Design optimization via genetic algorithms of accessible Ferris Wheels

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Abstract. The structural optimization of accessible Ferris wheels represents a significant challenge due to the scarcity of technical literature on the modeling and simulation of these structures. This article addresses the modeling, simulation, and optimization of an accessible Ferris wheel using an innovative approach with genetic algorithms. Developed in Python, the study strictly adheres to technical standards to ensure the safety of the equipment. The primary objective is to reduce the total mass of the structure while maintaining an adequate safety coefficient. The research involves adapting genetic algorithms to the specific problem, automating finite element modeling, defining the initial structure, and an iterative optimization process. Both static and modal analyses of the Ferris wheel were performed, yielding relevant results such as the total mass of the structure, displacements, and maximum stresses, in addition to the safety factor in the static analysis, considering wind forces. In the modal analysis, the first twelve vibration modes and their respective frequencies were identified. The results demonstrate that the optimization was effective, resulting in a structure with reduced total mass and a satisfactory safety factor, while the modal analysis provided critical information about frequencies that should be avoided.

Keywords: Finite element modelling; Genetic algorithm optimization; Accessible Ferris Wheel design; Accessibility; Amusement device design.

1 Introduction

The development of accessible and technologically advanced Ferris wheels represents a significant challenge in structural engineering and amusement ride design. Despite the global popularity of Ferris wheels, there is a noticeable gap in the technical literature, especially in Brazil, where studies on finite element modeling and structural optimization of these rides are scarce. This deficit is particularly concerning, considering that many Brazilian amusement parks rely on importing these rides, facing high costs and challenges in adapting to local standards.

The process was conducted using the Python programming language, ensuring flexibility and precision in simulations and optimizations. The technical standards NBR 15926-2 [1] and ISO/DIS 17842-1 [2] are utilized to ensure the safety of the equipment at all stages, from design to operation. These standards establish minimum requirements for the safety of amusement rides, covering aspects such as structural design, manufacturing, installation, and safe operation.

To contextualize the relevance of this work, it is important to highlight significant contributions in the field, such as the studies by Krolicki, Sullivan, and Willford [3] on the Vegas High Roller and the research by Almufti et al. [4] on wind action on large structures. Standing at approximately 167 meters tall, the subject of the mentioned research became the tallest Ferris wheel of its time and one of the most sought-after tourist attractions globally. Recently (2021), Petrovska presented comparative analyses between fixed and transportable Ferris wheels [5], highlighting the Ain Dubai, the world's tallest Ferris wheel, standing at 250 meters tall, approximately 80 meters taller than the Vegas High Roller. These references illustrate the complexity and challenges involved in the design and optimization of these structures.

The introduction of Genetic Algorithms (GA) in optimization applications was carried out by Goldberg [6] through simulations of genetic systems. According to Holland [7], this algorithm is an optimization technique inspired by the theory proposed by Charles Darwin, an abstraction of natural evolution. It is widely used when research has a vast range of possibilities, making the application of other algorithmic solutions impractical. Initially, it generates an initial population of potential solutions, then assigns a score to each individual in this population and selects the individuals with the highest scores. Next, elitism is applied, preserving the individuals with the best scores for the next generation. The selected individuals are then crossed, combining their genes to form a new generation. After that, the mutation stage is carried out, consisting of random alterations to one or more genes of the individuals. Additionally, in the use of the GA, decimation is performed, where the individuals with the worst scores are excluded, and this excluded portion is replaced by a new population.

The methodology details the functioning of GAs adapted to the problem at hand, including the selection, crossover, and mutation of individuals, as well as the decimation of the less fit. The finite element modeling of the Ferris wheel's structure was carried out considering critical parameters for the safety and efficiency of the design. In summary, this article not only advances technical knowledge about Ferris wheels but also contributes to social inclusion by promoting accessibility in amusement parks. The presented innovation reinforces the national engineering capability, reducing dependence on imported technologies and positioning itself at the forefront of structural optimization and safety of amusement park equipment.

2 Methodology

For this study, an in-house built GA tool developed by Colherinhas et al. [8] was used, adapted for the Python software (Fig. 1). This adaptation allows interaction with a finite element method (FEM) program, in this study used ANSYS software, optimizing the process of selecting the dimensions of the Ferris wheel according to the study's objectives. During the adaptation, a graphical user interface (GUI) (Fig.2) was developed that facilitates the input of parameters such as rod dimensions, number of rods, gondola mass, and rod length for the insertion of gondolas, as well as the dimensions of the rod cross-sections. The developed GUI proved to be extremely useful, allowing quick modifications for the analysis of specific cases without the need to alter the code, and enabling saving configurations obtained through the optimization processes. This GUI is currently under development and refinement. The final version of this software will be patented.

