Optimized design of composite steel and concrete trusses to minimize cost and environmental impact

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Abstract. The use of composite structures has grown significantly in recent decades, in a global scenario characterized by the need to reformulate the image of the civil construction sector, responsible for an enormous environmental impact. In this context, composite steel and concrete trusses have applicability in structural design with large spans. This research consists in presents the optimization problem of steel and concrete composite trusses focusing on the cost and CO_2 emission, via genetic algorithm (GA), using Matlab software. Three trusses models were considering: Pratt, Howe and Warren associated with solid slab, for the optimized design according to ABNT NBR 8800:2008. It was verified which type of truss provides the best results for spans of variable lengths. Witch the graphical interface for efficient user interaction and the agility provided by the GA, the developed program identified that the best results were obtained with the Pratt-type metallic truss and that the upper flange was in a critical situation due to the combined bending effect. Optimizing the cost and CO_2 emission of composite steel and concrete trusses has proven to be an excellent tool for automating these tasks.

Keywords: composite steel and concrete trusses, cost optimization, CO_2 emission, genetic algorithm.

1 Introduction

Composite steel and concrete structures are characterized by the joint work of a steel profile associated with concrete parts forming a single structural element. NBR 8800:2008 prescribes that the truss steel component can be associated, through shear connectors, in the following types of concrete slab: solid slab in loco, composite slab prefabricated slab [1]. Among the many features that make the use of composite steel and concrete trusses attractive, especially in works with spans greater than 18m, is the elimination of formwork and shoring, reduction in volume and weight of the structure and reduction of material costs for construction [2].

For the design of trusses in general, the experience of the design engineer is taken into account in determining the initial profiles to be used. An alternative to solve this difficulty is to employ structural optimization techniques based on metaheuristic algorithms, either to minimize costs or environmental impacts, as described by Kravanja, Silih and Kravanja [3] and Luo, Li and Kang [4] who proposed minimizing the cost of manufacturing composite steel and concrete beams. Vieira [5] studied the optimization of the environmental impact of prefabricated structures, Camp and Huq [6] optimized the cost and emission of carbon dioxide (CO_2) in reinforced concrete frames, Yepes, Martí and García-Segura [7] applied cost and CO_2 emission optimization in precast prestressed concrete road bridges, in addition to Tormen et al. [8] and Medeiros and Kripka [9] who analyzed the optimization of costs and CO_2 emissions applied to composite steel and concrete beams and rectangular reinforced concrete columns, respectively.

Among the existing works in the literature on the subject, the works by Zhang et al. [10], Du et al. [11] and Liu et al. [12]. The authors identified that Warren, Pratt or Howe trusses increase the flexibility factor in lateral trusses and that displacement is overestimated in structures with a large number of random parameters. The results for the analyzes also reveal that panel configurations in the center of the structure can cause excessive displacements and that the flexural bearing capacity increases as more shear connections are used.

With the increase in the use of composite structures in recent decades, many researchers started to look for optimized solutions for dimensioning, topology, shape, cost and even environmental efficiencys. This is the case of Kravanja, Silih and Kravanja [3] and Luo, Li and Kang [4] who minimized the cost in composite steel and concrete beams with different solution algorithms and verified the importance of considering design uncertainties and the evaluation of the mechanical behavior of the structure.

Among the various solution algorithms already described in the scientific community, the genetic algorithm (GA) stands out for ensuring a complex search mechanism in restricted optimization problems, allied to its easy implementation [13]. There are many applications for the method as indicated by Kuan-Chen Fu, Zhai and Zhou [14] and Câmara Neto, Landesmann and Batista [15], who used GA in the optimized design of steel beams and composite steel beams for reduce the weight of the structure having different purposes: in the first case for bridges and in the last for multi-storey buildings. Lazzari, Alves and Calenzani [16] proposed a computational program for optimized dimensioning of space frames according to ABNT NBR 8800:2008.

