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MULTIOBJECTIVE OPTIMIZATION OF REINFORCED CONCRETE BUILDINGS

Estevão A. Bandeira
estevaobandeira@usp.br
Department of Structure Engineering and Geotechnics of the Polytechnic School of the University of São Paulo
Av. Prof. Almeida Prado, n° 83, 05508-070, São Paulo, Brazil.
Yuri Farias da Silva
yurifarias@usp.br
Department of Structure Engineering and Geotechnics of the Polytechnic School of the University of São Paulo
Av. Prof. Almeida Prado, n° 83, 05508-070, São Paulo, Brazil.
Valério Silva Almeida
valerio.almeida@pq.cnpq.br
Department of Structure Engineering and Geotechnics of the Polytechnic School of the University of São Paulo
Av. Prof. Almeida Prado, n° 83, 05508-070, São Paulo, Brazil.

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 projects, it counts on vary computational programs that automate great part of the structural projects' 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 project's conception and not always the solution found is the most viable in economic and executive terms. In view of this problem, the current work aims to initiate the development of a computational model of structural optimization of tall buildings in reinforced concrete 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 through the use of 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 comparative studies, qualitative and quantitative, between structural conceptions with and without the optimization technique in order to verify the consequences of its use.

Keywords: Parametric Optimization; Tall Buildings; Genetic Algorithms; Position of Columns.

1 Introduction

Great advances occurred in the last decades in the design field with the development of some specific software for structural designs elaboration. It counts with vary computational programs that automate a large amount of the structural conception process because they assist the designers in the development of complex structures and provide preliminary information like reaction values, structural dimensioning, structural detailing and even costs. At the moment, in the definition stage of structural elements' distribution there is still a high-level dependency on the designer, for the time spent on the structural topology conception, such as pillars, beams and slabs, is long. This definition is based on the designer's knowledge and experience and the solution found not always is the most viable in economic and executive terms.

Taking this into account, the advances in researches about structural optimization are important because they seek to decrease the waste of time spent on the design conception and to minimize costs of its execution.

For what was presented by Oliveira [1] and Machairas, Tsangrassoulis and Axarli [2], the discussion about this topic is quite recent but was not explored and simulated in depth as a result of the great complexity in finding the Pareto's optimality in front of the multiobjectives and multi constraints that concern a building's design. The justification of the scientific exploration of this topic is clear and this work intends to be the seed of a future construction and an artificial intelligence model that seeks the structural conception automatically.

Having that in mind, this work aims to initiate the development of a computational model of structural optimization for tall buildings in reinforced concrete that seeks to reduce the designer's dependency and to minimize the costs – such as its concrete volume and steel weight – upon the search of pillar's positions and dimensions restricted to an imposed architecture, by the use of the heuristic method of Genetic Algorithms (GA), in the generation of diverse feasible solutions which are obtained by reticulated bars analysis model based on the Finite Elements Method (MEF).

In this first work, it is presented the initial scopes and the procedure descriptions that must be implemented to achieve such objective. However, the implementations were not finalized nor tested, so they will not be described in this article. The expected goal for other works is to present comparative studies, quantitative and qualitative, between structural conceptions with and without the optimization technique so the consequences of its use could be seen. The structural optimization will count with the minimization of an objective function that should meet the vertical and horizontal displacement verification, simplified dimensioning of the pillars' reinforcement, global stability of the structure (with the real element's stiffness calculated with the steel rate obtained in the simplified dimensioning) and uncertainties related to the construction location as parameters of optimization.

2 Bibliographic Review

The work of Eltaweel and SU [3] mention that the classic study behind design conception integrates the initial development and process organization, in which initial ideas are introduced as well as changes in the initial conception and design improvement in order to achieve the optimized result.

Conceptually, the structural optimization can be classified in three major groups, i.e.: parametric, topological and configuration's optimization. The first one corresponds to a parameters analysis without changing the structural shape. Those parameters can be related to constructive or geometric properties, such as Young's modulus or a plate thickness, Lima [4].

The structural optimization has been presenting positive results in the civil construction, automobile industry and aerospace industry by defining the cost reduction as the main goal. There are three types of structural optimization: dimensional, geometric (shape) and topological optimization, according Cordeiro [5].

