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Optimization of steel beams with external pretension, considering the environmental and financial impact.

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Abstract

With the advancement technology for reinforced concrete structures, it becomes increasingly feasible to use this technology for steel structures. The objective of this work is to present the formulation of the optimization problem of steel beams with external pretension with straight or polygonal tracing cables, considering the environmental and economic impacts. For the objective function formulation, the minimization of CO_2 emission and cost in the design of the structure was considered. As constraints were established the states limits imposed by ABNT NBR 8800:2008. The program was developed within the MATLAB Platform (2016) and the optimization problem solution was obtained through the native Genetic Algorithms method. Routine validation was performed using examples found in the literature and an analysis of the predominant collapse modes was performed. The results indicate that monosymmetric profiles have gains when it comes to reducing CO_2 emissions and cost when compared to doubly symmetrical profiles, in addition it was observed that straight cables generate better values of CO_2 emission and cost when compared to polygonal cables.

Keywords*: Optimization, Genetic Algorithm, steel beams, external pretension, CO_2 emission.*

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1 INTRODUCTION

One of the great goals of engineering is to develop projects with maximum safety and minimum costs. However, given the current scenario, the environmental impact has become an important factor in the structures design, so that studies have sought more sustainable systems for civil construction.

Thus, a tool used to obtain optimal solutions of financial cost and environmental impact in the structures design is optimization through algorithms that use meta-heuristics. These algorithms have proven relevant in the minimization of costs and environmental impacts.
The application of optimization techniques to the design of structural elements has steadily increased in recent decades as observed in the studies performed by, Senouci and Al-Ansari (2009), Erdal, Dogan and Saka (2011), Hare et al. (2013), Breda, Pietralonga and Alves (2020), Arpini et al (2021), Mousavi, Yazdi, Yazdi (2022).

However, as stated by Santoro and Kripka (2020), Tormen *et al.* (2019), Payá-Saforteza *et al.* (2009), Camp and Huq (2013), Park *et al.* (2014), Yepes, Martí and García-Segura (2015) and Yu *et al.* (2020), optimizations focused only on financial cost may not be enough to determine an optimal solution to the problem. Studies for the life-cycle of materials and their impact on the environment become an important. Oliveira *et al.* (2014) show in their study that most CO2 emission of civil construction if from concrete industry and the main responsible is in cement production.

Santoro and Kripka (2020) point out the advantages of using high-strength concrete in reducing CO_2 emissions for reinforced concrete columns and at the same time point out that for the beams these concretes don’t have much influence.

Tormen *et al.* (2020) present a study to minimize CO_2 emissions for composite steel and concrete beams. The authors analyze the influence of the characteristic strength to concrete compression as well as the influence of the degree of interaction between the slab and the steel beam in the reduction of CO_2.

Arpini *et al.* (2022) present the formulation of the optimization problem for composite floor systems in order to reduce CO_2 emissions using genetic algorithm. The authors point out in the study that the best solution from an economic point of view is not always the best solution from an environmental point of view.

As in recent years, environmental problems have proved to be an alarming factor in society, so the optimization of structural systems taking into account the reduction of CO_2 and not only the costs involved in construction is very relevant.

Steel beams with external pretension are structural elements that have a high degree of strength, supporting high loads and not using concrete, tend to emit less CO_2 in their manufacture. The steel cables used in the external pretension can be positioned outside the section or inside the beam. The cables used are the same used in the structures of prestressed concrete, with some differential accessories to anchor and divert the cables.

According to Lou *et al.* (2019) external pretension is more effective in reducing tension at the bottom base of the steel beam in the middle of the span than in the center of the support. And according to Lou *et al.* (2016) the external pretension in composite beams significantly improves the behavior of the structure in the short term, but as for the long-term response, the pretension doesn't seem to influence much.

Abbas *et al.* (2018) developed a study in which the optimization of steel beams with pretension and without pretension was compared. Through the results, it can be observed that prestressed steel beams require a lower cross section than steel beams without pretension.

Aydin (2022) did a study aimed at optimizing the costs of prestressed steel trusses using cables positioned below the lower flange and molded with desviators. The optimization variables defined were the sections of the elements and layout of the truss, cable profile, dimension of the desviators. The optimization algorithm used was Jaya. Through the results it was observed that the pretension provided a savings in the costs of the steel truss project.

In the case of works on composite beams of steel and concrete with external pretension, it is worth mentioning the works of Nie *et al.* (2007), Chen *et al.* (2009), El-Sisi *et al.* (2021) and Hassanin *et al.* (2021), who made comparative studies between composite beams with pretension and without pretension. The results show that the pretension improves the overall performance of composite beams.

This study aims to propose the optimization problem formulation of CO_2 emission and the cost of steel beams with external pretension using the straight and polygonal tracing of the tendons for double symmetrical and monosymmetric profiles. The optimization problem solution was obtained by Genetic Algorithm native in platform Matlab.