Among several works with GA application, Ramos and Alves [17] addressed the optimization of cellular composite beams, through Matlab software, to minimize the weight, providing optimal solutions in which the weight of the studied profile was reduced by 20% and Breda, Pietralonga and Alves [18] presented the optimization for the design of composite steel and concrete floor systems, according to ABNT NBR 8800:2008, with results where the weight of the concrete and the cost of the structure were minimized.

Deciding which structural design alternative simultaneously brings both cost benefits and minimal CO_2 emissions is not as easy as it sounds. Faced with the world picture characterized by the use of building materials on a scale already seen, Miller, Don and Mulvey [19] proposed the optimization in terms of the incorporated energy for different slab models and found values close to the molds of alternative construction methods. Vieira [5] proposed the use of GA to minimize the emission CO_2 promoted by precast concrete structures considering the interference of several variables which made it possible to make sustainability measurable. Camp and Huq [6] proposed the optimization of reinforced concrete frames to minimize the total cost and CO_2 emissions involved in the construction process and found that reducing CO_2 induces a modest increase in the final cost. Yepes, Martí and García-Segura [7] applied optimization in road bridges with the objective of minimizing the cost and environmental impact and found that the costs and minimum emissions increase as the span length is increased.

Tormen et al. [8] also proposed the optimization of costs and CO_2 emission, however, applied to sections of composite steel-concrete beams and the results indicated that the optimal solutions from a financial point of view were similar to those obtained by the environmental impact analysis. Medeiros and Kripka [9] applied the same metaheuristic optimization method as Tormen et al. [8] for the optimization of monetary and environmental costs of rectangular reinforced concrete columns, with costs for the purchase of materials and environmental defined according to the life cycle of each input. The authors are concise in their assertion that structural optimization, with the objective of reducing the cost of the structure, consequently reduces the environmental costs related to CO_2 emissions, regardless of the environmental impact indicator considered, justifying the need for the study carried out.

The objective of this work is to present the formulation of the structural optimization problem of composite steel and concrete trusses, simply supported, to minimize the cost and CO_2 emission, in view of the current scenario more susceptible to the use of composite structures and the growing need to carry out projects with low carbon content to avoid depleting the environment. To solve the problem, Matlab's native genetic algorithm was used and numerical examples are presented to show the applicability of the proposed formulation.

2 Design of composite trusses by NBR 8800:2008

In Brazil, NBR 8800:2008 [1] prescribes the structural design of composite steel and concrete trusses, where bending forces must be jointly resisted by the structural steel truss profile and the concrete slab. The three most used steel truss models are called Pratt, Howe and Warren as shown in fig. 1.

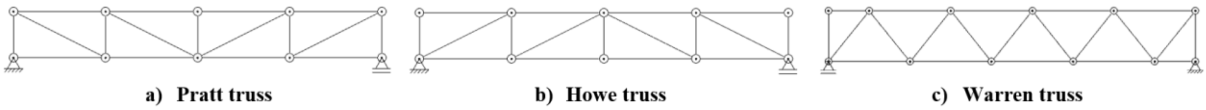

Figure 1. Main geometric configurations for steel trusses

As for the gravitational loads on the trusses, the diagonals and the uprights are subject, respectively, to traction and compression forces in the Pratt truss, compression and traction in the Howe truss and in the Warren truss, part of the diagonals are subjected to loads of compression and traction part. The internal efforts of the ideal steel trusses are determined from the Displacement Method. The design compression resistance force ($N_{c,Rd}$) of the profile is obtained by eq. (1).

$$N_{c,Rd} = \frac{\chi Q A_g f_y}{\gamma_{a1}} \tag{1}$$

where χ is the reduction factor associated with the compressive strength, Q is the strength reduction factor under the effects of local instabilities, A_g is the cross-sectional area, f_y is the steel yield stress and γ_{a1} is the reduction factor resistance that, in cases of tubular profiles, must meet the criteria of NBR 16239:2013 [20]. The design tensile strengths correspond to the smallest value obtained between the ultimate limit states (ELU) of gross section yield and net section rupture ($N_{t,Rd}$) provided by eq. (2) and eq. (3) respectively.