Through these three types of structural optimization it is possible to analyze the topology, the configuration, the material's type and the structural dimensioning. The dimensional optimization has as variables cross sections and pieces' length. The geometric optimization consists in finding the best structural configuration, optimizing its contour. The topological optimization searches the best location and distribution for its structural elements.

In Suyoto, Indraprastha and Purbo [6] it is used the *Grasshopper* to perform the case study about an office tower in Kebayoran Lama, Jacarta, applying the parametric approach as auxiliary instrument for decision-making and design's idealization.

This study mentions in its solutions that the parametric analysis achieves different results for the problem. Those different results would not be achieved if it had been done analysis with traditional approaches due to the dependency of the designer's experience and to the compatibility of different fields designs (climatic, thermal comfort, façade study, among others).

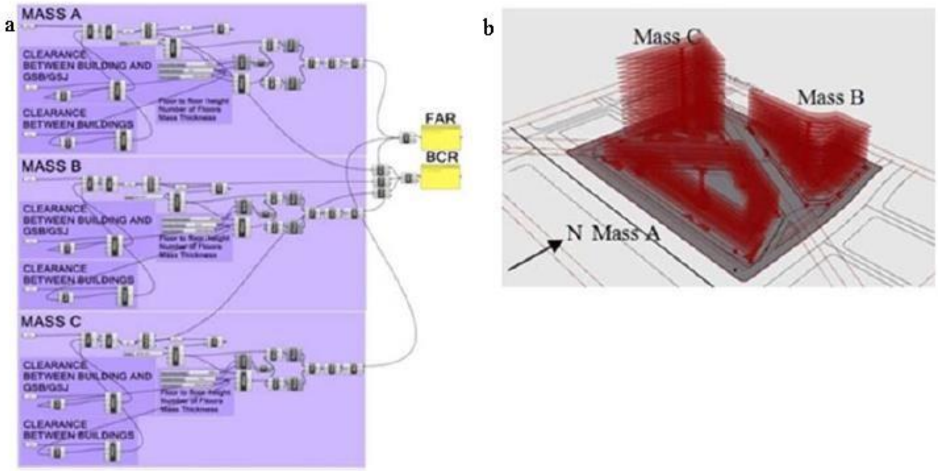

Figure 1- Mass study for maximum area by [6].

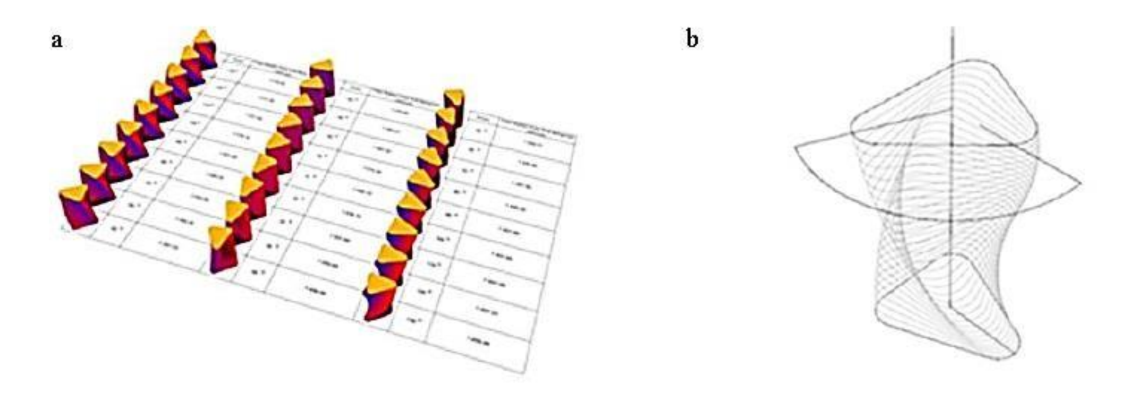

Figure 2 - Study of heat increase by external walls (a) Heat increase for various rotation angles; (b) Building profile and its rotation angles by [6].

The parametric approach, however, demanded more time and the algorithms development as the problem's solution showed up very costly, hence it demanded various changes and improvements during the analysis.

In regarding to the optimization use for the best building's structural elements' localization few works have already been explored this topic, citing Kripka [7] that seeked to optimize the pillar's position in a grid numeric model, varying its position relative to the beam. He adopted a Quasi-Newton method because the Hessian matrix is obtained by an approximate way. The objective function chosen was the minimization of the sum of the squared negative moments.