2 OPTIMIZATION PROBLEM FORMULATION

The optimization aims to reduce the emission of CO_2 or the financial cost of a bi-supported steel beam using external pretension, with requests for uniform and concentrated loads. The steel profile is type I and can be monosymmetric or doubly symmetrical. The ABNT NBR 8800:2008, which deals with the design of steel structures, was used to model the problem and establish the beam design criteria.

The metaheuristic used is Genetic Algorithm based on the theory of evolution proposed by Charles Darwin. This algorithm performs well on highly nonlinear problems and a good sensitivity to excluding local minimums from optimal solutions. MATLAB 2016a, which natively has the genetic algorithm in its library, was the platform used to develop the optimization problem.

2.1 Design Variables

In the genetic algorithm the variables behave as a population formed by individuals who modify through mutations and recombinations to find an optimized solution. Figures 1 and 2 show the design variables representation for monosymmetric and doubly symmetrical profiles.

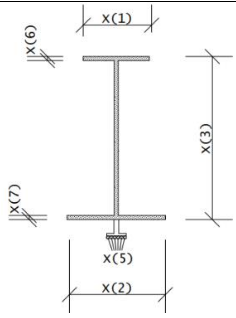
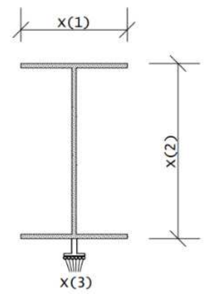
	
(a) Monossimetric Profile Variables	(b) Doubly Simmetric Profile Variable

Figure 1 - Cross-section design variables.

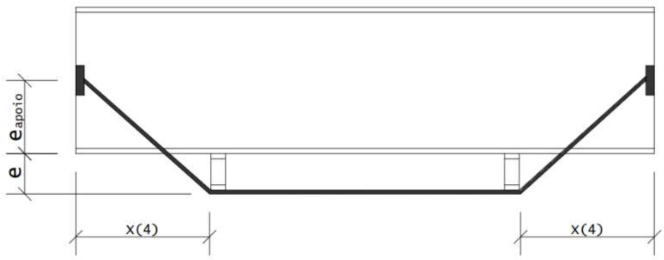


Figure 2 - Longitudinal section design variables.

Equations 1 and 2 represent, the maximum and minimum limits of the variables of steel beams with monossimetric profiles.

$$l_b = [10 \ \ 10 \ \ 50 \ \ 1 \ \ 0 \ \ 1{,}6 \ \ 1{,}6] \quad (1)$$
$$u_b = [55 \ \ 55 \ \ 200 \ \ 5 \ \ 20 \ \ 4{,}44 \ \ 4{,}44] \quad (2)$$

For monossimetric profiles, the lower and upper flanges can have different values, thus the variables $x(1)$ and $x(2)$ represent the width of the top and bottom flanges, respectively; $x(6)$ and $x(7)$ equivalent to the thickness of the upper and lower flanges. The variable $x(3)$ represents the height of the steel profile. In addition to these variables related to the steel profile, the characteristics of the tendons are represented by $x(4)$ and $x(5)$ that show the slope length and the number of tendons, respectively.

For doubly symmetrical profiles, equations 3 and 4 define the limits.

$$l_b = [10 \ \ 14{,}8 \ \ 0 \ \ 1] \quad (3)$$
$$u_b = [55 \ \ 200 \ \ 20 \ \ 5] \quad (4)$$

The optimization for double symmetric profiles has a reduction in the number of variables, in relation to the monossymmetric solution, because there is no longer the possibility of differentiating the width of the profile flanges. Like this $x(1)$represents the width of the flanges $x(2)$ the height of the profile, $x(3)$the amount of tendons and $x(4)$ the length of inclination of the tendons.

In both types of profiles all variables are continuous, except for the slope length that was defined as a vector of 5 positions ranging from 10% to 30% of the beam span, with a step of 5%.

2.2 Objective Function

The objective function is the main function of the optimization problem, in this study two different objective functions were proposed, one formed by the sum of CO_2 emissions generated in the manufacture of each element and another consisting of the sum of the cost of each optimized item, that is, the steel profile and the amount of tendons. The objective functions for the optimization of cost and environmental impact, measured in Reais and kg of CO_2 emission, respectively, are presented in equations (5) and (6).

$$MinCusto = V_a m_a C_a + N_s A_s L_s m_a C_s \tag{5}$$
$$MinCO_{2eq} = V_a m_a E_a + N_s A_s L_s m_a E_s \tag{6}$$

Being V_a the steel volume of the beam profile (m³), m_a the specific mass of steel (kg/m³) equal to 7850, C_a the cost of steel (R$/kg), E_a CO_2 emission from the steel profile (kgCO_2/kg), $N_s$the total amount of tendons, A_s the area of the tendons section (m^2), L_s the length of the tendons (m), C_s the cost of tendons (R$/kg) and E_s CO_2 emission from tendons (kgCO_2/kg).