$$N_{t,Rd} = \frac{A_g f_y}{\gamma_{a1}} \tag{2}$$

$$N_{t,Rd} = \frac{A_e f_u}{\gamma_{a2}} \tag{3}$$

where A_g is the gross cross-sectional area, A_e is the net effective cross-sectional area and f_u is the breaking strength of steel. For the design bending moment resistance (M_{Rd}) applicable in circular tube sections, the verification of eq. (4) which, if not met, determines the adoption of a new profile.

$$\frac{D}{t} \leq 0{,}45 \frac{E}{f_y} \tag{4}$$

where D is the outside diameter and t is the tube thickness. The M_{Rd} is obtained as a function of the slenderness calculated for the tube (λ) and through the eqs. (5-7).

$$If\ \lambda < \lambda_{inf}: M_{Rd} = \frac{M_{pl}}{\gamma_{a1}} \tag{5}$$

$$If\ \lambda_{inf} \leq \lambda \leq \lambda_{sup}: M_{Rd} = \frac{W}{\gamma_{a1}} \times \left(f_y + 0{,}021 \frac{E}{\lambda}\right) \tag{6}$$

$$If\ \lambda > \lambda_{sup}: M_{Rd} = \frac{W}{\gamma_{a1}} \times \left(0{,}33 \frac{E}{\lambda}\right) \tag{7}$$

where λ_{inf} is the lower slenderness, λ_{sup} is the upper slenderness, M_{pl} is the plastification moment and W is the elastic modulus of strength. As for the combined efforts, the bars subjected to the simultaneous action of axial traction or compression force and bending moments must be checked according to eq. (8) and eq. (9).

$$If\ \ N_{Sd}/N_{Rd} \geq 0{,}2: \frac{N_{Sd}}{N_{Rd}} + \frac{8}{9}\left(\frac{M_{x,Sd}}{M_{x,Rd}} + \frac{M_{y,Sd}}{M_{y,Rd}}\right) \geq 1{,}0 \tag{8}$$

$$If\ \ N_{Sd}/N_{Rd} < 0{,}2: \frac{N_{Sd}}{2N_{Rd}} + \left(\frac{M_{x,Sd}}{M_{x,Rd}} + \frac{M_{y,Sd}}{M_{y,Rd}}\right) \geq 1{,}0 \tag{9}$$

where N_{Sd} and N_{Rd} are the requesting and resistant axial efforts and M_{Sd} and M_{Rd} are the requesting and resistant bending moments. In composite trusses the interaction between steel and concrete is complete and the M_{Rd} of the composite section is obtained by multiplying the tensile strength of the lower truss flange by the lever arm. As presented by Fakury, Castro e Silva and Caldas [21], composite trusses are subject to several service limit states (ELS), however the research is restricted to approach the ELS of deflection beyond the acceptable limit. The calculation for maximum deflection of the center of the span (δ) of simply supported composite trusses is performed by eq. (10).

$$\delta = \frac{5qL^4}{384EI} \tag{10}$$

where q is the uniformly distributed load, L is the distance between the supports and I is the moment of inertia of the beam's cross section. The maximum deflection in composite floor and roof trusses shall not exceed $L/350$ and $L/250$ respectively [1].

