Topological optimization of composite truss beams considering CO_2 emissions

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Abstract. In order to provide more sustainable solutions to the construction of composite truss beams, the present work proposes a formulation to optimize dimensional, geometric and topologic parameters aiming to minimize CO_2 emissions. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are used to solve the optimization problem considering the choice of steel profiles, characteristic strength of concrete, formwork, number of panels and truss total height. The methodology is applied to a problem where three different models of truss are considered - Pratt, Howe and Warren - and an analysis of the best solution's emissions composition is made. In conclusion, results shows that the better result to the optimization problem was obtained in the Warren model and both optimization algorithm presents consistent solutions.

Keywords: optimization, composite truss, sustainable design, CO2 emissions, truss topology optimization.

1 Introduction

Reducing greenhouse gas emissions is one of the greatest challenges on this century [1]. The IPCC's Sixth Assessment Report estimates that the emission of greenhouse gases from human activities is responsible for approximately 1.1°C of warming compared to pre-industrial levels and is expected to reach or exceed 1.5°C of warming [2]. In 2020, even though the economic activity was severely reduced due to the pandemic, building construction demand for steel and cement was still responsible for 3.2 gigatons of CO_2 in energy-related emissions and, thereby, contributing 10% of global carbon emissions [3]. Therefore, it is essential that actions are taken in favor of decreasing greenhouse gas emissions and avoiding even more consequences that arise from global warming.

Many studies have pointed to structural optimization as an option to reduce environmental impact, as it allows a more efficient and rational use of construction materials [4-11]. This is mainly because the current dimensioning method is usually done by trial-and-error, making the solution's efficiency depend on the designer's experience or at the expense of laborious manual adjustment work [12]. In this way, with the structural optimization, it is possible to obtain the combination of parameters that minimizes the impact caused by the construction, which makes the process more practical and the structure more economical while still attending security conditions [13].

Different methodologies have been employed to measure the environmental impact of buildings, among then the Life Cycle Assessment (LCA), which is a method that studies the environmental inputs and outputs related to a product or service life-cycle since its production until the end of its service life [14]. A parameter that is often used to account this impact on structural optimization of various structures is the CO_2 emission, as done by Payá-Zaforteza et al. [4], García-Segura [15] and Santoro and Kripka [16].

Recent studies have been using several different algorithms in the structural optimization, such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). GA was first proposed by John Holland [17] and is based on Darwin's theory of evolution: It starts with an initial population of solutions to the problem and, in each generation, crossings are made from the most fit individuals and mutations are added, simulating natural selection and resulting, in the end, on the best solution to the problem [10]. PSO, on the other hand, was first proposed by Kennedy and Eberhart [18] and is based on a population of solutions, called particles, that are classified according to its fitness. Then, each particle is accelerated towards the best particle and also towards their own best previously founded solution. In each interaction, particles approach the best solution from a different direction and will very likely find a position, that is, a solution, that is best than the initial one, creating a new best solution to be followed in the next interaction. The optimization stops when the maximum number of interactions is reached [19].

Several studies have used GA and PSO to optimize a large range of structures, such as reinforced concrete [20-22], composite beams [23-25], composite cellular beams [26-27], steel trusses [28-30], etc. However, the optimization of composite truss beams is yet to be undertaken.

Composite trusses are structures composed of a steel truss united by shear connectors to a concrete slab. The consideration of the concrete slab as a compressive resistant element provides a significant increase to the flexural strength of the beam, since, in general, about 50% of the weight of a truss is resisted by the compressed flange [31]. In this way, composite truss beam presents itself as a very economical option, especially in situations where it is necessary to overcome spans greater than 20 meters [32]. Another advantage of composite trusses is the fact that they are relatively light and allow the passage of complex electrical, ventilating and communication systems, while still overcoming building height limitations or allowing the construction of higher beams, which minimizes deflection and vibrations [33-34].

The composite slab is composed of a metallic formwork covered with a layer of concrete and a reinforcing mesh to absorb concrete's retraction stresses on its upper part. The shape of the truss can consist of different types of profiles, such as tubular, double angles brackets, etc. and follow different assembly models, like Pratt, Howe and Warren. The dimensions, geometry and topology of a truss significantly influence the distribution of forces in each bar and, consequently, the total weight of the structure. Studies, such as Kaveh and Ahmadi [35] and Tarabay and Lima [36], indicated that the best solutions are found in the simultaneous optimization of these three parameters and Muller and Klashorst [37] corroborate with then, showing an average economy of 22% in comparison to the dimensional-only optimization.