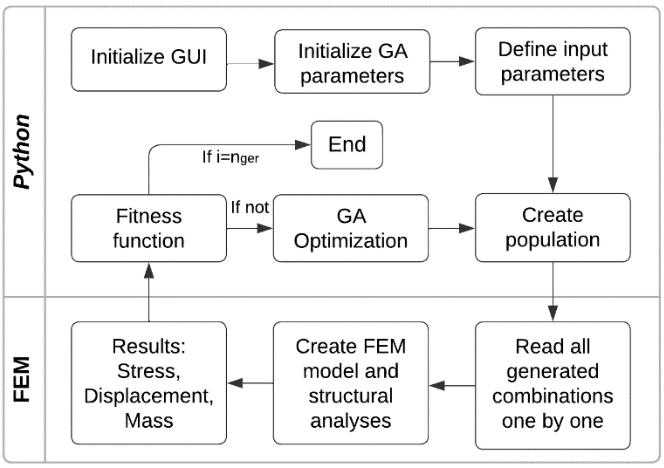


Figure 1. Flowchart of Implemented GA.

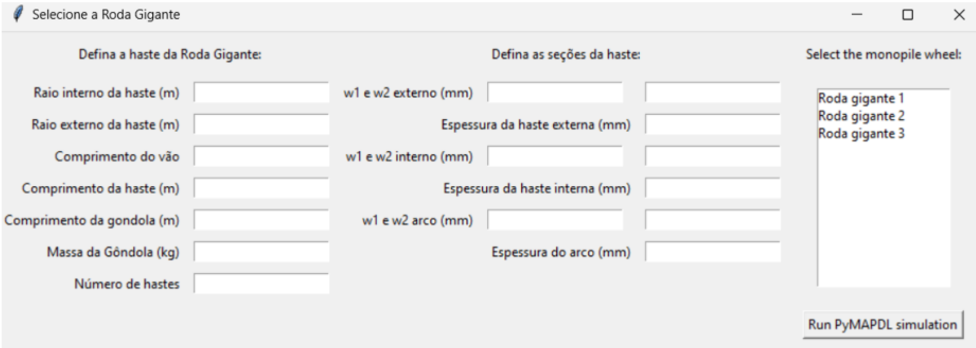


Figure 2. The software's graphical user interface.

The main code written in Python includes the optimization parameters of the GA. The number of generations, number of individuals per generation, intervals for decimation, probabilities of decimation, elitism, mutation, and crossover is defined, respectively, as $N_{gen} = 100$, $N_{ind} = 100$, $N_{dec} = 20$, $P_{dec} = 20\%$, $P_{elit} = 2\%$, $P_{mut} = 2\%$, $P_{cross} = 60\%$.

The dimensions of the cross-sections, taken from NBR 6591:2008 [9], include square and rectangular sections. Initially, these values are inserted into separate vectors and then combined into a matrix to automate the GA procedure. The dimensions of the cross-sections in millimeters are presented in Table 1, while the thickness' sections are taken as 2.00, 2.25, 2.65, 3.00, 3.35, 3.75, 4.25, 4.50, 4.75, 6.30 mm.

Table 1. Dimensions of cross sections, in mm [9]

$\text{Width}_{\text{ext}}$	$\text{Height}_{\text{ext}}$	$\text{Width}_{\text{int}}$	$\text{Height}_{\text{int}}$	$\text{Width}_{\text{arc}}$	$\text{Height}_{\text{arc}}$
30	50	30	30	30	50
40	60	40	40	40	60
50	70	50	50	50	70
60	80	60	60	60	80

After generating the initial population, the individuals are transferred to the FEM program through the fitness function. At this stage, the dimensions of the individuals are read, and the Ferris wheel is modeled. The subsequent static analysis provides values for the total mass, stresses in the model, and deformations in the elements.

The results obtained in the static analysis are transferred back to Python, where they are saved. The safety factor of the structure is calculated by dividing the maximum stress obtained in the simulations by the yield strength of the material. The optimization aims to reduce the total mass of the Ferris wheel while maintaining an adequate safety coefficient. This is a multi-objective problem, with the safety factor being a component of this multi-objective function. In the fitness function, weights are specified for the total mass and the safety factor, with values of three and one, respectively. For cases where the calculated safety factor for an individual is greater than three, a value of three is considered to limit the individual's score and avoid generations with high safety factors and total mass.