3 Optimization problem

Following the technical requirements of NBR 8800:2008, two minimization objective functions were established for the optimization of composite trusses: cost according to eq. (11) and CO_2 emission according to eq. (12).

$$Min\ (C) = C_{steel\ truss} + C_{slab} + C_{formwork} \tag{11}$$

$$Min\ (CO_2) = CO_{2(steel\ truss)} + CO_{2(slab)} + CO_{2(formwork)} \tag{12}$$

Where $C_{steel\ truss}$ corresponds to the cost of the metallic truss, C_{slab} is the cost for the production of the slab, $C_{formwork}$ is the cost of the slab formwork, $CO_{2\ (steel\ truss)}$ corresponds to the value of the CO_2 emission of the profiles used in steel trusses, $CO_{2\ (slab)}$ is the value of the CO_2 emission of the slab and $CO_{2\ (formwork)}$ is the value of the CO_2 emission of the slab formwork. The cost and CO_2 emission for the materials used in the production of composite steel and concrete trusses were previously registered in the code and the values are presented in tab. 1.

Table 1. Cost and CO_2 emission for composite trusses materials [9, 22-25]

Material	Unity	Cost (R$)	Emission ($kgCO_2$)	Material	Unity	Cost (R$)	Emission ($kgCO_2$)
f_{ck} = 20 MPa	m³	295.00	130.68	f_{ck} = 45 MPa	m³	384.01	185.32
f_{ck} = 25 MPa	m³	307.42	139.88	f_{ck} = 50 MPa	m³	455.43	216.40
f_{ck} = 30 MPa	m³	317.77	148.28	Steel profile	kg	4.50	1.12
f_{ck} = 35 MPa	m³	329.15	162.36	Wood shape	m²	44.26	8.90
f_{ck} = 40 MPa	m³	341.57	172.77				

The cost of the m³ of concrete as well as the m² of the wood shape were extracted from the input price reports, made available by the Caixa Econômica Federal, through the National System of Prices and Indexes for Civil Construction [22]. In turn, the cost per kg of steel profile VMB350 was defined based on the catalog made available by the company Vallourec [23]. The CO_2 emissions for each material, in $kgCO_2$, were defined based on the Life Cycle Assessment (LCA) methodology, which details all the material's constructive stages and disclosed in recent surveys, such as Santoro and Kripka [24] and Medeiros and Kripka [9], which present the CO_2 emission for each m³ of concrete and m² of wood shape, respectively. The CO_2 emission for each kg of steel profile VMB350 was obtained after adapting the values published by the Worldsteel Association [25].

Applying the GA provided by the Matlab R2020a software, five design variables were considered: profile of the lower truss flange, profile of the upper truss flange, profile of diagonals and uprights, characteristic compressive strength of the concrete (f_{ck}) and thickness of the concrete slab. The steel truss profiles were limited to a circular tubular profile (TC) catalog with 142 options of variable diameter and thickness, the concrete strength in the range of 20 to 50MPa and the thickness of the solid concrete slab between 9 and 20cm, respecting the minimum thickness required for the 19mm stud bolt shear connectors. Thus, the lowerbound (LB) and upperbound (UP) vectors that return the lower bound and upper of the design variable range, respectively, according to the arrangement of the variables listed above, were as follows: LP = {1, 1, 1, 1, 9} and UP = {142, 142, 142, 7, 20}.

As constraints, the equations that govern the ELU for the axial compression efforts of the upper flange and combined bending, the ELU for the axial tensile efforts of the lower flange, the ELU for the axial compression efforts of the diagonals and uprights and the Excessive deformation ELS. An initial population of 200 individuals was registered on the Matlab platform, with an elite individual rate equal to 0.05, an intermediate type crossing rate of 0.8, in addition to the random mutation rate. The GA is applied to an initial random population resulting in an optimal local solution. This answer is then added to the initial population and GA is run again until the best structural optimization solution is defined.

4 Analysis Results

To show the applicability of the proposed formulation, 3 examples were analyzed varying the spans of 8m, 16m and 24m. For all examples, the 3 types of trusses were analyzed, as well as the optimal solution given as a function of cost and CO_2 emission. It is important to emphasize that for the three situations, all metallic truss models share the same geometric and loading configurations to be inserted by the user: panel 2m wide and 1m high, 2m spacing between beams, tubular profile circular (TC) of 141.3mm x 6.4mm in the lower and upper flanges, TC profile 101.6mm x 5.0mm in the diagonals and uprights, f_y of 345 MPa, E of the steel of 2x10^5 MPa, thickness of 15cm slab, gneiss-type aggregate and 25 MPa f_{ck}. The difference between the examples presented is in the span length that the metal truss must span. The program results screen for optimizing the cost of the Pratt truss over a span of 4 panels and therefore 8m in length is shown in fig. 2, while the results for the spans of 8m, 16m and 24m, respectively, are shown in tab. 2, both for cost optimization and CO_2 emission optimization.