Therefore, the present work proposes a program that performs the topological optimization of a composite truss beam, considering the current safety verifications and aiming to find the solution that causes minimum environmental impact, through different metaheuristic algorithms - GA and PSO.

2 Formulation and implementation of the optimization problem

The developed program is implemented with the software Matlab 2016a [38] and considers a simply supported composite truss beam of steel and concrete. The truss is entirely made out of double angle brackets and is attached to the composite slab by stud bolt shear connectors on its upper chord. For the problem's geometric, material and loading parameters, the program seeks the combination of variables that provides the minimum CO_2 emission and still meets the ultimate security and serviceability criteria.

Seven variables are considered in this study: steel profile of the upper chord (x_1), steel profile of the lower chord (x_2), steel profile of the web members (x_3), characteristic strength of the concrete slab (x_4), decking profile (x_5), number of panels (x_6) and truss total height (x_7).

The first three variables represent the choice of steel profile used in each element of the truss. This choice is made from the options found on a commercial catalog of structural angle-shaped profiles [39] and, thereafter, its properties are taken into account for the structural verification and CO_2 emission. x_4 varies between commercial strength values, ranging from 5 to 5 MPa, between 20MPa - the minimum compressive strength prescribed by ABNT NBR 6118:2014 [40] for structural elements - and 50 MPa. x_5 represents the choice of formwork to the concrete slab and is chosen amongst the options contained on a commercial catalog [41]. x_6 represents the number of panels of the truss and it varies from 1 to the number that provides a minimum panel length of 50 cm. Finally, x_7 represents the total height of the truss and varies from 50cm to one eighth of the span. Furthermore, the total number of shear connectors is determined in a way that assures total interaction between truss and slab and also meets the spacing limits prescribed by ABNT NBR 8800:2008 [42]. Fig. 1 shows an example of composite trussed beam and indicates the variables considered in the program.

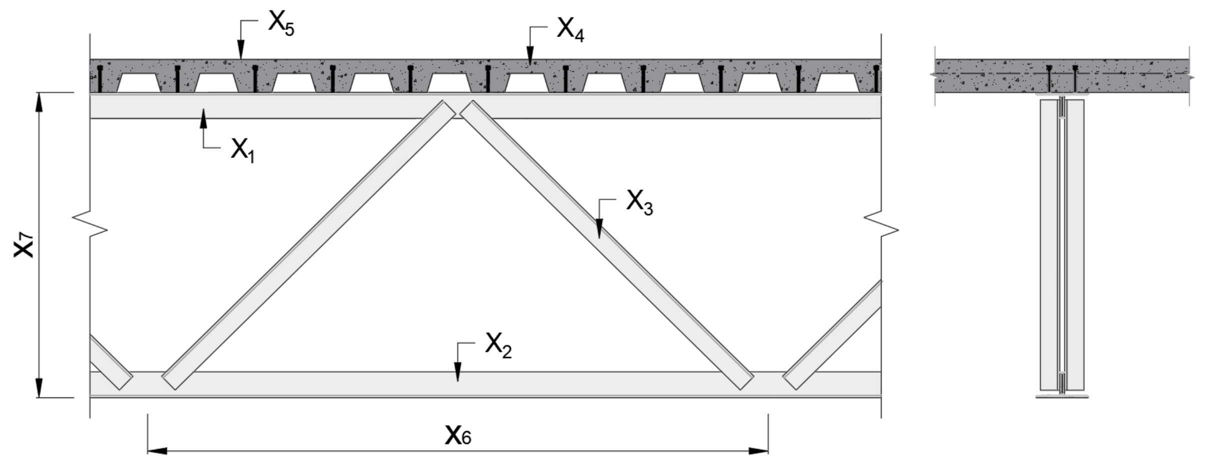


Fig. 1 Variables of the composite trussed beam considered in the program.