2.3 Constraints

The constraints of the problem were defined according to ABNT NBR 8800:2008, considering the last limits and service states for the sizing of a bi-supported steel beam. The constraints of the problem are presented in equation (7).

$$C = \begin{cases} C(1) = \frac{M_{Sd}}{M_{Rd}} - 1 \le 0 & C(8) = \frac{k_c}{0{,}76} - 1 \le 0 \\ C(2) = \frac{M_{Sd\_vazio}}{M_{Rd}} - 1 \le 0 & C(9) = \frac{\delta_t}{\delta_{adm}} - 1 \le 0 \\ C(3) = \frac{V_{Sd}}{V_{Rd}} - 1 \le 0 & C(10) = \frac{\delta_{t\_vazio}}{\delta_{adm}} - 1 \le 0 \\ C(4) = \frac{N_{Sd}}{N_{Rd}} - 1 \le 0 & C(11) = \frac{N_{Sd}}{N_{Rd}} + \frac{8M_{Sd}}{9M_{Rd}} - 1 \le 0 \\ C(5) = \frac{d}{4b_f} - 1 \le 0 & C(12) = \frac{N_{Sd}}{N_{Rd}} + \frac{8M_{Sd\_vazio}}{9M_{Rd}} - 1 \le 0 \\ C(6) = \frac{d}{1{,}5b_f} + 1 \le 0 & C(13) = \frac{\sigma_{cd}}{f_{cd}} - 1 \le 0 \\ C(7) = \frac{k_c}{0{,}35} - 1 \le 0 & C(14) = \frac{\sigma_{td}}{f_{yd}} - 1 \le 0 \end{cases} \tag{7}$$

Being the constraints$C(1)$ and $C(2)$ verification during the use phase of the structure and at the act of stress, respectively. The constraints $C(3)$ checks the beam for cutting effort and $C(4)$ checks the beam at normal exertion. $C(5)$, $C(6)$, $C(7)$ and $C(8)$ geometric constraints of the profiles used. The equations $C(9)$ and $C(10)$ restrict maximum deformation on the beam during use and at the time of pretension. Constraints $C(11)$ and $C(12)$ are related to the verification of the beam to combined bending during the phase of use and the act of pretension, respectively. Finally, the constraints $C(13)$ e $C(14)$ are related to the limitation of maximum compression and tensile stresses, respectively. The values of the financial cost and CO_2 emission used in the examples are shown in table 1.

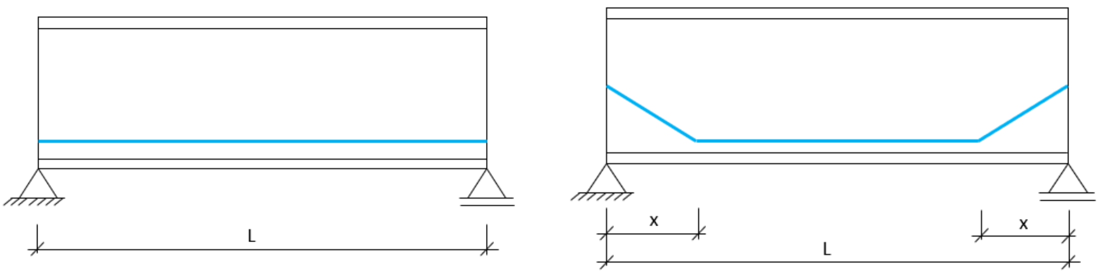
Table 1 - Cost and CO_2 emission values for each component of the structure.

	Financial cost (R$/kg)	*$CO_{2\ emission}$ ($kgCO_2/kg$)*
Steel profile	10.00	1.116
Tendons	12.69	1.050
Source	SINAPI (2022)	Santoro and Kripka (2020)

To Genetic Algorithm was used the initial population contains 100 individuals. The rate of elite individuals and crossing of the intermediate type are 0.05 and 0.85, respectively, whereas the mutation rate is random.

3 RESULTS AND DISCUSSIONS

Two examples of beams with external pretension were analyzed, using tendons with straight or polygonal tracing, in which we sought to optimize the CO_2 emission and cost, verifying which would have the best result. Figure 3 shows the straight and polygonal tracing of the tendons, with "L" being the length of the beam and "x" the inclined length. The inclined length varies according to the beam span, which can be 10%, 15%, 20%, 25% and 30% of the span. The positioning of the cable, is the distance from the cable to the top face of the bottom table, being positive above and negative below.



(a) Straight Cable (b) Polygonal cable

Figure 3 - Tracing of the prestressing tendons.

3.1 Example 01 – Abbas *et al.* (2018)

The first example analyzed was extracted from Abbas *et al.* (2018) and these are prestressed beams with monosymmetrical steel profile. Abbas *et al.* (2018) performed a first analysis using Ansys, in which the exact values of the properties of the materials were entered as input data. Subsequently, an Ansys optimization algorithm was used to find the optimized solution of steel beams with external pretension. The authors analyzed two objective functions, which are the minimization of tension and the minimization of the total volume of steel of the beam. The constraints applied were referring to the maximum stresses in the steel profile and the tendons, maximum shear stress in steel and the maximum deflection in the middle of the beam span.

