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MULTIOBJECTIVE OPTIMIZATION OF REINFORCED CONCRETE BUILDINGS

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ABSTRACT

The application of parametric and topological optimization in the conception of buildings is a problem of high complexity due mainly to the large number of variables of interest to be optimized and to its nature intrinsically multiobjective. Due to the computational development occurred in the last decades, it has arisen the opportunity for a broader study and development of numeric models in this field. For the conception of structural designs, it counts on vary computational software that automate great part of the structural desgin conception process. However, in the stage of definition of the structural elements position, such as columns and beams, there is still a high level of dependency of the designer because it is long the time spent in the conception and not always the solution found is the most viable in economic and executive terms. With that, the current work is the initial development of a computational model of structural optimization of reinforced concrete buildings to decrease the designer dependency with the objective of minimizing the costs – such as concrete volume and steel weight – through the search of columns positions and its dimensions, restricted to an imposed architecture. It must be employed the evolutionary computation philosophy using the heuristic method of genetic algorithms, in the generation of the various feasible solutions, which are obtained by the results of the model of analysis by spatial framed structures, based on the finite element method. For the generation of the cost function, it will be considered the determination of the section area of the column and the steel needed that attends the equilibrium of each reinforced concrete section subjected to biaxial (oblique) bending with axial force state. Lastly, it will be performed a qualitative and quantitative comparative analysis between structural conceptions with and without the optimization technique in order to verify the consequences of its use.

KEYWORDS

Parametric Optimization, Reinforced Concrete Building, Genetic Algorithms, Position of Columns.

1. INTRODUCTION

In the last decades great advances occurred in the design field with the development of some specific software for structural design, in which several software can automate most of its conception process by assisting its user in the development of complex structures and providing preliminary information, such as elements dimensions, detailing and costs. However, at the stage of defining elements positions there is still a high-level dependency on the designer. Usually, time spent on the structural topology conception, such as columns, beams and slabs, is long and it is based on the designer knowledge and experience and, sometimes, the proposed solution is not economic and executive feasible. Regarding these particularities, the advances in structural optimization research are important because they intend to reduce time consumption on the design conception stage and minimize execution costs.

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According to Oliveira [1] and Machairas, Tsangrassoulis and Axarli [2], the discussion about this topic is quite recent but not deeply explored and reproduced in a realistic approach as result of the great complexity in finding the Pareto's optimality against the number of constraints that concern a building design. The reason of the scientific exploration of this topic is clear and this work intends to be the seed of an artificial intelligence model that automatically seeks for feasible structural conceptions without user interference.

From this perspective, the current work aims to initiate the development of a computational model of structural optimization for reinforced concrete buildings that seeks to reduce the designer dependency and minimize its costs – such as concrete volume and steel weight – upon the search of columns positions and dimensions, which are restricted to an imposed architecture, by the use of the heuristic method of Genetic Algorithms (GA) with frame bars analysis model based on the Finite Element Method (FEM) and Newton method for non-linear problems for the cross-section equilibrium of columns under oblique bending and axial load, following the characteristic ratio of the parabola-rectangle diagram for compression and the tensile stress curve for steel referenced in NBR 6118 [3].

2. OPTIMIZATION PROCESS

The model proposal is based on a GA technique application in which it is developed an automatic generation model for the possible sets of columns and beams for the building, which represents an initial population that implies in distribution of columns and beams of a referenced architectural plan, according to the procedure later explained in this article. Thus, the building model is automatically generated by the FEM with columns and beams and vertical loads, which represents permanent loads. Also, it is defined an objective function - which must be minimized - that returns the steel amount and the cross-section area for each structural element following standard guidelines established by NBR 6118 [3]. Therefore, the processes that must be developed to generate the optimized model with the best disposal of columns and seeking the economic aspect as ideal solution.

2.1. Reference Mesh

Due to the imposed architecture, a reference mesh is generated with equidistant n horizontal division and m vertical divisions, totalizing $(m+1)(n+1)$ nodes for columns possible positions that are associated to a cartesian coordinates. One example of the column and beam set elaborated by the routine is shown in Figure 1, with n=10 and m=8.