Therefore, the function to be minimized is shown in Eq. 1.

$$CO_{2,total} = CO_{2,steel} + CO_{2,concrete} + CO_{2,connector} + CO_{2,formwork} + CO_{2,mesh} \tag{1}$$

Where:

$$CO_{2,steel} = E_s \cdot (\sum L_u \cdot A_u + \sum L_l \cdot A_l + \sum L_{wm} \cdot A_{wm}) \cdot \rho_s \tag{2}$$

$$CO_{2,concrete} = \ E_c \cdot b_e \cdot \ L \cdot \ h_{eq} \tag{3}$$

$$CO_{2,connector} = E_s \cdot n_{sc} \cdot A_{sc} \cdot \ L_c \cdot \rho_s \tag{4}$$

$$CO_{2,formwork} = E_f \cdot L \cdot b_e \cdot C_f \tag{5}$$

$$CO_{2,mesh} = E_m \cdot L \cdot b_e \cdot C_m \tag{6}$$

Where $CO_{2,total}$ is the total emission of CO_2 of the whole composite truss; $CO_{2,steel}$, $CO_{2,concrete}$, $CO_{2,connector}$, $CO_{2,formwork}$, $CO_{2,mesh}$ are the total emissions of CO_2 of the steel, concrete, connectors, formwork and mesh, respectively; E_s is the emission of CO_2 per unit mass of produced steel, taken as $1.116\ kgCO_2/kg$ [16]; L_u, L_l and L_{wm} are the lengths of each upper chord, lower chord and web members of the truss, respectively; A_u, A_l and A_{wm} are the areas of each upper chord, lower chord and web members of the truss, respectively; ρ_s is the specific mass of steel, taken as 7850kg/m³; E_c the emission of CO_2 per unit volume of concrete with the corresponding characteristic strength, taken from Santoro and Kripka [16]; b_e is the effective width of the concrete slab; L the length of the beam; h_{eq} the equivalent thickness of concrete layer, given by the geometry of the steel formwork; n_{sc} is the number of shear connectors on the beam, which is determined to guarantee total interaction between truss and slab; A_{sc} and L_c are the area and length of the shear connectors, respectively; E_f is the unitary emission of CO_2 per unit mass of steel to the formwork, taken as $2.638\ kgCO_2/kg$ [43]; C_f is the mass of steel of a square meter of formwork; E_m is the unitary emission of CO_2 per unit mass of steel to the reinforcing mesh, taken as $1.924\ kgCO_2/kg$ [43]; C_m is the mass of mesh in a square meter of slab.

Furthermore, not only the optimal solution must be the one who provides de lowest CO_2 emission, it must also meet the criteria of ultimate limit states (ULS) and serviceability limit states (SLS). To this end, the Brazilian standardization [42] defines verifications that need to be met, as shown in Eq. 7 to 12.

$$1 - \frac{N_{Rd,u}}{N_{Sd,u}} \leq 0 \tag{7}$$

$$1 - \frac{N_{Rd,l}}{N_{Sd,l}} \leq 0 \tag{8}$$

$$1 - \frac{N_{Rd,wm}}{N_{Sd,wm}} \leq 0 \tag{9}$$

$$1 - \frac{M_{Rd}}{M_{Sd}} \leq 0 \tag{10}$$

$$\begin{cases} 1 - \left(\dfrac{N_{Rd,u}}{N_{Sd,u}} + \dfrac{8}{9}\dfrac{M_{Rd}}{M_{Sd}} \right) \leq 0, & if \;\; \dfrac{N_{Rd,u}}{N_{Sd,u}} \geq 0.2 \\ 1 - \left(\dfrac{N_{Rd,u}}{2N_{Sd,u}} + \dfrac{M_{Rd}}{M_{Sd}} \right) \leq 0, & if \;\; \dfrac{N_{Rd,u}}{N_{Sd,u}} < 0.2 \end{cases} \tag{11}$$

$$1 - \frac{\delta}{\delta_{lim}} \leq 0 \tag{12}$$

Where $N_{Rd,u}$, $N_{Rd,l}$ and $N_{Rd,dm}$ are the axial resistance of the upper chord, lower chord and web members, respectively; $N_{Sd,u}$, $N_{Sd,l}$ and $N_{Sd,dm}$ are the axial forces acting on the upper chord, lower chord and web members, respectively; M_{Rd} and M_{Sd} are the bending moment resistance and the acting bending moment on the composite section; δ is the maximum deflection on the beam; and δ_{lim} is the limit deflection.

