Kaveh and Fakoor [1] and Ramos and Alves [2].

The search for optimal solutions has been explored over the past decades through bio-inspired algorithms, with the Particle Swarm Optimization (PSO) algorithm being particularly notable. Similarly, these metaheuristic algorithms have been applied in different optimization areas as observed in the works of Luh and Lin [3], Yu and Xu [4], Babaei and Sanaei [5], Arpini et al. [6], Erlacher et al. [7] among others. The widespread use of the algorithm is due to its easy computational implementation and ability to search for global solutions to optimization problems. Yepes et al. [8] introduced a method for optimizing the expenses and emissions in the design of precast-prestressed concrete road bridges, utilizing a hybrid glowworm swarm optimization algorithm. Silva et al. [9] analyzed the optimization problem of composite floor systems with cellular beams, minimizing the CO_2 emission of the floor. The authors conclude that using a cellular beam can reduce the final CO2 emission of the floor by over 20%.

The present work aims to propose the optimization problem formulation of composite floor systems composed of cellular beams and steel deck slab, minimizing the CO_2 emission and cost of the material used in the floor. The PSO is implemented within the Matlab platform to optimize the problem solution. To verify the efficiency of PSO, the solutions will be compared with those proposed in the literature. A comparative analysis of CO_2 emissions and its monetary costs will be conducted to determine the most relevant factors during the optimization process.

2 Optimization Problem Formulation

This optimization problem's objective is to minimize the CO2 emissions and costs of a composite floor system comprising cellular beams, considering the beams' topology and manufacturing process.

2.1 Design variables and parameters

The geometric parameters and structural framing layout of the composite floor system incorporating cellular beams are depicted in Figures 1 and 2. The design variables must be specified in the initial stage of defining each optimization problem. In this study, 19 design variables are employed for the secondary beams, girders, edge beams, steel deck floor, and columns within the optimization problem. These variables, detailed in Table 1, are treated as discrete variables. Figure 1 illustrates the composite floor system's geometric parameters and structural framing layout with cellular beams.

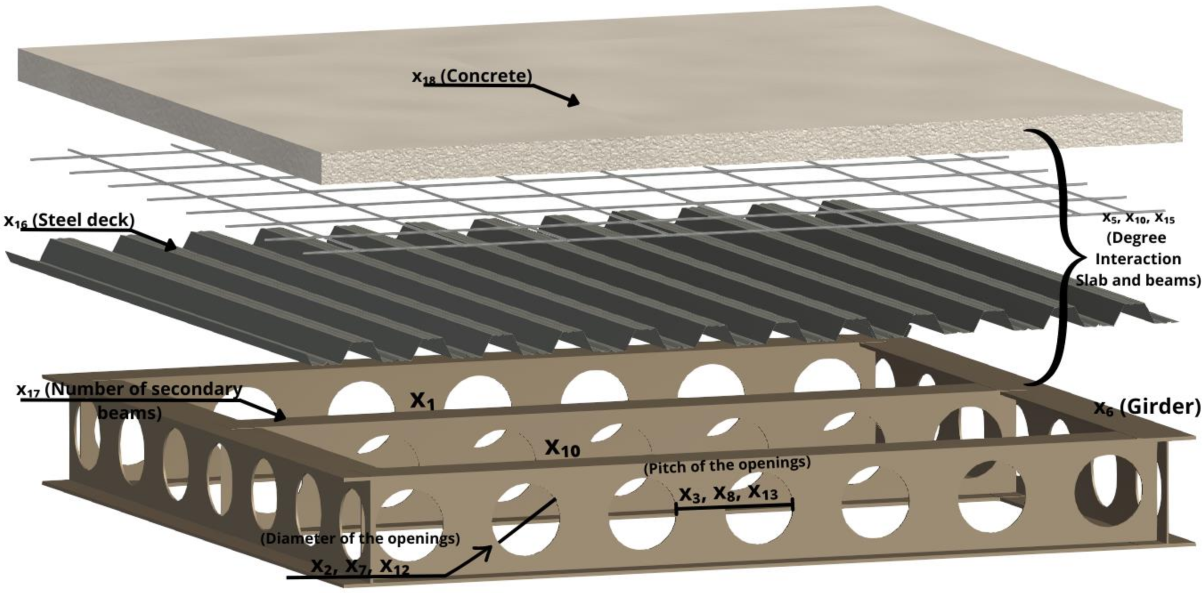

Figure 1. Design variables of the composite floor system with cellular beams

Table 1 The design variables of the composite floor system with the cellular beams