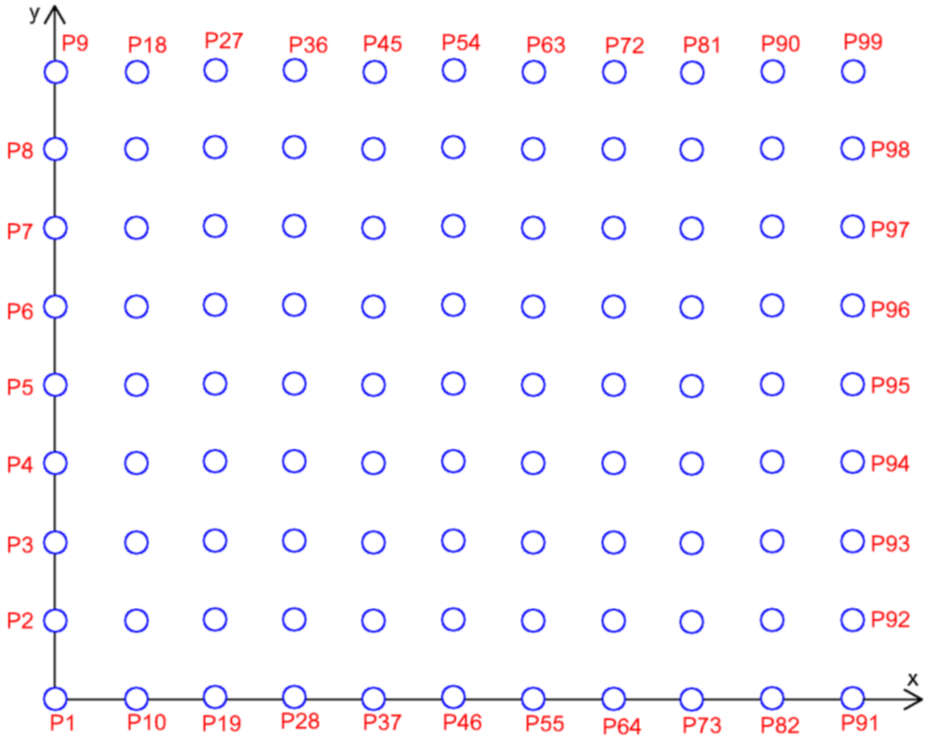

Figure 1. Reference mesh of points defined by the routine.

2.2. Generation of the Building Structure

With the nodal network a GA algorithm developed under the Galib library, created by Wall [4], is employed to generate the building structure. It aleatorily selects a set of a predefined *k* number of nodes used to allocate the columns of the building. After that, combining the selected nodes with the corner nodes, all lines that vertically and horizontally crosses these nodes will become the beams of the building. It can be clearly seen in the Figures 2 and 3 with a hypothetical example of selected nodes for columns: 2, 51, 80, 84.

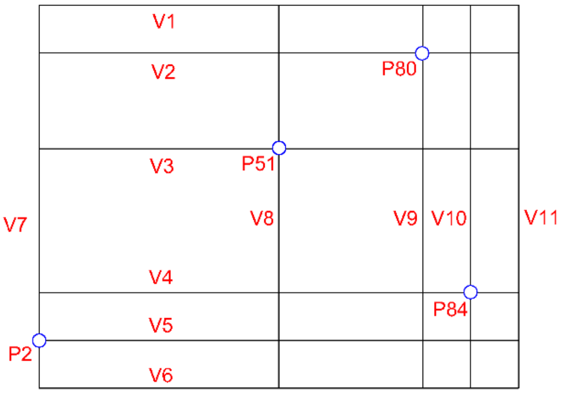

Figure 2. Reference mesh with points 2, 51, 80 and 84 defined by GA.

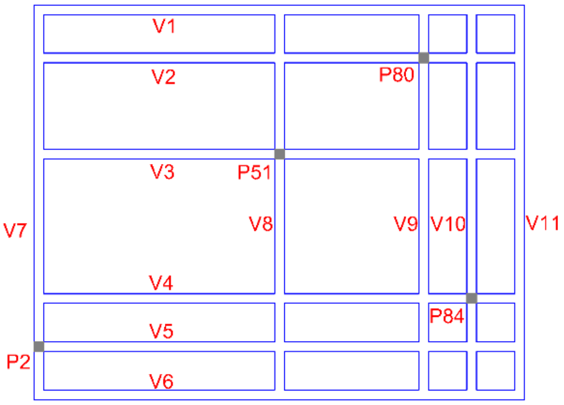

Figure 3. Form's blueprint.

Another example is shown in Figures 4 and 5, in which the columns randomly selected from the reference mesh were 25, 48, 73, 91.