He optimized the support position over the beam and performed examples in which its detailing was obtained by the TQS software, checking if the structural cost was minimum. Despite obtaining the minimums, unfirming the loads, the structural global costs' reduction, assuming the automatic detailing done by the TQS, the minimum was not obtained for the support positions. He finishes performing the optimization the support positions considering two practical examples and pointed out the lack of practical examples in the literature.

In the article of [2] a study synthesis about optimization algorithms for building design was performed. The authors cite two approaches for multiobjective optimization problems. The first uses a weighted sum function which each objective is normalized and added with its weight in order to obtain one only cost function. The second is denominated as Pareto [8] optimality, which determines the best value when there is no other possible solution that improve an objective without affect negatively at least one objective. According to them, in problems with a great solution space the sensibility and uncertainty analysis before the optimization is one way to simplify the problem.

The authors cite that the best tools and algorithms for building design is, beyond tools that allow researchers to use their knowledge to reduce the solution space or tools capable to direct the search towards the correct path and cite how some of the tools' features of the future as, among others, the use of machine learning for optimization problems with great solution space, graphic user interface with 3D visualization of the building, to import architectural models made in BIM and to export structural models to multidisciplinary software, to perform sensibility and uncertainty analysis to estimate the impact of each design variable.

It is presented in [1] a formulation that aims the multiobjective function of pillars positions within a building blueprint employing Genetic Algorithms as the optimal search procedure. However, the author has not employed as a criteria the pillars' sizing cost by the Brazilian norm, once the commercial software used does not have this feature. Neither consider the wind effect in his analysis, nor the building stability parameters verification or horizontal displacement limits. Furthermore, the author performed a parametric optimization of the pillars' positions for the pavement – as done by [7] only for grid models, not for the whole building.

For the structural optimization employment, the use of computational algorithms that provide optimized results that could make an excellent option to decrease the need of numerous verifications to identify the best structural conception of a given design. With the evolution of the computer capability diverse optimization methods could be utilized.

The optimization is done in three stages (preparation stage, optimal global search and solution refinement), as well as those performed by Hamdy, Hasan, and Siren [9]. The preparation stage suits to create good initial populations performing sensibility analysis of the variables and ordering each one by sensibility indexes. During the second stage the GA is employed with the created populations after the design variables' sensibility analysis to obtain the more refined solutions.

In between the existing optimizations methods, there are deterministic methods such as the Quasi-Newton method employed by [7] and the stochastic methods.

The deterministic methods provide efficiency and speed but do not provide a level of confidence to find the solutions for multi convex problems. In Vieira [10], in which is used deterministic methods for the optimization analysis, it is mentioned that similar results are always obtained when the starting point is maintained in the optimization. However, there is undefinition about the use of deterministic algorithms because it does not ensure that the presented result is in fact the global optimum, especially in non-convex problems.

The stochastic methods can provide a level of confidence that the best solutions will be found, however demand greater processing time because they involve the generation of random solutions with the objective to exploit a set of possibilities, and if the solution grow up its analysis will increase exponentially due to the great number of variables.

Though the time spent with processing is bigger, the stochastic methods provide a better guarantee for the results, especially for multi convex problems that present several local optimums, thus being ideal for the structural optimization when the number of its variables does not exceed a dozen of values. Note that depending of the randomness of the results' generation throughout the evolutionary process it is recommended that a meta-analysis must be performed.

There are several stochastic methods in the literature, but in this work, it will be used the Genetic Algorithms method, which allows to perform the study of a greater number of solutions with a reduced time. The Genetic Algorithms are inspired by the book of Charles Darwin [11] "The Origin of Species" from 1859. These algorithms are a search method that uses concepts from genetics and is based on the evolution of living beings with the principle of natural selection and the survival of the fittest being.

The Genetic Algorithms method has several researches related to structural studies, quoting, for example, the work of [2], [10], Castilho [12], Albuquerque [13]. The latter [13], mentioned that there is a trend for the use of this method in structural studies due to the excellent results obtained and ease to implement.

The Genetic Algorithms (GA's) were developed by Holland [14] and popularized by Goldberg [15], in which the author's main objective was to investigate and to project artificial systems similar to the natural principle of species.