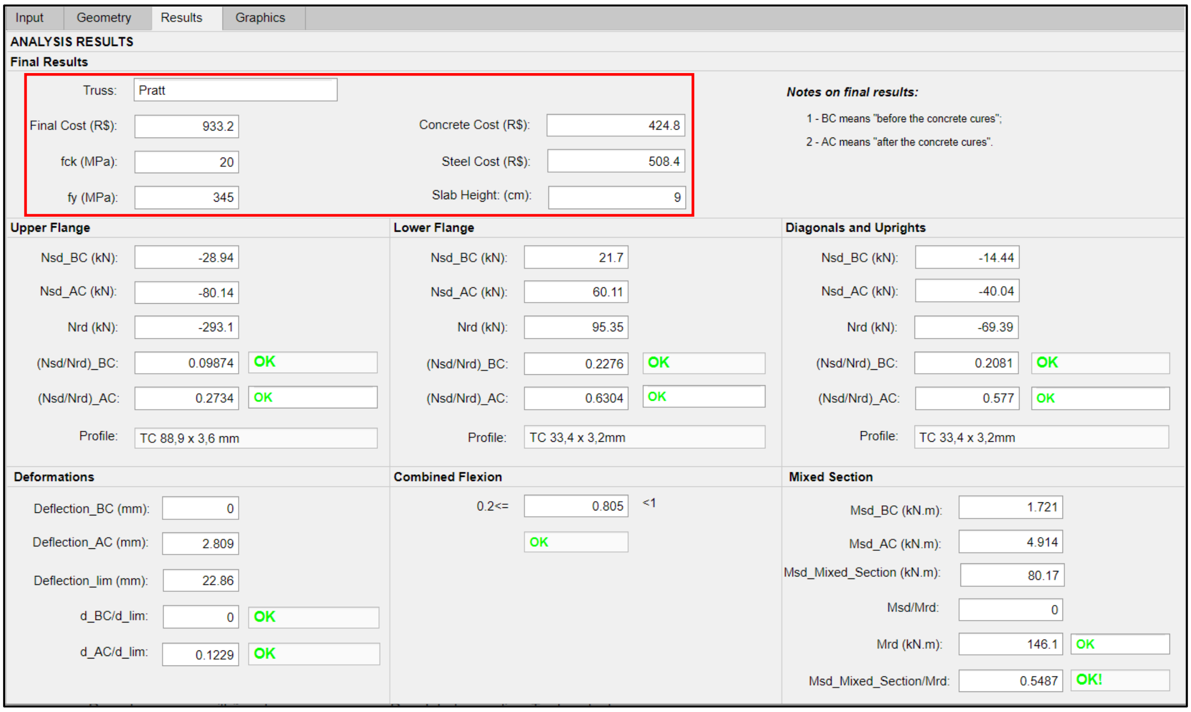

Figure 2. Cost optimization for Pratt truss and span of 8.0 m

Table 2. Final results of cost optimization and CO_2 emission in spans of variable length