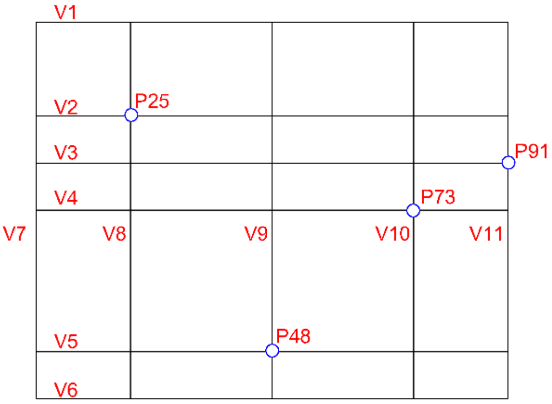

Figure 4. Reference mesh with points 25, 48, 73 and 91 defined by GA.

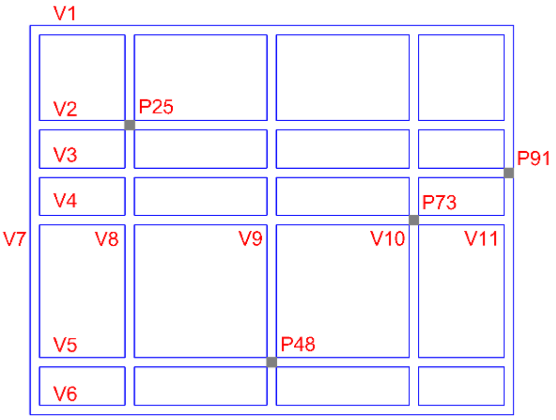

Figure 5. Form's blueprint.

2.3. Structure Analysis

After the building is generated, some permanent and accidental loads are added for each floor, so the structural analysis could be performed by using the model developed by Almeida [5] and extended by Aquino [6], both based on the FEM. After that, reactions, internal loads and displacements are calculated for the entire structure, presenting alphanumeric results and drawings (dxf file).

2.4. Structure Dimensioning

With the results provided from the FEM analysis, it is performed the beams and columns dimensioning according to the standard guidelines [3]. The beam heights are calculated, with its widths as constants, while its steel area is calculated according to bending moments and shear internal loadings.

Meanwhile the columns are dimensioned by the iterative searching for equilibrium of cross-section using the Newton-Raphson method for the solution of the coupled equilibrium equation. Nonlinearity is considered for the concrete with the use of the characteristic diagram of the parabola-rectangle for compression and the idealized steel for tensile stress according to the standard guidelines [3]. Initially, all columns have 20x20cm cross-section with the minimum area of steel imposed by standard guideline limits. The adopted method will search for the combination of cross-section dimensions with steel area that attends the coupled equilibrium equations of the columns subjected to the trio (N, My and Mz).

After the iterative balancing process, the area of steel and cross-section of each element is obtained, with that it is possible to calculate the total weight of steel (*Pt*) and total volume of concrete (*Volt*) used in the structure by summing the total weight of steel in the beams (*Pv*) with the total weight of steel in the columns (*Pp*) and summing the total volume of concrete in the beams (*Volv*) with the total volume of concrete in the columns (*Volp*), respectively.

$$Pt = Pv + Pp \qquad (1)$$

$$Volt = Volv + Volp \qquad (2)$$

2.5. Final Objective Function

After the structural dimensioning, the objective function to be minimized (F) is obtained by the weighted sum of the total steel weight and volume of building as described in Equation (3).

$$F = Pt.p1 + Volt.p2 \tag{3}$$

where p1 and p2 are heuristically obtained weights to normalize the different values of the sum, since the sensitivity of Pt and Volt are of different order of magnitude. Thus, in this optimization process, the result will be modified and analysed repeatedly, according to the GA process that calls the building analysis model, and at the end, with the results of the concrete and steel quantities, for each group of columns and beams provided by the GA, a comparison of these results is carried out, so that it is possible to determine if a solution is the best compared to the others and select the group that best attends the design needs, reducing the consumption of concrete and steel. Figure 6 presents a simplified flowchart of the process to be used in the optimization process.