According to Cheung and Reis [16], the genetic algorithms initiate the search process creating an initial random set of possible solutions denominated as "population", which individuals are denominated "chromosomes". The chromosome is a string which its characteristics or "genes" could be coded through a binary, real, among others, representation. The chromosomes tend to evolve gradually throughout successive iterations producing new fitter or more capable individual generations in terms of the fit function.

Every generation the chromosomes are evaluated through the fitness function, classifying the solutions to select and create the next generation, considering the chromosomes with high values for the objective function with high chances to be preserved for the next generation. After numerous iterations the algorithm converges to an optimum problem solution or suboptimal.

3 Optimization Process

Within this philosophy the model proposal is based on the package GA so that a pillar set must be defined, representing an initial population, that will imply in a feasible architectural blueprint together with beams to be defined according to a rule indicated in the item 3.2. Thus, the building model is automatically generated by the FEM with pillar and beams bars, vertical loads, which represents permanent and live loads, and horizontal loads, which simulates the wind effect. It is defined a objective function, which must be minimized, that returns the steel amount, the cross section area defined for each structural element following the sizing procedure established by the NBR 6118 [17] norm.

Therefore, the processes that must be developed is described below so it searches the optimization model for the best pillars' distribution, seeking the economic aspect as ideal solution.

3.1 Reference Mesh

A process is developed for the generation of a rectangular reference mesh with n horizontal divisions and m vertical divisions. Those should be associated to cartesian coordinates, which are equally spaced, and they will be the possible positions to allocate pillars. Automatically, the incidence of horizontal and vertical beams is obtained in this mesh.

Still in this routine it is made the beams launch, which are distributed in every pillar set, connecting them both in the horizontal as in the vertical of the design. One example of the pillar and beam set elaborated by the routine could be seen in figure 4, with $n = 10$ and $m = 8$.

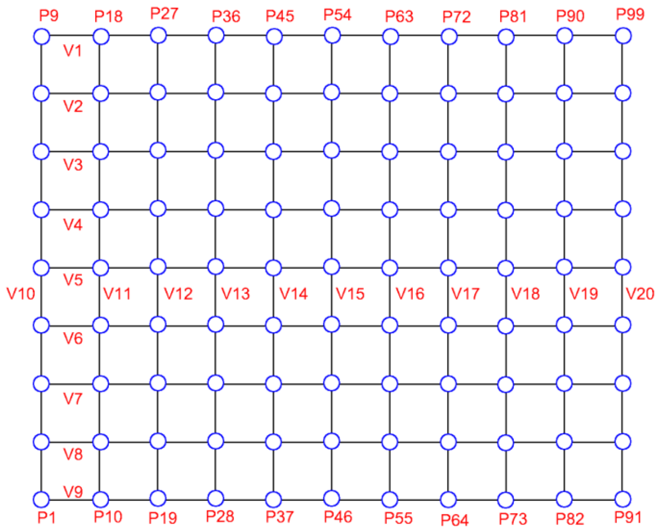

Figure 3 – Reference mesh of points defined by the routine.

3.2 Generation of Pillars Sets

With the network of points defined by the process indicated in the item 3.1, it is used a program based on Genetic Algorithms, which was developed for the C++ language by Wall [18] from Massachusetts Institute of Technology, named Galib. Using the "GA1DArrayGenome" class, a function was developed to return a set of random integer numbers of length previously determined representing a number k of pillars. This way, it is eliminated from the reference mesh the $[(n+1)(m+1)-k]$ pillars. For the beams, it was adopted the idea to maintain the ones that passes vertically and horizontally over the k pillars and the corner beams. See in the figures 4 and 5 a hypothetical example of selected points for pillars: 2, 51, 80, 84.

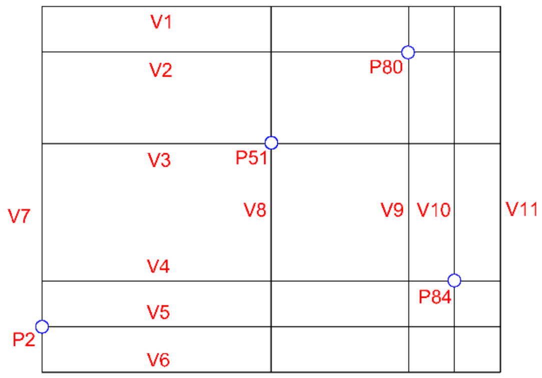

Figure 5 – Reference mesh with points 2, 51, 80 and 84 defined by GA.