Structural element	Design variables
Secondary Beams	x_1 : Laminated profile according to Gerdau® catalogue (2023)
	x_2 : Diameter of the openings (mm)
	x_3 : Pitch of the openings
	x_4 : Expansion factor
	x_5 : Degree of the interaction between slab and beams
Girders	x_6 : Laminated profile according to Gerdau® catalogue (2023)
	x_7 : Diameter of the openings (mm)
	x_8 : Pitch of the openings

	x_9 : Expansion factor
	x_{10} : Degree Interaction between Slab and Beams
	x_{11} : Laminated profile according to Gerdau® catalogue (2023)
Edge Beams	x_{12} : Diameter of the openings (mm)
	x_{13} : Pitch of the openings
	x_{14} : Expansion factor
	x_{15} : Degree of the interaction between slab and beams
Steel deck floor	x_{16} : Formwork type according to Metform® (2006)
	x_{17} : Number of the secondary beams
	x_{18} : Concrete strength (f_{ck}) (MPa)
Columns	x_{19} : Laminated profile according to Gerdau® catalogue (2023)

Table 2 provides the ranges of these design variables. The ranges for the sections of the secondary beams (x_1), girders (x_6), edge beams (x_{11}), and columns (x_{19}) are defined according to the design specifications. Similarly, the design specifications also determine the ranges for the formwork type (x_{16}) of the steel deck floor.

Table 2. The ranges of the design variables

Design variable	Range
Diameter of the openings	0.80 mm$\leq x_2, x_7, x_{12}\leq$1.10 mm
Pitch of the openings	1.20$\leq x_3, x_8, x_{13}\leq$1.50
Expansion factor	1.30$\leq x_4, x_9, x_{14}\leq$1.60
Degree of the interaction between slab and beams	0.40$\leq x_5, x_{10}, x_{15}\leq$1.00
Number of the secondary beams	1.80 m$\leq x_{17}\leq$3.20 m for MF-50 2.00 m$\leq x_{17}\leq$4.00 m for MF-75
Concrete strength (f_{ck})	20 MPa$\leq x_{18}\leq$50 MPa

2.2 Objective Function

The objective function of the optimization problem aims to identify the optimal solution from both an environmental impact and cost-efficiency perspective in the construction of the composite floor system with cellular beams. This entails finding the configuration that results in the lowest total CO2 emissions and minimizes the cost of the structural elements based on the emissions and costs associated with each component of the composite floor system, as described by eq. (1) and eq. (2).

$$\text{Minimize } CO_2 = CO_{2(\text{girders})}+CO_{2(\text{secondary beams})}+CO_{2(\text{edge beams})}+CO_{2(\text{steel deck floor})}+CO_{2(\text{columns})} \quad (1)$$

$$\text{Minimize Cost} = \text{Cost}_{(\text{girders})} + \text{Cost}_{(\text{secondary beams})} + \text{Cost}_{(\text{edge beams})} + \text{Cost}_{(\text{steel deck floor})} + \text{Cost}_{(\text{columns})} \quad (2)$$

where $CO_{2(\text{girders})}$ and $\text{Cost}_{(\text{girders})}$, $CO_{2(\text{secondary beams})}$ and $\text{Cost}_{(\text{secondary beams})}$, $CO_{2(\text{edge beams})}$ and $\text{Cost}_{(\text{edge beams})}$, $CO_{2(\text{steel deck floor})}$ and $\text{Cost}_{(\text{steel deck floor})}$, $CO_{2(\text{columns})}$ and $\text{Cost}_{(\text{columns})}$ are the CO_2 emissions and costs from the girders, secondary beams, edge beams, steel deck floor and columns, respectively.

Where:

$$CO_{2,\text{beam}} = CO_{2(\text{profile})} + CO_{2(cut)} + CO_{2(\text{welding})} \quad (3)$$

$$Cost_{(\text{beam})} = \text{Cost}_{(\text{cel profile})} \quad (4)$$

where $CO_{2(\text{profile})}$ and $\text{Cost}_{(\text{cel profile})}$, $CO_{2(\text{cut})}$, $CO_{2(\text{welding})}$ represents the CO_2 emissions and costs of profile, cut and welding process of cellular profile fabricate process respectively.