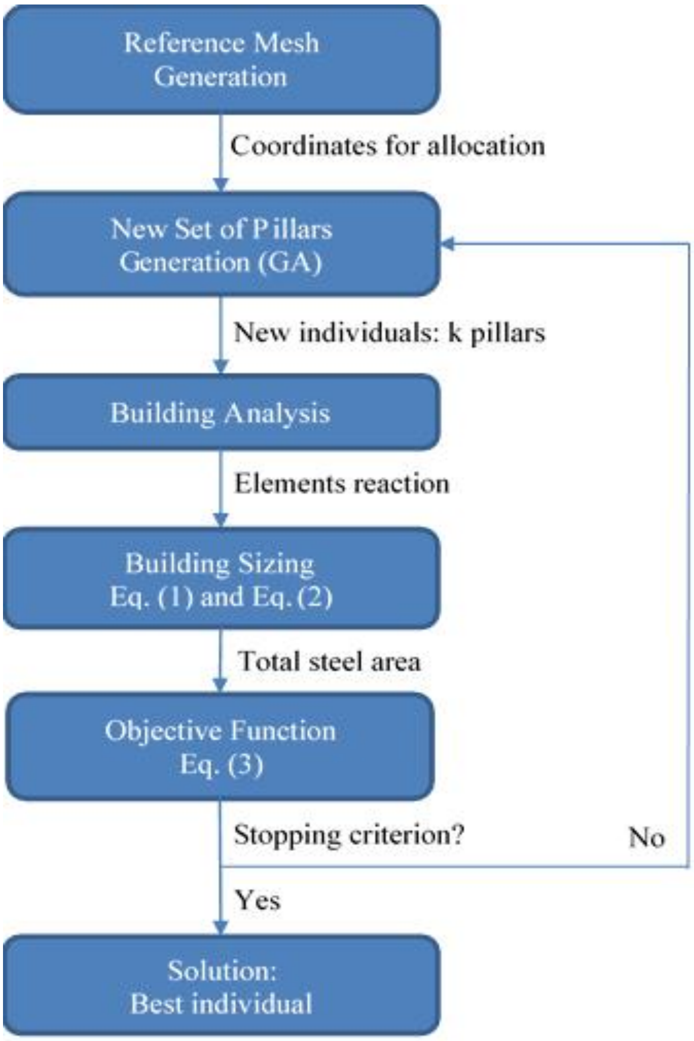

Figure 6. Flow chart of the process to find the best columns positions.

3. NUMERICAL APPLICATION

In the simulation of this example, the following information was used as input data for the model: a structure composed of 2 floors, ceiling height of 3 meters, mesh dimension of 15x8 meters, a nodal network with *m*=15, *n*=8 and *k*=8 columns, and a population of 50 and 200 genes. The reference grid model is shown in Figure 7.

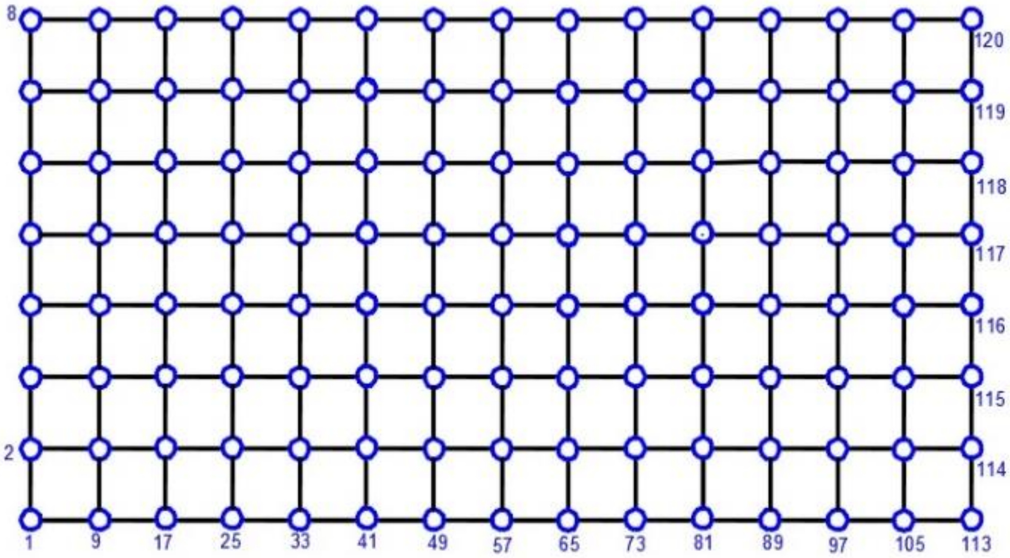

Figure 7. Reference mesh.