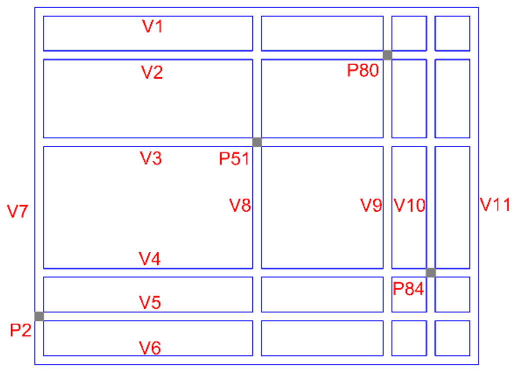

Figure 5 – Form's blueprint.

Another example can be seen in figures 6 and 7, in which the pillars randomly selected from the reference mesh were 25, 48, 73, 90.

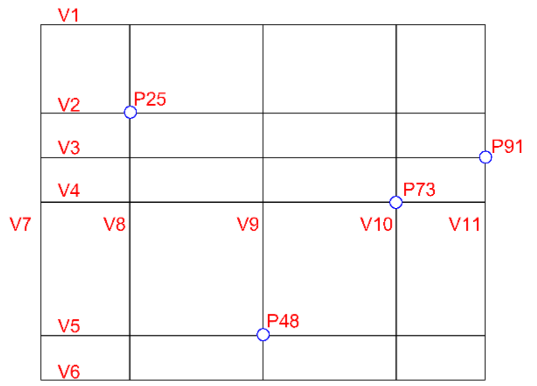

Figure 6 – Reference mesh with points 25, 48, 73 and 91 defined by GA.

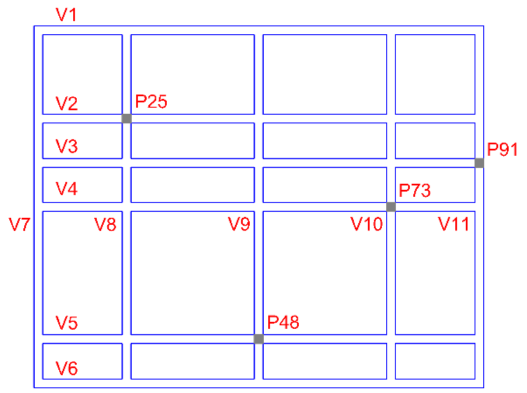

Figure 7 – Form's blueprint.

The distributed loads in the pavement will be redistributed on the beams such that they will act with the same resultant once that depending on the pillar position it could generate more or less associated beams. The wind effect is obtained by NBR 6123:1988 [19] wind norm for each floor and will be distributed in the k pillars. The element's initial dimensions are determined by a pre-sizing.

3.3 Building Analysis

For the third process stage it was employed the building analysis model developed by Almeida [20] and extended by Aquino [21] that incorporates foundations structures and geometric nonlinearity, both based on FEM. After defining the k pillars a model will be generated automatically, assembling a system of beams and pillars bars with permanent and live loads for each floor. Thus, it is calculated the reactions and displacements for the entire structure, presenting alphanumeric results and diagrams in dxf.

3.4 Building Sizing

With the results obtained from the building analysis, it is performed the beams and pillars sizing according to the norm [17]. The beams have its widths fixed while its heights and steel area are dimensioned following the bending moments and shear stresses. The pillars are dimensioned by the iterative search of equilibrium - applying the Newton-Raphson method - throughout the use of the resolution of the coupled equilibrium equations. It is considered nonlinearity for the concrete with the use of the parable-rectangle characteristic diagram for compression and the idealized steel for traction according to the norm [17].

Due to the norm limits, it is possible to not dimension the section of a certain pillar for oblique bending subjected to the trio (N, My, Mz), such as the model automatically changes its geometry until it finds a dimension that enables the accommodation and its equilibrium.

Thus, for each beam and pillar it is obtained the steel area amount and the dimensions of its cross section, with which it is possible to determine the steel's total weight and concrete's total volume by the sum of all elements.

$$Pt = Pv + Pp \tag{1}$$

$$Volt = Volv + Volp \tag{2}$$

With Pt, Pv and Pp being the steel's total weight, steel's weight from beams and steel's weight from pillars respectively, and $Volt$, $Volv$ and $Volp$ being the concrete's total volume, the concrete's volume from beams and the concrete's volume from pillars respectively.