The beam and loads used in example 01 can be seen in Figure 4. For this example, as well as Abbas *et al.* (2018), we considered steel profile ASTM A36, tendons CP 190 diameter of 9.5 mm. Three possible values were adopted for the losses of the pretension, 0%, 10% or 20%. Although the loss value of 0% does not exist in practice, the analysis was made only to have comparison parameters. Table 2 shows the input data from the optimization algorithm.

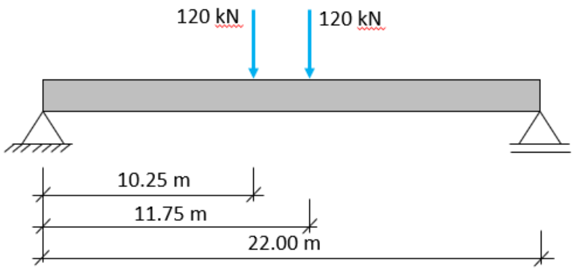


Figure 4 - Beam and loading of Example 01.

Table 2 - Input data from Example 01.

	Monosymmetric Profile	Doubly symmetrical profile
L (m)	22	22
Unlocked length (m)	0	0
Distance between stiffeners (m)	22	22
t_{table} (mm)	-	20.8
Cable positioning (cm)	-5	-5
Positioning the cable on the support (cm)	-10	-10
t_w (mm)	10.4	10.4
Cb	1	1
Profile Cost (R$/kg)	10	10

The models analyzed were named according to the symbology of Figure 5, and the first letter referring to the profile type, monosymmetric (M) or double symmetrical (D), the second letter represents the tracing, straight (R) or polygonal (P), and the symbols after the hyphen indicate the percentage of losses of 0% (P0), 10% (P10) or 20% (P20).

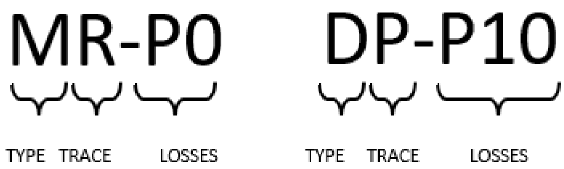


Figure 5 - Designation of the models analyzed in Example 01.

In Table 3, it can be noted the optimal values presented by Abbas *et al.* (2018) and the values when the CO 2 emission is optimized for the monosymmetric and doubly symmetrical profiles. It is noteworthy that in the study used as reference was not specified number of tendons but the area necessary for external pretension, being this value of 130.3 mm² of tendon steel area.

Table 3 - Result of the CO 2 emission optimization of Example 01

Model	Sloping length (% vão)	Nº de cabos	A cabos (mm²)	$t_{f\,sup}$ (mm)	$t_{f\,inf}$ (mm)	$b_{f\,sup}$ (mm)	$b_{f\,inf}$ (mm)	t_w (mm)	d (mm)	A (cm²)
Abbas *et al.* (2018)	-	-	130.3	22.6	20.8	391.8	390.8	10.4	984.3	267.69
MR-P0	0	8	448	16.2	16.0	270	220	10.4	1070	186.87
MP-P0	30	8	448	16.0	16.0	270	230	10.4	1060	186.91
MR-P10	0	8	448	16.0	16.0	270	220	10.4	1080	187.39
MP-P10	25	8	448	16.0	16.0	270	220	10.4	1080	187.39
MR-P20	0	9	504	16.0	16.0	270	220	10.4	1080	187.39
MP-P20	25	9	504	16.0	16.0	270	220	10.4	1080	187.39
DR-P0	0	9	504	20.8	20.8	270	270	10.4	1060	218.23
DP-P0	30	9	504	20.8	20.8	270	270	10.4	1060	218.23
DR-P10	0	10	560	20.8	20.8	270	270	10.4	1070	219.27
DP-P10	30	10	560	20.8	20.8	270	270	10.4	1070	219.27
DR-P20	0	1	56	20.8	20.8	280	280	10.4	1120	228.63
DP-P20	30	1	56	20.8	20.8	280	280	10.4	1120	228.63

Table 3 shows that cable consumption increased by approximately 244% since the steel profile decreased by approximately 30%.

For all models analyzed, table 4 shows the CO_2 emission values of the steel and tendons profile, as well as the total CO_2 emission of the prestressed beam and the ratio between the total CO_2 emission of each model in relation to that of Abbas *et al.* (2018). It is observed that the most interesting solution from the point of view of CO_2 emission is the beam prestressed with monosymmetric profile, regardless of the type of stroke. It should also be noted that the loss of stress has little influence on the total value of CO_2 emission. As can still be observed in Table 4, the best result found had a reduction of 29% in relation to the literature, the worst case had a reduction of 15%.