Metal truss	Cost (R$)	Cost of concrete (R$)	Cost of Steel (R$)	CO_2 emission ($kgCO_2$)	CO_2 in concrete ($kgCO_2$)	CO_2 in steel ($kgCO_2$)
Span of 4 panels and length of 8 m						
Pratt	933.20	424.80	508.40	314.30	188.20	126.10
Howe	956.30	424.80	531.50	320.00	188.20	131.80
Warren	933.20	424.80	508.40	314.30	188.20	126.10
Span of 8 panels and length of 16 m						
Pratt	2732.00	849.60	1882.00	826.30	376.40	449.90
Howe	3030.00	849.60	2180.00	939.50	376.40	553.10
Warren	2865.00	849.60	2015.00	835.50	376.40	459.10
Span of 12 panels and length of 24 m						
Pratt	6403.00	1274.00	5129.00	1845.00	564.50	1280.00
Howe	7694.00	1274.00	6419.00	2157.00	564.50	1592.00
Warren	6868.00	1274.00	5593.00	1911.00	564.50	1346.00

For all optimal solutions, a slab with a height of 9cm, f_{ck} of 20 MPa and f_y of 345 MPa were obtained. The analysis of the final results indicates that in all cases, the Pratt truss provided the best results for both cost optimization and CO_2 emission optimization. On the other hand, the Howe truss provided optimal solutions superior to other models, not being the most recommended as the span length is increased. The TC profiles of the optimal cost and CO_2 emission solutions are described in tab. 3.

Table 3. Circular tubular steel profiles of the optimized solutions

Metal truss	Span length (m)	Cost optimization ($D \times e$) mm			Optimization of CO_2 emission ($D \times e$) mm		
		Upper flange	Lower flange	Diagonals and uprights	Upper flange	Lower flange	Diagonals and uprights
Pratt	8.00	88.9x3.6	33.4x3.2	33.4x3.2	88.9x3.6	33.4x3.2	33.4x3.2
	16.00	88.9x6.4	60.3x6.4	38.1x3.2	114.3x4.5	88.9x4.0	38.1x3.2
	24.00	168.3x5.6	101.6x8.0	48.3x3.6	168.3x5.6	114.3x6.4	48.3x3.6
Howe	8.00	88.9x3.6	33.4x3.2	38.1x3.2	88.9x3.6	33.4x3.2	38.1x3.2
	16.00	114.3x4.5	101.6x4.0	60.3x3.6	114.3x4.5	114.3x4.0	60.3x3.6
	24.00	168.3x6.4	141.3x6.4	88.9x3.6	168.3x6.4	141.3x6.4	88.9x3.6
Warren	8.00	88.9x3.6	33.4x3.2	33.4x3.2	88.9x3.6	33.4x3.2	33.4x3.2
	16.00	101.6x5.0	114.3x4.0	38.1x3.6	114.3x4.5	73.0x5.0	38.1x3.6
	24.00	168.3x5.6	141.3x6.4	48.3x4.5	168.3x5.6	88.9x10.0	60.3x3.6

In the 8m span, the use of the capacity to resist the axial traction and compression efforts of the TC profiles used reaches 98.36% for the lower flange and 90.65% for the diagonals and uprights of the Howe truss, respectively. With the strength of the TC profiles reaching values close to the limit, the structural design considering the Howe-type metal truss, in spans greater than 8m, tends to require TC profiles with a larger diameter, an increase in the cost of production of the structure and a higher emission rate of CO_2.

In the 16m span, the solutions optimized for CO_2 emission had larger diameter TC profiles in the upper and lower flanges in the Pratt truss, in the lower flange in the Howe truss and in the upper flange in the Warren truss when compared to the TC profiles of cost optimization. This divergence in diameters is justified in the Pratt and Howe trusses, due to the ratio of axial tensile forces requesting on the resistant efforts of the lower flange, exceeding the 90.00% utilization rate, accepted in the adoption of TC profiles in the lower flange of diameters larger.

In the last case verified, the span of 24m, the optimal design of the composite steel truss, considering the Pratt truss, generates a cost 16.78% lower if compared to the optimal solution obtained with the Howe truss. In optimizing the CO_2 emission, the comparison between the same truss models indicates that the total emission in the Pratt truss is 14.16% lower, making it the best solution for a span of this length. The ratios of the optimal solution for each truss over the overall optimal solution, for the different spans, are shown in fig. 3.