Table 4 presents the CO_2 emissions and costs of the objective function's components.

Table 3. CO_2 emission and material costs

MATERIAL	CHARACTERISTICS	CO_2 EMISSION ($kgCO_2/m^3$)	SOURCE	COSTS ($R\$/m^3$)	SOURCE
Concrete	20 MPa	140.05	Santoro and Kripka [10]	463.14	SINAPI (2023)
	25 MPa	149.26		474.87	
	30 MPa	157.65		491.01	
	35 MPa	171.64		504.22	
	40 MPa	182.14		518.15	
	45 MPa	194.70		532.09	
	50 MPa	225.78		546.02	
Steel Profile	VMB350	1.12 ($kgCO_2/kg$)	World Steel Association [11]	15.00R$/kg	Local Supplier (2024) [12]
Steel Deck Formwork (280 MPa)	MF50/0.80 mm	2.64 ($kgCO_2/kg$)		90.5 R$/m²	Local supplier (2024)
	MF50/0.95 mm			107.64 5 R$/m²	
	MF50/1.25 mm			141.645 R$/m²	
	MF75/0.80 mm			99.005 R$/m²	
	MF75/0.95 mm			117.005 R$/m²	
	MF75/1.25 mm			154.485 R$/m²	
Reinforcement Mesh	600 MPa	1.92 ($kgCO_2/kg$)		10.48 R$/kg	SINAPI (2023)
Stud Bolt	(ø19mm, 105mm)	0.23 $kgCO_2/m^3$		11.40 R$/kg	Cordeiro [13]

The restrictions proposed in Silva et al.'s work [9] were adopted for the study in question.

3 Simulations and Results Analysis

To assess the efficiency of the proposed formulation, the example presented by Arpini et al. [6] was analyzed (Figure 2). In this example, the authors investigated the CO_2 emissions of a composite floor system composed of full web beams and obtained the solution to the optimization problem using a Genetic algorithm. The problem involves a composite floor structure with a composite slab measuring 7.5 x 7.5 meters, using MF-75 steel deck with a thickness of 0.95 mm and a height of 15 cm, and concrete with a characteristic strength of 25 MPa, made with gneiss aggregate. In addition to the self-weight of the structure, a variable live load of 5 kN/m² was applied to the structural loading.

The optimized solutions were obtained first by minimizing structural costs and calculating the CO_2 emissions and second by minimizing CO_2 emissions and calculating the cost of structures. Figure 3 presents the optimization problem evolution for each situation analyzed.

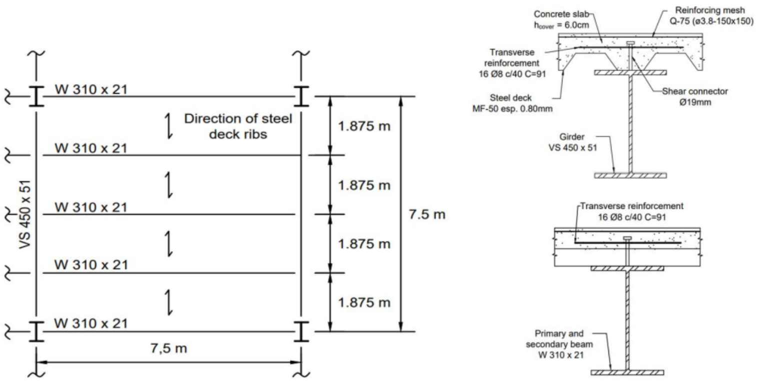

Figure 2. Floor System Optimized in Arpini et al. (2022)

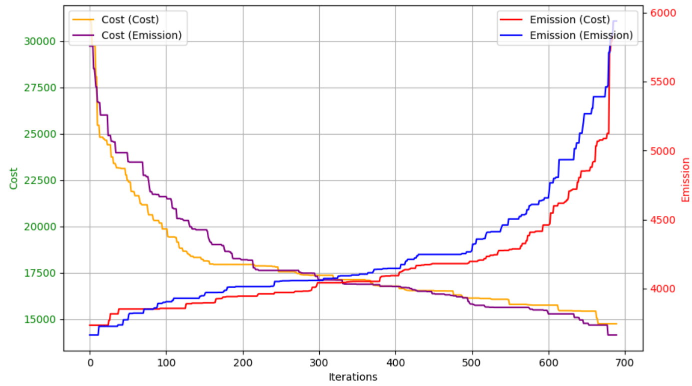

Figure 3. Graph CO_2x Cost Optimization

As can be observed in the graph, the solutions obtained for the two optimizations provided very similar final values, demonstrating that the two functions are not competitive for a future multi-objective optimization study. Table 5 presents the final geometry for the profiles found and the analysis of the final emissions of the values obtained by Arpini et al. [6].