Table 4 - CO_2 emission values for Example 01

Model	Profile CO_2 emission ($kgCO_2$)	Tendons CO_2 emission ($kgCO_2$)	Total CO_2 emission ($kgCO_2$)	Authors CO_2/ t Abbas *et al.* (2018) CO_2
Abbas *et al.* (2018)	5160.59	22.40	5182.95	1.000
MR-P0	3602.52	77.00	3679.52	0.710
MP-P0	3602.42	77.13	3679.55	0.710
MR-P10	3611.93	77.00	3688.93	0.712
MP-P10	3611.79	77.16	3688.95	0.712
MR-P20	3614.86	86.63	3701.49	0.714
MP-P20	3611.71	86.80	3698.51	0.714
DR-P0	4206.09	86.63	4292.72	0.828
DP-P0	4206.09	86.77	4292.86	0.828
DR-P10	4226.13	96.25	4322.38	0.834
DP-P10	4226.13	96.42	4322.55	0.834
DR-P20	4406.53	9.63	4416.16	0.852
DP-P20	4406.53	9.64	4416.17	0.852

Table 5 shows the main values obtained for the design and cost analysis variables and table 6 shows the cost values of the steel and tendons profile, as well as the total cost of the prestressed beam and the ratio between the total cost of each model compared to that of Abbas *et al.* (2018). The most interesting solution from an economic point of view is also the prestressed beam with monosymmetric profile.

Table 1 – Cost Optimization Results - Example 01

Modelo	Sloping length (% vão)	Nº de cabos	A cabos (mm²)	$t_{f\,sup}$ (mm)	$t_{f\,inf}$ (mm)	$b_{f\,sup}$ (mm)	$b_{f\,inf}$ (mm)	t_w (mm)	d (mm)	A (cm²)
Abbas *et al.* (2018)	-	-	130.3	22.6	20.8	391.8	390.8	10.4	984.3	267.69
MR-P0	0	8	448	24.5	16.0	200	260	10.4	1000	190.48
MP-P0	15	7	392	21.9	16.0	220	260	10.4	1020	191.86
MR-P10	0	8	448	25.7	16.0	190	260	10.4	1010	191.10
MP-P10	30	8	448	26.8	16.0	180	260	10.4	1020	191.40
MR-P20	0	10	560	25.9	16.0	190	260	10.4	1000	190.53
MP-P20	30	10	560	25.9	16.0	190	260	10.4	1000	190.53
DR-P0	0	9	504	20.8	20.8	270	270	10.4	1060	218.23
DP-P0	30	9	504	20.8	20.8	270	270	10.4	1060	218.23
DR-P10	0	10	560	20.8	20.8	270	270	10.4	1070	219.27
DP-P10	30	10	560	20.8	20.8	270	270	10.4	1070	219.27
DR-P20	0	12	672	20.8	20.8	270	270	10.4	1080	220.31
DP-P20	30	12	672	20.8	20.8	270	270	10.4	1080	220.31

Table 6 - Cost values of Example 01.

Model	Profile cost (R$)	Cost of Tendons (R$)	Total cost (R$)	Total cost / cost ratio Abbas *et al.* (2018)
Abbas *et al.* (2018)	46228,94	270.10	46499.04	1
MR-P0	32895.10	928.66	33823.70	0.727
MP-P0	33134.90	815.38	33950.30	0.730
MR-P10	33002.50	928.66	33931.10	0.730
MP-P10	33054.70	930.26	33984.90	0.731
MR-P20	32905.00	1160.83	34065.90	0.733
MP-P20	32905.00	1162.83	34067.90	0.733
DR-P0	37688.90	1044.75	38733.70	0.833
DP-P0	37688.90	1046.55	38735.50	0.833
DR-P10	37868.60	1160.83	39029.40	0.839
Dp-P10	37868.60	1162.83	39031.40	0.839
DR-P20	38048.20	1393.00	39441.20	0.848
Dp-P20	38048.20	1395.39	39443.60	0.848

Comparing the best result found with the solution of Abbas *et al.* (2018) in Tables 5, it can be observed that the cable area was approximately 244% larger and the area of the steel found had a cost reduction of approximately 27%, the worst case of approximately 15%

According to tables 4 and 6, the steel profile is the main responsible for the final composition of both cost and CO_2 emissions. This underscores the importance of using the prestressing cables in order to minimize the sections of the steel profile.

It is observed that the straight tracing cables led to a lower cost, but the type of tracing did not impact the CO_2 emissions. It is emphasized that in the analyses, the cost and CO_2 emission of the desviators necessary for the tracing of polygonal cables were not accounted for.

Figure 6 shows the normalized values of CO_2 emission and cost in relation to those of Abbas *et al.* (2018). The best result was obtained when the CO_2 emission was optimized, because although the amount of cables is the same as that obtained in cost optimization, the area of the steel profile was smaller. In addition, it had a reduction of around 27% and 29% in CO_2 emissions and in the cost of the ideal model found. The worst result found was the beam prestressed with polygonal cable, with 20% losses and double symmetrical profile.