This simulation resulted in 8,632 cases, with time computing of 63,639 seconds, and the result demonstrated by the computational model presented the following set of columns and their coordinates: column 10 (2;2), column 15 (2;7), column 50 (7;2), column 55 (7;7), column 63 (8;7), column 95 (12;7), column 98 (13;2) and column 119 (15;7), disposal of these columns can be visualized in Figure 8. This architectural plan presented the following results: 1.92 m³ of concrete and 611.04 kg of steel. Using the reference of cost prices from SINAPI [7] for the composition of costs, the total cost is R$ 3,600.36 (presented in Table 1).

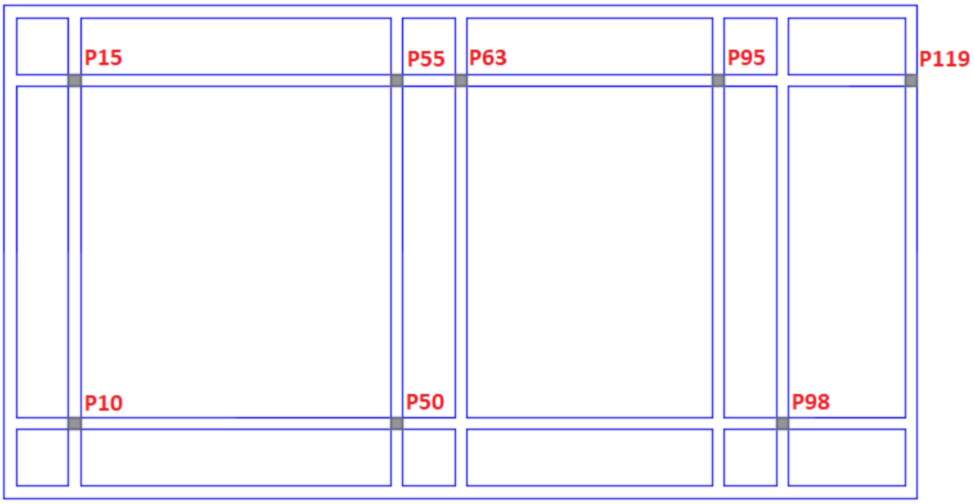

Figure 8. Form's blueprint – Numerical application.

For comparison purposes with the numerical application presented in this section, a structural model was created with the same input data as the example, but with fixed column arrangement, following standards used by designers, such as column arrangement in corners and other columns being symmetrically distributed in the structure, avoiding long-span beams. The arrangement of the columns is shown in Figure 9, and it presents the following positions and coordinates: 1 (1;1), 5 (1;5), 8 (1;8), 57 (8;1), 64 (8;8), 113 (15;1), 117 (15;5) and 120 (15;8). The results obtained with this structural model were the following: 2.16 m³ of concrete, 874.81 kg of steel and total cost of R$ 5,009.64. Table 1 presents a comparison of sizing and final cost values obtained by the two models, conventional and automatically optimized.

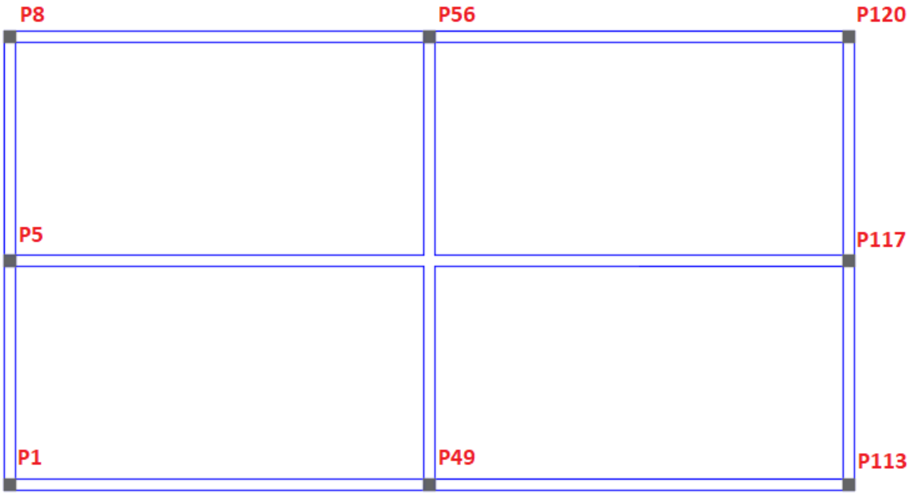

Figure 9. Form's blueprint - Conventional design.

It can be inferred from Figure 10 the behavior of the structural optimization against the GA formulation, noting that the results found tend to decrease along time processing, thus improving its performance to find a result closer to the optimal one.