At last, the PSO algorithm considered the Adaptive Penalty Method (APM) proposed by Barbosa and Lemonge [29], using 100 individuals and a limit of 100 interactions with tolerance of 10^{-9}. As for the GA, the program considered the native algorithm available in Matlab 2016a [38].

3 Results and discussions

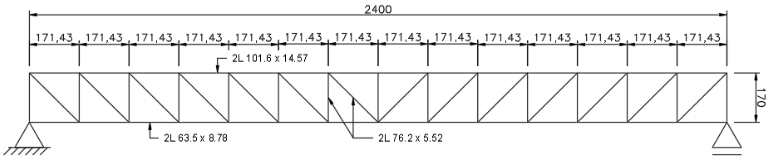
In order to verify the developed program, the solutions obtained by the optimization via GA and via PSO for a problem were analyzed considering three truss models: Pratt, Howe and Warren. The problem in question is a secondary beam with 24 meters of span, spaced 2 meters from the nearest beam and considered shored. As for the loading, the building is considered residential with high-floors, just as described in ABNT NBR 6120:2019 [44]. The dead and live load factor were considered as 1.35 and 1.5, respectively. The concrete is composed of gneiss aggregate and that the steel profiles are made of ASTM A572-42 steel with yield strength of 345 MPa and modulus of elasticity of 200 GPa.

The optimization was performed 50 times for each algorithm in order to ensure that the solutions found were not local minima. The results are shown in Table 1 and the topology of each model of truss is shown in Fig. 2.

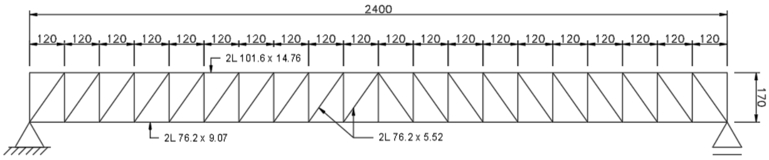
Table 1. Optimization results.

Algorithm	**Truss Model**	**Lower Chord (mm)**	**Upper Chord (mm)**	**Web Members (mm)**	**N° Panels**	**Height (cm)**
GA	Pratt	2L 63.50 x 8.78	2L 101.6 x 14.57	2L 76.20 x 5.52	14	170 cm
	Howe	2L 76.20 x 9.07	2L 88.90 x 12.58	2L 76.20 x 5.52	20	170 cm
	Warren	2L 76.20 x 7.29	2L 101.6 x 14.57	2L 76.20 x 5.52	12	205 cm
PSO	Pratt	2L 63.50 x 8.78	2L 101.6 x 14.57	2L 76.20 x 5.52	14	170 cm
	Howe	2L 76.20 x 9.07	2L 88.90 x 12.58	2L 76.20 x 5.52	20	170 cm
	Warren	2L 63.50 x 7.44	2L 101.6 x 14.57	2L 76.20 x 5.52	12	200 cm

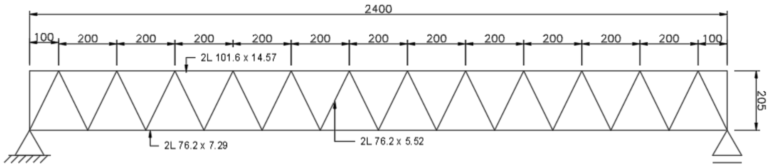
In all cases, the choice of the characteristic strength of the concrete slab resulted in 20 MPa, the minimum possible value. The choice of formwork was also unanimous in the MF50 option with 11cm hight, 0.8mm of width and reinforcing mesh of ϕ3.8cm x ϕ3.8cm, 15cm x 15cm, the minimum possible admissible one for a floor beam. This is probably because of the low distance between beams and loading.



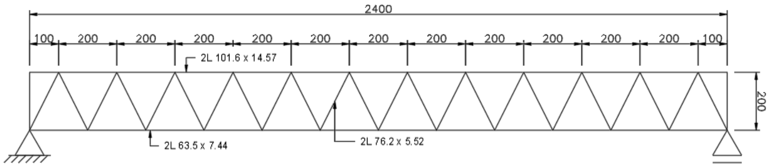
A. PRATT MODEL



B. HOWE MODEL



C. WARREN MODEL (GA)



D. WARREN MODEL (PSO)

Figure 2. Truss topology of each solution.