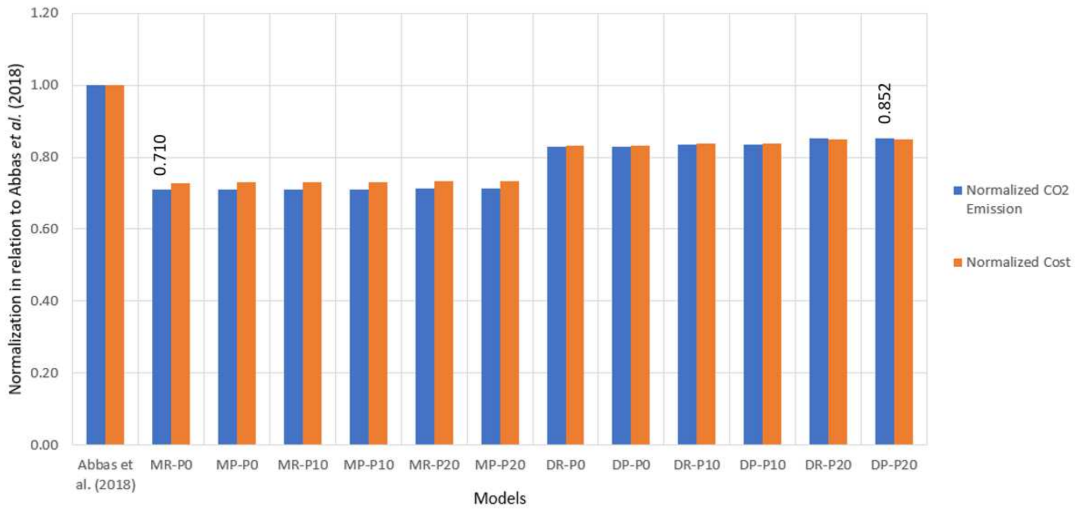


Figure 6 – CO_2 emission and Cost graph for Example 01.

According to Figure 6, the optimization of CO2 emissions showed the best relationships with the exception of the DR-P20 and DP-P20 models. That is, there is no standard for obtaining the best solution, and it will always be necessary to analyze the needs to be met and compare the results obtained.

Figure 7 presents an analysis of the predominant collapse modes according to the constraints that govern the problem. For each model and each type of design constraint, the utilization index (ratio between request and resistance) was plotted. As can be observed, the three modes of collapse that most influenced the analysis were the flexor moment, the deflection and the combined bending, since the ones that least influenced the modes of collapse were the bending moment in the act of pretension, the deflection in the act of pretension and the cutting effort.

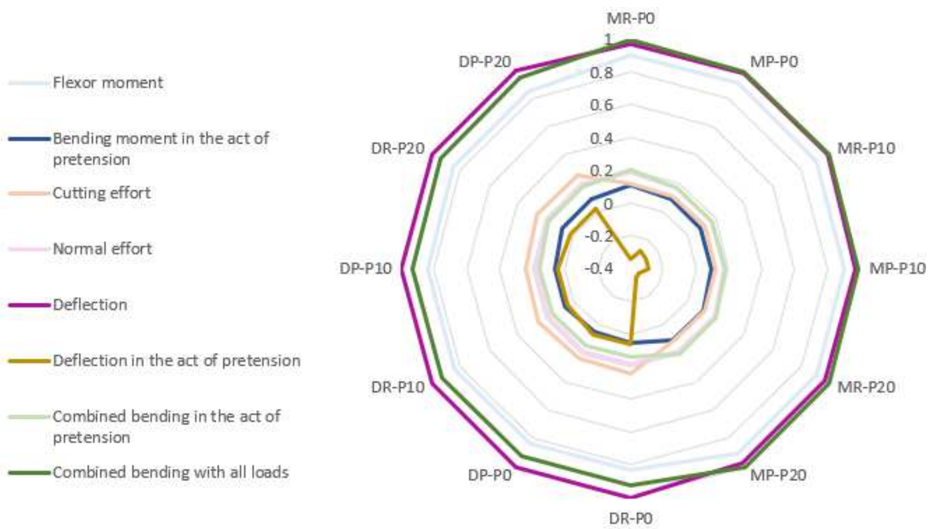


Figure 7 – Constraints analysis to CO_2 emissions optimization of Example 1

3.2 Example 02 – Mageveske *et al.* (2021)

For example 02, we used as reference the study presented by Mageveske *et al.* (2021), in which the cost of double symmetrical I profiles with external pretension, prestressing losses of 20%, tendons diameter of 15.2 mm and straight tracing was optimized and genetic algorithm was used to find the optimization problem solution. We sought to optimize the profile section, with the exception of the thickness of the upper and lower table and the web, which remained constant. This example was originally taken from Rezende (2007), but a comparative analysis will be made with the best result of Mageveske *et al.* (2021) and the values found in this study.

The uniform load used is shown in the Figure 8. ASTM A572-55 steel was considered for steel profiles and CP210 tendons with 15.2 mm diameter. Table 7 shows the input data for the study. Only monosymmetric sections will be analyzed, with the variation of losses by 0%, 5%, 10% and 20%. The web thickness will be the same in all analyses, equal to 8mm, a value found in the optimization of Mageveske *et al.* (2021).