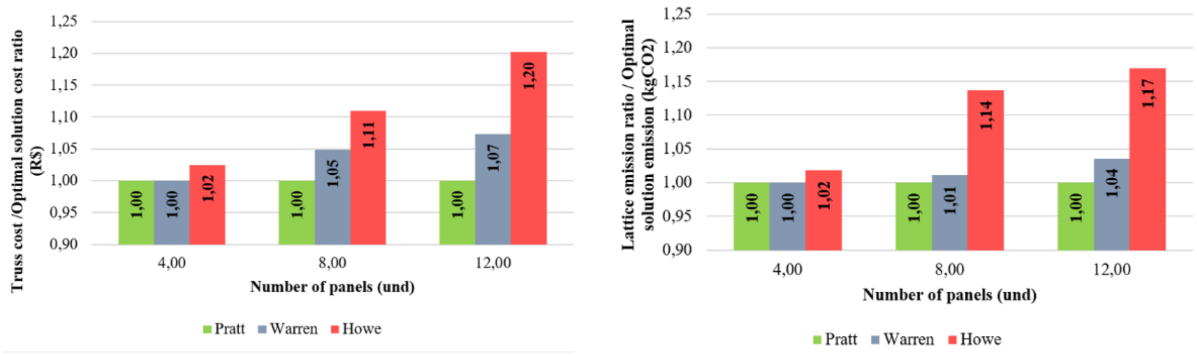

Figure 3. Normalized comparison chart for optimal solutions of Pratt, Howe and warren trusses at different spans

In the examples presented, the upper flange is the most critical design element as the combined bending effect occurs for all members. Alternatives for improving the strength conditions in this stretch must be studied. In a general context, the optimal solutions obtained with Pratt-type trusses are more advantageous, require less funding and cause less environmental impact given the extent of CO_2 emissions. The most affordable optimal solutions for sections of 4 panels, 8 panels and 12 panels correspond to savings of 2.42%, 9.83% and 16.78%, respectively, if compared to the costliest optimal solutions for each section. Regarding CO_2 emission, the optimal solutions indicated for the sections of 4 panels, 8 panels and 12 panels generate a quantity that is 1.88%, 12.05% and 14.46%, respectively, lower when compared to the solutions best results for higher CO_2 emissions for each stretch.

5 Conclusions

The genetic algorithm available in the Matlab software platform describes itself as an efficient tool to carry out the proposed optimization routine due to its efficiency in performing operations with matrices. The examples analyzed show that for solid slabs and considering profiles with a circular tubular section, among the optimal solutions the Pratt-type metal truss provides better results for minimizing cost and CO_2 emission. The proposed program made the process of sizing and optimization of composite steel and concrete trusses more agile, making it an excellent tool for automating these tasks.