From Tab. 1 it can be observed that the solutions provided by GA and PSO converge to the same solution in all cases, except in the Warren model. In the Warren model, however, the difference between the two solutions is basically the choice of the lower chord profile and a slight change in the height of the truss, which generates a difference lower than 0.2% in the total emission, as shown in Fig. 3. The convergence of the two algorithms confirms the accuracy of the solutions presented and, although there were differences in one case, they were not significative.

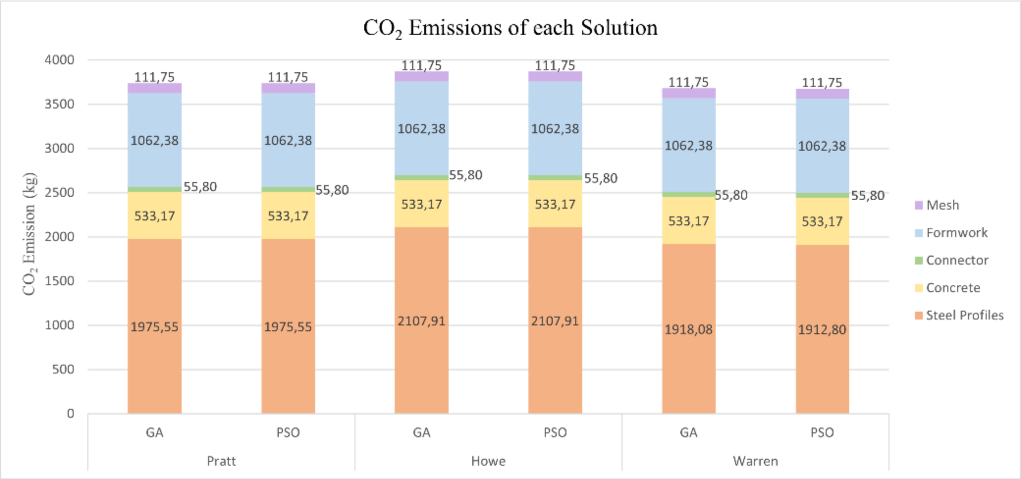


Figure 3. CO_2 Emissions of each solution.

The most economical solution was provided by the Warren model, with 3675.9 $kgCO_2$, followed by Pratt, with 3738.6 $kgCO_2$, and the least economical was Howe, with 3871.0 $kgCO_2$. It can be seen, therefore, that the Warren model caused more than 5% less emissions in relation to the Howe model, being the most adequate for this problem. On average, 53.1% of emissions come from truss profiles, 14.2% from concrete emissions, 1.5% from shear connector emissions, 28.2% from formwork emissions and 3.0% from reinforcing mesh emissions. Also, from the truss profiles emission, an average of 22.4% comes from the profiles of the lower chords, 37.2% from the upper chords and 40.4% from the web members.

As shown in Fig. 4, the most restrictive criterion, in all cases, was axial stress (Eq.8) and combined bending (Eq. 11) in the upper chord.