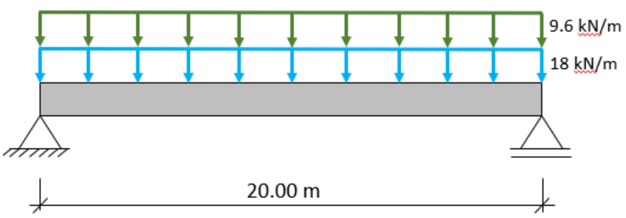


Figure 8 - Beam and loading of Example 02

Table 7 - Input data from Example 02.

	Monosymmetric Profile
L (m)	20
Unlocked length (m)	0
Distance between stiffeners (m)	20
t_{table} (mm)	-
Cable positioning (cm)	-3
Positioning the cable on the support (cm)	-9
t_w (mm)	8.0
Cb	1
Profile Cost (R$/kg)	10

The beams analyzed are designated according to Figure 9, the first letter being the type of stroke, straight (R) or polygonal (P), the second installment the value of the loss of pretension, being 0% (P0), 5% (P5), 10% (P10) or 20% (P20) and the third letter the objective function of optimization, the cost (C) or the emission of CO_2 (E).

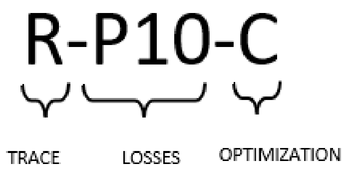


Figure 9 - Designation of the models analyzed in Example 02.

Table 8 shows the main values obtained for the project variables as well as the total CO_2 emission and total cost.

Tabela 2 – Valores totais de Emissão de CO_2 e Custo para o Exemplo 02.

Model	Comp. inclinado (% vão)	Nº of tendons	$t_{f\ sup}$ (mm)	$t_{f\ inf}$ (mm)	$b_{f\ sup}$ (mm)	$b_{f\ inf}$ (mm)	t_w (mm)	d (mm)	Total CO_2 emission (kg CO_2)	Total Cost (R$)	CO_2 Authors/ CO_2 Mageveske *et al.* (2021)	Cost Authors / Cost Mageveske *et al.*(2021)
Mageveske et al (2021)	-	7	12.5	12.5	430	430	8.0	1000	6728.97	40824.60	1	1
R-P0-C	0	5	18.1	16.0	210	260	8.0	1040	-	26672.70	-	0.653
P-P0-C	25	5	21.9	16.0	310	110	8.0	1080	-	28043.80	-	0.687
R-P5-C	0	7	22.7	16.0	290	100	8.0	1080	-	28075.90	-	0.688
P-P5-C	30	7	22.7	16.0	290	100	8.0	1080	-	28078.80	-	0.688
R-P10-C	0	6	16.3	16.0	230	260	8.0	1040	-	26940.80	-	0.660
P-P10-C	30	6	20.8	16.0	180	270	8.0	1050	-	27234.30	-	0.667
R-P20-C	0	5	16.7	16.0	270	240	8.0	1070	-	27665.30	-	0.678
P-P20-C	30	5	16.7	16.0	270	240	8.0	1070	-	27669.90	-	0.678
R-P0-E	0	6	26.1	16.0	270	100	8.0	1050	3208.68	-	0.477	-
P-P0-E	30	6	25.7	16.0	270	100	8.0	1060	3203.80	-	0.476	-
R-P5-E	0	5	17.6	16.0	210	270	8.0	1060	3076.54	-	0.457	-
P-P5-E	30	5	16.7	16.0	220	270	8.0	1060	3076.80	-	0.457	-
R-P10-E	0	6	18.4	16.0	210	270	8.0	1030	3108.28	-	0.462	-
P-P10-E	30	5	16.1	16.0	270	260	8.0	1040	3135.86	-	0.466	-
R-P20-E	0	6	17.1	16.0	220	270	8.0	1050	3121.58	-	0.464	-
P-P20-E	30	6	16.3	16.0	230	270	8.0	1050	3121.75	-	0.464	-

The model that generated the best result was the monosymmetric profile with straight cables and 0% losses, optimizing the cost. Comparing these results with those obtained in Mageveske *et al.* (2021) it can be observed that the number of cables was lower, generating 2 fewer cables. The values found for the best solutions were approximately 31% lower for Cost and 54% lower for CO_2 emissions.

Figure 10 presents the CO_2 emission and the total cost plotted with normalized values in relation to the solution of Mageveske *et al.* (2021). With this analysis it becomes possible to conclude that the best result found was when the cost was optimized. However, when compare the two optimizations, there is greater efficiency in optimizing CO_2 emissions.