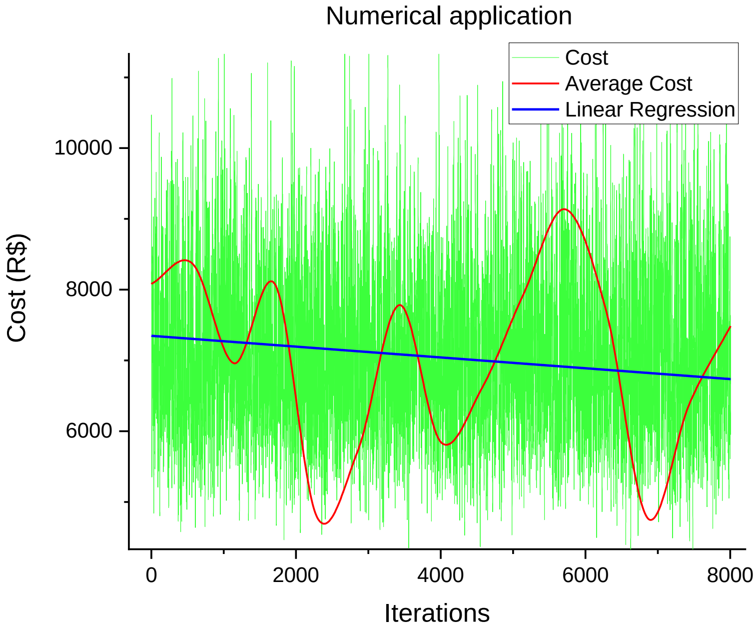

Figure 10. Simulation results with GA.

Table 1 compares the results found in the conventional design (Figure 9) and results found through the simulation model for the example (Figure 8). In addition, this table presents the difference in obtained results. Cost composition and the quantitative of the main items that are significant for the cost of columns, concrete and steel. Besides, positional optimization reached a cost 28.13% lower than the conventional method.

Table 1. Comparative results of traditional and optimized positioning

Conventional Design - Columns Arrangement						
Column			**Steel Bars**			**Total Cost (R$)**
Number	**Bw x H (cm)**	**Concrete Volume (m^3)**	**Quantify (unit)**	**φ Diameter (mm)**	**Weight (kg)**	
1	20x20	0.24	4	20	58.81	365.83
5	20x20	0.24	4	25	91.89	530.24
8	20x20	0.24	4	25	91.89	530.24
49	20x20	0.24	6	20	88.22	511.97
56	20x30	0.36	8	25	183.78	1023.71
113	20x20	0.24	6	20	88.22	511.97
117	20x30	0.36	8	25	183.78	1023.71
120	20x20	0.24	6	20	88.22	511.97
	TOTAL	**2.16**			**874.81**	**5009.64**

Columns Arrangement - Optimized Positioning						
Column			**Steel Bars**			**Total Cost (R$)**
Number	**Bw x H (cm)**	**Concrete Volume (m^3)**	**Quantify (unit)**	**φ Diameter (mm)**	**Weight (kg)**	
10	20x20	0.24	4	20	58.81	365.83
15	20x20	0.24	4	25	91.89	530.24
50	20x20	0.24	6	20	88.22	511.97
55	20x20	0.24	4	25	91.89	530.24
63	20x20	0.24	4	16	37.64	235.76
95	20x20	0.24	4	25	91.89	530.24
98	20x20	0.24	4	25	91.89	530.24
119	20x20	0.24	4	20	58.81	365.83
	TOTAL	**1.92**			**611.04**	**3600.35**

4. CONCLUSIONS

Among the contributions proposed by this work, there is an alternative to the positioning of the columns, aiming to reduce the dependence of the designers. Results of the traditional design method compared to results obtained through the present model developed, demonstrated the efficiency of this method and the importance of this research. If this analysis is done without the use of GA, for example, by using k = 4, n = 10 and m = 8, as exemplified throughout the article, there is a total of 3,764,376 possibilities. For each iteration analysis, it takes about 5 seconds, which would take approximately 217 days to perform all combinations. The use of GA optimization reduces the time cost of analysis, since its searching is more efficient, avoiding the need to compute all possible cases of each design.

Design limitations such as the maximum distances between columns, minimum and maximum span of beams, delimitation of the positioning of the columns avoiding positioning on door and window spans, obstruction of parking spaces, limitations of overhangs, etc., are some of the restrictions to be implemented into the model in the future. In the present study, the volume and reinforcement calculations of the beams were not considered, and this insertion is also an object for future work.

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