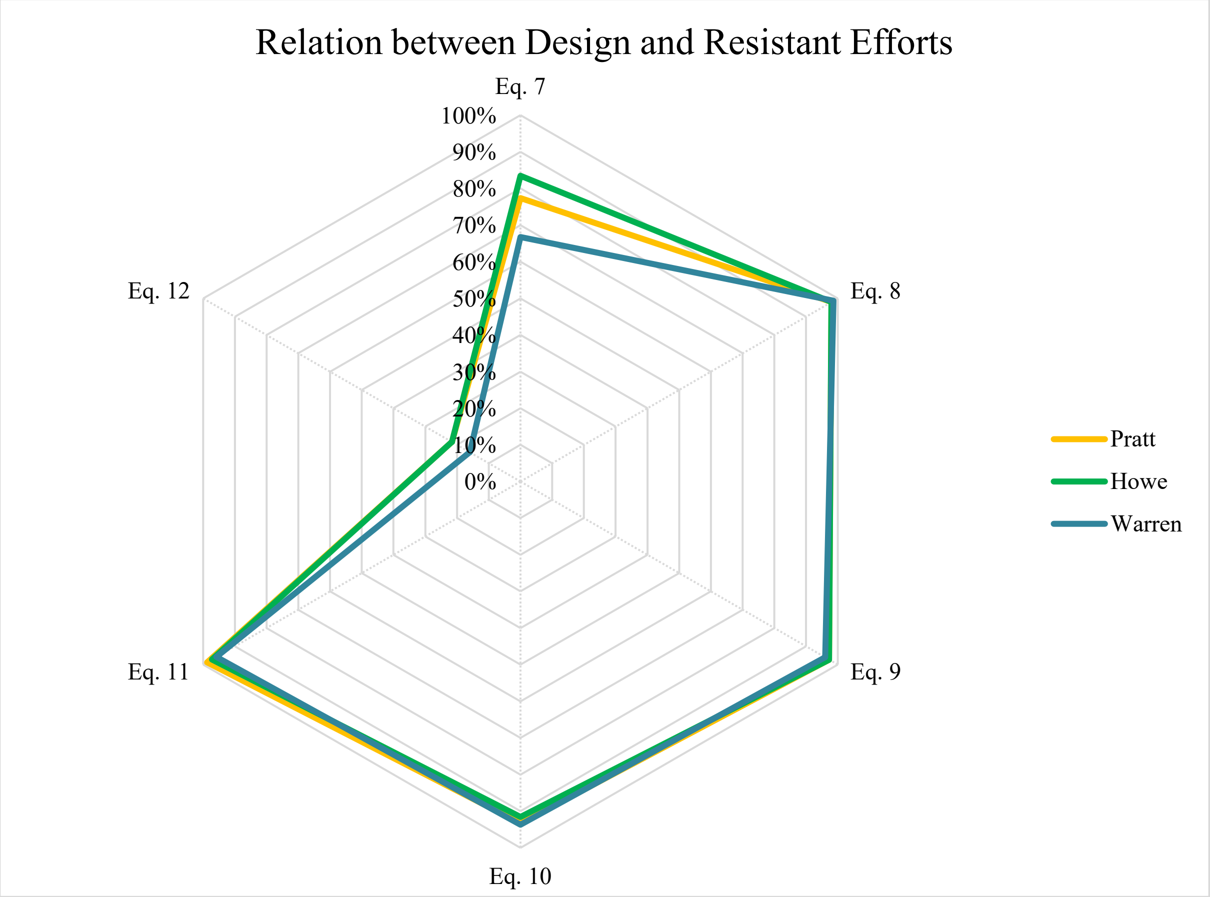


Figure 4. Relation between Design and Resistant Efforts.

4 Conclusion

This paper sought to propose a formulation to the topological structural optimization of a composite truss with the objective of minimizing its environmental impact. Two different heuristic algorithms were used and three models were considered in and example and it was concluded that:

- Both algorithms provided coherent results, being equal or very similar in all cases;
- The Warren model was more than 5% more economic than the Howe model for the problem in question;
- The larger amount of CO_2 produced by the beam was due to the steel profile, followed by the formwork and concrete slab.