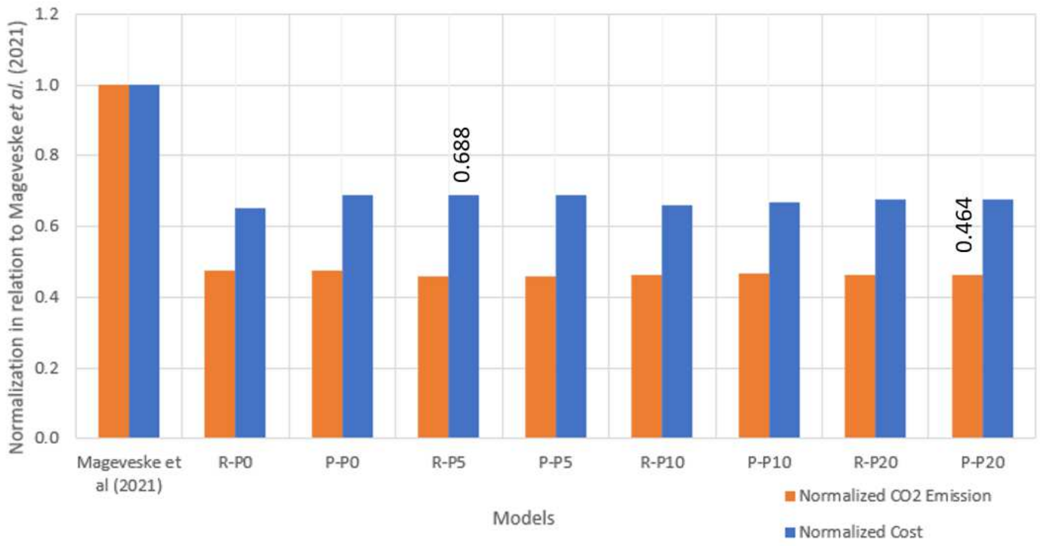


Figure 10 – Graph of the normalized solutions of Example 2

For each model and each type of sizing constraint, the utilization index (ratio between request and resistance) was plotted in Figure 11. It can be noted that the modes of collapse that governed the analyzed example were combined bending with all loads, the flexor moment and the deflection. On the other hand, those who least interfered in the modes of collapse were the deflection in the act of pretension, the cutting effort, the deflector moment in the act of pretension.

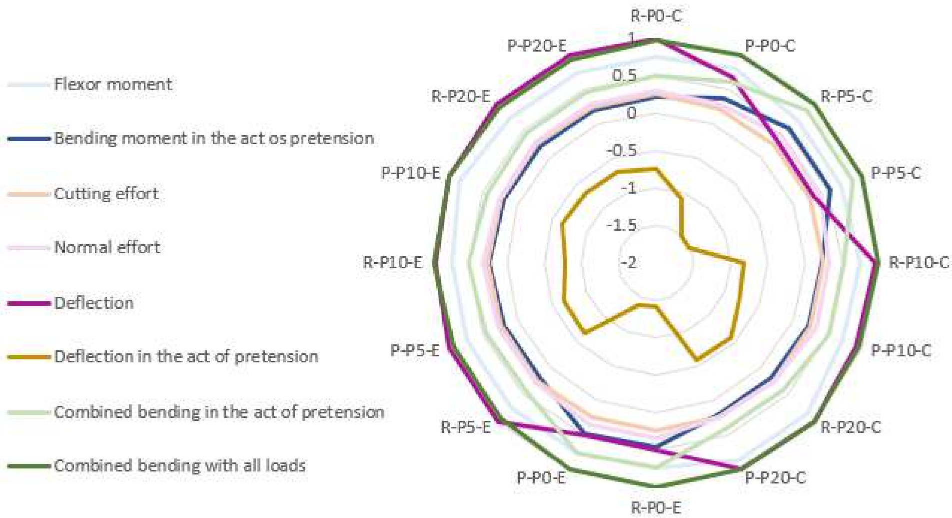


Figure 11 – Constraints analysis for CO_2 emission solution Example 2

5 CONCLUSIONS

This study aimed to propose the formulation of cost optimization and CO_2 emission of steel beams, using monosymmetric or double symmetrical profiles, with external pretension, using cables with straight or polygonal tracing. For this, two examples were analyzed, and in the first one the loss of pretension was varied, and both monosymmetric and double symmetrical profiles were analyzed. In the second example, losses were also varied, but only monosymmetric profiles were analyzed, considering that it was the profile that presented the best solution in example 1.

For all optimized models, better solutions were obtained than the examples in the literature. With the first example, it is concluded that monosymmetric profiles generate more economical results with lower CO_2 emissions than doubly symmetrical profiles. In addition, there was a reduction of approximately 27% in CO_2 emissions and 29% in cost in the best solutions found.

In the second example, the values found were approximately 31% lower for the cost and approximately 54% lower for CO_2 emissions when the CO_2 emission was optimized.

For all models analyzed, because they are steel beams, the option of inclined cable did not influence the final solution of the problem, being the best solutions obtained with the use of straight cables.

Regarding the structural behavior, it was noted that the modes of rupture that governed the examples were combined bending, the flexor moment and the deflection. On the other hand, the modes of rupture that least influenced were the deflection in the act of pretension, the cutting and the deflector moment in the act of pretension.

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