Table 4. CO_2 emission and material costs

Parameters	Unidade	Arpini et al. [6] GA	PSO (Cost)	PSO (Emission)
Number of secondary beams	Un	5	4	4
Distance between beams	m	1.875	2.5	2.5
Profile of the secondary beam	--	W 310x21	W 310x23,8	W 310x21,0
Expansion factor of the secondary beam	--	--	0.28	0.27
Profile of the edge beam	--	--	W 150x13	W 150x13

Expansion factor of the edge beam	--	--	0.15	0.14
Profile of girder	--	W 450x51	W 360x32,9	W 360x32,9
Expansion factor of girder	--	--	0.35	0.33
Profile of the column	--	W 310x21	W 200x15	W 200x15
Emission	Kg	4062.5	3734.94	3689.24
Cost	R$	--	14755.02	14367.19

It can be observed in Table 4 that the optimization of CO_2 emissions and costs of composite floor systems with cellular beams, conducted using the Particle Swarm Optimization (PSO) method, resulted in identical profiles. This outcome indicates a significant correlation between the minimization of CO_2 emissions and cost reduction. Figure 4 shows the final geometry of the floor found. One can also observe a reduction in the number of internal beams when compared to the solution by Arpini et al. [6]. This led to an increase in the thickness of the form used, which became 0.95mm. This final composition of the structure resulted in a final reduction of emissions by 9.2% when compared to the final solution presented by Arpini et al. [6].

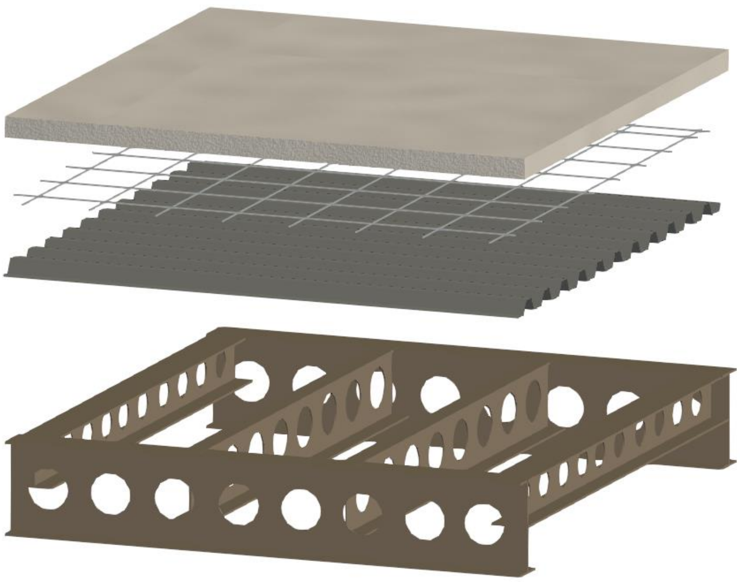

Figure 4. Final geometry of the floor found

4 Conclusions

In conclusion, it is evident that optimizing for cost and CO_2 emissions, although not conflicting objectives, shows similar trends in the trajectory of the objective function. Additionally, optimizing the composite floor system with cellular beams for cost did not result in significant cost savings compared to CO_2 emissions optimization. Despite the structural differences and varied geometric profiles, the economic and environmental outcomes were practically indistinguishable when comparing final values.

Regarding the Particle Swarm Optimization (PSO) algorithm employed in this study, it effectively minimized both cost and CO_2 emissions, demonstrating comparable or superior performance in terms of solution consistency with a smaller standard deviation. This underscores the PSO algorithm's effectiveness in seeking optimal solutions for the composite floor system with cellular beams, addressing both economic and environmental goals simultaneously.

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