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References

[1] BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. NBR 8800: Design of steel structures and composite steel and concrete structures for buildings. Rio de Janeiro, 2008.
[2] S. Neal; R. Johnson; R. M. Lawson and D. L. Mullett. "Design of composite trusses**"**. *The Steel Construction Institute*: Ascot, 1992.
[3] S. Kravanja; S. Silih and Z. Kravanja. "The multilevel MINLP optimization approach to structural synthesis: the simultaneous topology, material, standard and rounded dimension optimization". *Advances in Engineering Software*, v.36, pp.568-583, 2005.
[4] Y. Luo; A. Li and Z. Kang. "Reability-based design optimization of adhesive bonded steel-concrete composite beams with probabilistic and non-probabilistic uncertainties". *Engineering Structures*, v.33, pp.2110-2119, 2011.
[5] A. A. Vieira. "Reduction of the environmental impact of precast concrete structures through optimization by genetic algorithm". Master's Thesis (Structural Engineering), São Carlos: EESC, 2014.
[6] C. V. Caamp and F. Huq. "CO_2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm". *Engineering Structures*, v.48, pp.363-372, 2013.
[7] V. Yepes; J. V. Martí and T. García-Segura. "Cost and CO_2 emission optimization of precast-prestressed concrete U-beam road bridges by a hybrid glowworm swarm algorithm". *Automation in Construction*, v.49, pp.123-134, 2015.
[8] A. F. Tormen; Z. M. C. Pravia; F. B. Ramires and M. Kripka. "Optimization of steel concrete composite beams considering cost and environmental impact". *Steel and Composite Structures*, v.34, n,3, pp.409-421, 2020.
[9] G. F. Medeiros and M. Kripka. "Optimization of reinforced concrete columns according to diferente environmental impact assessment parameters". *Engineering Structures*, v.59, pp.185-194, 2014.
[10] D. Zhang; Q. Zhao; F. Li; Y. Huang. "Experimental and numerical study of the torsional response of a modular hybrid FRP-aluminum triangular deck-truss beam". *Engineering Structures*, v.133, pp.172-185, 2017.
[11] H. Du; X. Hu; Y. Meng; G. Han; K. Guo. "Study on composite beams with prefabricated steel bar truss concret slabs and demountable shear connectors". *Engineering Structures*, v.210, 2020.
[12] B. Liu; Y. Liu; L. Jiang; K. Wang. "Flexural behavior of concrete-filled rectangular steel tubular composite truss beams in the negative moment region". *Engineering Structures*, v.216, 2020.
[13] J. M. R. Cortes; G. G. Paula Jr. "Genetic algorithm to solve a constrained location problem". In: *XXXVI Brazilian Symposium on Operations Research*, São João Del-Rei: 2004.
[14] F. A. Kuan-Chen Fu; Y. Zhai; S. Zhou. "Optimum design of welded steel plate girder bridges using a genetic algorithm with elitism". *Journal of Bridge Engineering*, ed.10, pp.291-301, 2005.
[15] J. Câmara Neto; A. Landesmann; E. M. Batista. "Application of genetic algorithms for dimensioning steel-concrete composite beams". In: Latin American Congress of Metallic Construction, São Paulo, 2008.
[16] J. A. Lazzari; E. C. Alves; A. F. G. Calenzani. "Optimized dimensioning of frames in steel structures via genetic algorithms". *Steel Structure Magazine*, v.9, n.1, 2020.
[17] J. R. S. Ramos; E. C. Alves. "Numerical analysis of collapse modes in optimized design of cellular composite beams". *Steel Structure Magazine*, v.9, n.2, pp.222-240, 2020.
[18] B. D. Breda; T. C. Pietralonga; E. C. Alves. "Optimization of the structural system with composite beam and composite slab using genetic algorithm". *IBRACON Magazine of Metallic Structures*, v.13, n.6, 2020.
[19] D. Miller; J. H. Don; M. Mulvey. "Concrete slab comparison and embodied energy optimisation for alternate design and construction techniques". *Construction and Building Materials*, v.80, pp.329-338, 2015.
[20] BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. NBR 16239: Design of steel structures and composite steel and concrete structures for buildings with tubular profiles. Rio de Janeiro, 2013.
[21] R. H. Fakury; A. L. R. Castro and Silva and R. B. Caldas. Sizing of structural steel and steel-concrete composite elements. São Paulo: Pearson Education do Brasil, 2016.
[22] CAIXA ECONÔMICA FEDERAL. National System of Prices and Indexes for Civil Construction: Input and compositions report for the 1st quadrimester of 2020. Vitória, 2020.
[23] VALLOUREC TUBES DO BRASIL. Circular, Square and Rectangular Section Structural Tubes. Belo Horizonte, 2017.
[24] J. F. Santoro; M. Kripka. Minimizing environmental impact from optimized sizing of reinforced concrete elements. *Computers and Concrete*, v.25, n.2, pp.111-118, 2020.
[25] WORLDSTEEL ASSOCIATION. LCI data for steel products. Pittsburgh, 2017.