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References

[1] Intergovernmental Panel on Climate Change. "Contribution of working groups I, II and III to the fourth assessment report on intergovernmental panel on climate change". *Climate change 2007: Synthesis report*, Geneva, Switzerland.
[2] Intergovernmental Panel on Climate Change. "Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change". *Climate Change 2022: Impacts, Adaptation, and Vulnerability*, Cambridge University Press.
[3] UN Environment and International Energy Agency (2021): Towards a zero-emission, efficient, and resilient buildings and construction sector. *Global Status Report*, 2021.
[4] I. Paya-Zaforteza, V. Yepes, A. Hospitaler and F. González-Vidosa, "CO2-optimization of reinforced concrete frames by simulated annealing". *Engineering Structures*, vol. 31, no. 7, pp. 1501–1508, 2009, doi: 10.1016/j.engstruct.2009.02.034.
[5] D. Yeo and R. D. Gabbai, "Sustainable design of reinforced concrete structures through embodied energy optimization". *Energy Build*, vol. 43, pp. 2028–33, 2011, doi: 10.1016/j.enbuild.2011.04.014.
[6] V. Yepes, F. Gonzalez-Vidosa, J. Alcala and P. Villalba, "CO2-Optimization Design of Reinforced Concrete Retaining Walls Based on a VNS-Threshold Acceptance Strategy". *J. Comput. Civ. Eng.*, vol. 26, no. 3, pp. 378–386, 2012, doi: 10.1061/(asce)cp.1943-5487.0000140.
[7] C. V. Camp and F. Huq, "CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm". *Eng. Struct.*, vol. 48, pp. 363–372, 2013, doi: 10.1016/j.engstruct.2012.09.004.
[8] G. F. de Medeiros and M. Kripka, "Optimization of reinforced concrete columns according to different environmental impact assessment parameters". *Eng. Struct.*, vol. 59, pp. 185–194, 2014, doi: 10.1016/j.engstruct.2013.10.045.
[9] S. W. Choi, B. K. Oh, J. S. Park and H. S. Park, "Sustainable design model to reduce environmental impact of building construction with composite structures". *J. Clean. Prod.*, vol. 137, pp. 823–832, 2016, doi: 10.1016/j.jclepro.2016.07.174.
[10] T. Dede, M. Kripka, V. Togan, V. Yepes and R. V. Rao, "Usage of Optimization Techniques in Civil Engineering During the Last Two Decades". *Curr. Trends Civ. Struct. Eng.*, vol. 2, no. 1, 2019, doi: 10.33552/ctcse.2019.02.000529.
[11] 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, p. 409-421, 2020.
[12] N. D. Lagaros, "The environmental and economic impact of structural optimization". *Struct. Multidiscip. Optim.*, vol. 58, no. 4, pp. 1751–1768, 2018, doi: 10.1007/s00158-018-1998-z.
[13] B. K. Oh, S. W. Choi, and H. S. Park, "Influence of variations in CO2 emission data upon environmental impact of building construction". *J. Clean. Prod.*, vol. 140, pp. 1194–1203, 2017, doi: 10.1016/j.jclepro.2016.10.041.
[14] M. M. Khasreen, P. F. G. Banfill and G. F. Menzies, "Life-cycle assessment and the environmental impact of buildings: A review". *Sustainability*, vol. 1, no. 3, pp. 674–701, 2009, doi: 10.3390/su1030674.
[15] T. García Segura, V. Yepes, "Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety". *Engineering: the final public*, pp. 325–336, 2016, doi:10.1016/j.engstruct.2016.07.012.
[16] J. F. Santoro and M. Kripka, "Minimizing environmental impact from optimized sizing of reinforced concrete elements". *Comput. Concr.*, vol. 25, no. 2, pp. 111–118, 2020, doi: 10.12989/cac.2020.25.2.111.
[17] J. H. Holland, Adaptation in Natural and Artificial System. University of Michigan Press, Ann Arbor, USA, 1975.
[18] J. Kennedy and R. Eberhart, "Particle swarm optimization". *Proceedings of the IEEE International Conference on Neural Networks*. Perth, Australia, Oceania:1942–1948.
[19] A. A. A. Esmin, R. A. Coelho, and S. Matwin, "A review on particle swarm optimization algorithm and its variants to clustering high-dimensional data". *Artif. Intell. Rev.*, vol. 44, no. 1, pp. 23–45, 2015, doi: 10.1007/s10462-013-9400-4.
[20] V. Govindaraj and J. V. Ramasamy, "Optimum detailed design of reinforced concrete continuous beams using Genetic Algorithms". *Comput. Struct.*, vol. 84, no. 1–2, pp. 34–48, 2005, doi: 10.1016/j.compstruc.2005.09.001.
[21] C. A. C. Coello, A. D. Christiansen, and F. S. Hernández, "A simple genetic algorithm for the design of reinforced concrete beams". *Eng. Comput.*, vol. 13, no. 4, pp. 185–196, 1997, doi: 10.1007/bf01200046.
[22] V. K. Koumousis and S. J. Arsenis, "Genetic algorithms in optimal detailed design of reinforced concrete members". *Comput. Civ. Infrastruct. Eng.*, vol. 13, no. 1, pp. 43–52, 1998, doi: 10.1111/0885-9507.00084.
[23] B. D. Breda, T. C. Pietralonga, and E. C. Alves, "Optimization of the structural system with composite beam and composite slab using Genetic Algorithm". *IBRACON Structures and Materials Journal*, vol. 13, no. 6, pp. 1–14, 2020, doi: 10.1590/s1983-41952020000600002.
[24] A. H. Whitworth and K. D. Tsavdaridis, "Genetic algorithm for embodied energy optimisation of steel-concrete composite beams". *Sustainability*, vol. 12, no. 8, pp. 1–17, 2020, doi: 10.3390/SU12083102.
[25] A. B. Senouci and M. S. Al-Ansari, "Cost optimization of composite beams using genetic algorithms". *Adv. Eng. Softw.*, vol. 40, no. 11, pp. 1112–1118, 2009, doi: 10.1016/j.advengsoft.2009.06.001.
[26] F. Erdal, E. Doan, and M. P. Saka, "Optimum design of cellular beams using harmony search and particle swarm optimizers". *J. Constr. Steel Res.*, vol. 67, no. 2, pp. 237–247, 2011, doi: 10.1016/j.jcsr.2010.07.014.
[27] G. Erlacher and É. C. Alves, "Optimal Design of Composite Cellular Beams with Partial Interaction and its Environmental Impacts". *XLII Ibero-Latin-American Congress on Computational Methods in Engineering and III Pan-American Congress on Computational Mechanics, ABMEC-IACM*, Rio de Janeiro, 2021.