3.5 Final objective Function

After the structural sizing, the objective function to be minimized (F) is obtained by the weighted sum of the steel's total weight and the concrete's total volume as described in equation (3).

$$F = Pt.p1 + Volt.p2 \qquad (3)$$

With $p1$ and $p2$ being weights obtained heuristically to normalize the different values from this sum, once the sensibility of Pt and $Volt$ have different order of magnitude.

Thus, in this optimization process, the result will be modified and analyzed repeated times, according to the GA process that calls the building analysis program and at the end provided with the quantitative results of concrete and steel for each set of pillars and beams originated from the GA, there will be performed a comparison with the results so that it is possible to determine if a solution is the best among the others by satisfying the project's needs. Figure 8 presents a succinct flow chart of the optimization process to be employed.

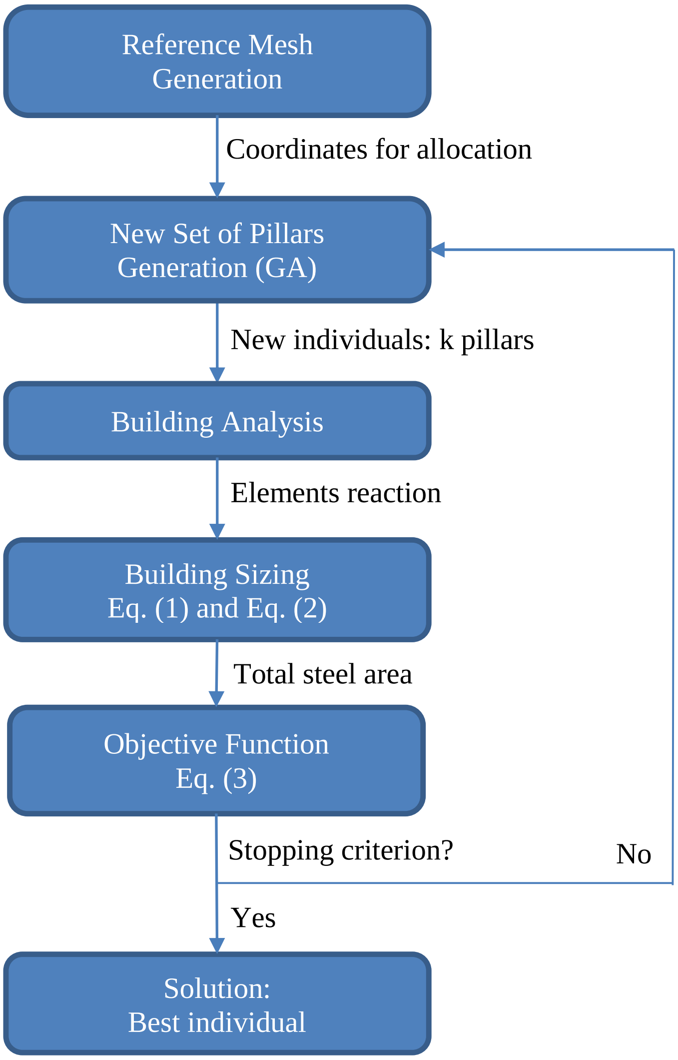

Figure 8 – Flow chart of the process to find the best pillars positions.

4 Conclusions

This article presents a model to obtain pillars positions in tall buildings considering permanent loads and live loads such as wind effect. It was not possible to finish the computational implementations of all models and its couplings once this work is the start of a master's work.

Among the proposed contributions to this work is to find an alternative to the pillars positioning aiming to reduce the dependency of the designer.

For example, if an analysis was made without the GA, using $k = 4, n = 10$ and $m = 8$, it would be a total of 3.764.376 possibilities. Each time the program performs an analysis it takes about 5 seconds, what would take approximately 217 days to perform all combinations. The use of the GA reduces the time of analysis, once its search is more efficient, not having the need to perform all possibilities.

Some projects limitations such as boundary distances between pillars, minimum and maximum beams spans, delimitation to the positioning of the pillars, among others, are some of the restrictions to be inserted in future models.

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