[28] R. E. and K. Behdi, "Particle Swarm Optimization in Structural Design". *Swarm Intell. Focus Ant Part. Swarm Optim.*, no. December, 2007, doi: 10.5772/5114.

[29] A. C. C. Lemonge and H. J. C. Barbosa, "An adaptive penalty scheme for genetic algorithms in structural optimization". *Int. J. Numer. Methods Eng.*, vol. 59, no. 5, pp. 703–736, 2004, doi: 10.1002/nme.899.

[30] A. Baghlani and M. H. Makiabadi, "An enhanced particle swarm optimization for design of pin connected structures". *Sci. Iran.*, vol. 20, no. 5, pp. 1415–1432, 2013.

[31] J. Wardenier, Y. Kurobane, J. A. Packer, D. Dutta, N. Yeomans. *Design guide for circular hollow section (CHS) joints under predominantly static loading*. Comité International pour le Développemente et l'Étude de la Construction Tubulaire. Germany, 1991.

[32] S. A. Raji, K. K. Abdulraheem, R.O. Rahmon and A. A. Adelowo, "Design Of A Composite Truss System In A Multistorey Building". *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, vol. 4, no. 3, 2017.

[33] J. Bujnak, P. Michalek, and W. Baran, "Experimental and theoretical investigation of composite truss beams". *MATEC Web Conf.*, vol. 174, pp. 6–13, 2018, doi: 10.1051/matecconf/201817404001.

[34] J. D. Martins. *Estudo teórico, numérico e experimental de treliças mistas em perfis tubulares*. Doctorate thesis, University of Ouro Preto, 2014.

[35] A. Kaveh and B. Ahmadi, "Sizing, geometry and topology optimization of trusses using force method and supervised charged system search". *Structural Engineering and Mechanics*, vol. 50, 2014, doi:10.12989/sem.2014.50.3.365.

[36] M. Almeida and K. Tarabay, "Otimização topológica, geométrica e dimensional de estruturas metálicas treliçadas, dimensionadas conforme a norma ABNT NBR 8800 : 2008". *REA*, vol. 11, pp. 21–38, 2022.

[37] T. E. Müller and E. van der Klashorst, "A quantitative comparison between size, shape, topology and simultaneous optimization for truss structures". *Lat. Am. J. Solids Struct.*, vol. 14, no. 12, pp. 2221–2242, 2017, doi: 10.1590/1679-78253900.

[38] MATLAB, "The language of technical computing." Version 2016a. The MathWorks, Inc, 2016. Available in: <https://www.mathworks.com/?s_tid=gn_logo>. Access: 19/08/2021.

[39] Gerdau, "Perfis estruturais Gerdau: Tabela de bitolas". Available in: <https://www2.gerdau.com.br/catalogos-and-manuais>. Access: 26/04/2022.

[40] ABNT NBR 6118, "Projeto de estruturas de concreto - Procedimento." Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards), Rio de Janeiro, 2014.

[41] METFORM, "Catálogo de Fôrmas". Available in: www.aecweb.com.br. Access: 26/04/2022.

[42] ABNT NBR 8800, "Design of steel and composite steel and concrete structures for buildings," Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards), Rio de Janeiro, 2008.

[43] Worldsteel Association. "LCI data for steel products". Available in: <https://www.worldsteel.org>. Acess: 27/05/2022: 2022.

[44] ABNT NBR 6120, "Cargas para o cálculo de estruturas de edificações" Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards), Rio de Janeiro, 2019.