If it is not the last generation, the code proceeds to the evolution strategy function, where the selection of individuals occurs. The roulette wheel selection method is used, ordering the individuals in descending order according to the score provided by the fitness function. Then, elitism is performed, preserving the fittest individuals. The BLX-alpha crossover, or blend crossover, is applied, allowing for greater genetic variability. New individuals are then generated and subjected to mutation. The process returns to the main function for the decimation stage, executed at previously defined regular intervals. Individuals with low fitness are excluded and replaced by a new population. This cycle repeats until the last generation, as illustrated in Fig. 1.

3 Definition of the Finite Element Model

In the present study, the modeling of the Ferris wheel utilizes three distinct types of elements: BEAM188, MASS21, and BEAM4. These elements are selected due to their specific mechanical properties that meet the analysis requirements of the Ferris wheel structure ($E = 210$ GPa, $G = 80$ GPa, $\nu = 0.3$, and $\rho = 7850$ kg/m^3).

A geometry for the Ferris wheel's rods is chosen in this initial study based on existing wheels, as illustrated in Fig. 3. This configuration includes internal elements arranged horizontally and diagonally, which contribute to the uniform distribution of stresses, preventing the formation of stress concentrators that could compromise structural integrity.

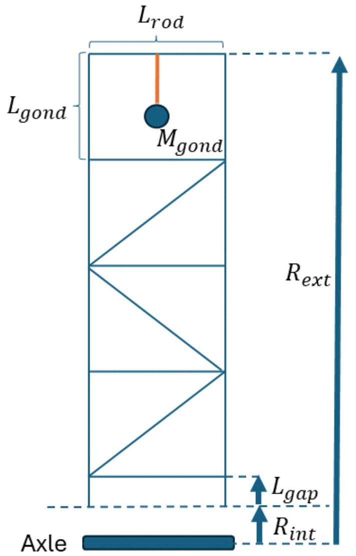


Figure 3. Rod Configuration.

For generating the finite element model, the process begins with the creation of nodes, which are connected using appropriate elements. To automate the process, orientation nodes are employed. After the creation of each rod for a part of the structure, the remaining is generated by exploiting its symmetry, replicating this part in angles around the axis of symmetry, until a 360 rotation is done, ensuring the necessary symmetry for the structure and the number of gondolas defined in the project.

The Ferris wheel axis is modeled as a hollow circular section element. Additionally, four connecting arcs are generated: two linking the ends of the rods and two located approximately halfway along the length of the rods. All these arcs share the same cross-section and, for simplification, are modeled as linear elements. To represent the gondolas, mass-type elements are applied, rigidly connected to the top element of the rod. The mass location is determined by the height of the gondola's center of gravity. In addition, a load representing the operational load is applied at the mass element node, considering each gondola occupied by four persons taller than 1.30 meters. A vertical imposed load of 0.75 kN per user is adopted, in accordance with NBR 15926-2 [1].

In the static analysis, gravity is applied to the simulation, generating the necessary forces due to the gondolas' masses. Additionally, the wind force is applied only to the gondolas. In this study, the terrain of the Ferris wheel is classified as category III. Furthermore, according to the National Institute of Meteorology, the wind speed in Brazil is usually below 15m/s. Consequently, following the NBR 15926-2 [1] standard, eq. (1) is used to calculate the wind force. Here, F_w represents the wind force in N, q_{eq} is the wind pressure in kN/m², which depends on the height of the structure. In this case, the Ferris wheel's height is approximately 23 meters, resulting in q_{eq}. The force coefficient c_f, according to the NBR 6123 [10] standard, for the gondola situation with the wind direction perpendicular to the gondola, is c_f. The area A is the lateral area of the gondola that is perpendicular to the wind action. Additionally, due to the low acceleration, the driving and braking forces on the Ferris wheel are disregarded in the analysis. The static solution provides the total mass of the structure, the maximum displacement of the elements, and the maximum stress in the structures.

$$F_w = q_{eq} c_f A \tag{1}$$

The result of the modeling is presented in Fig. 4, where the Ferris wheel and its structural components are displayed. The beams and mass elements, representing the loaded gondola, are shown. Furthermore, the constraints applied to the central nodes of the Ferris wheel structure, the coordinate system, and the wind force acting laterally on the gondolas can be observed.

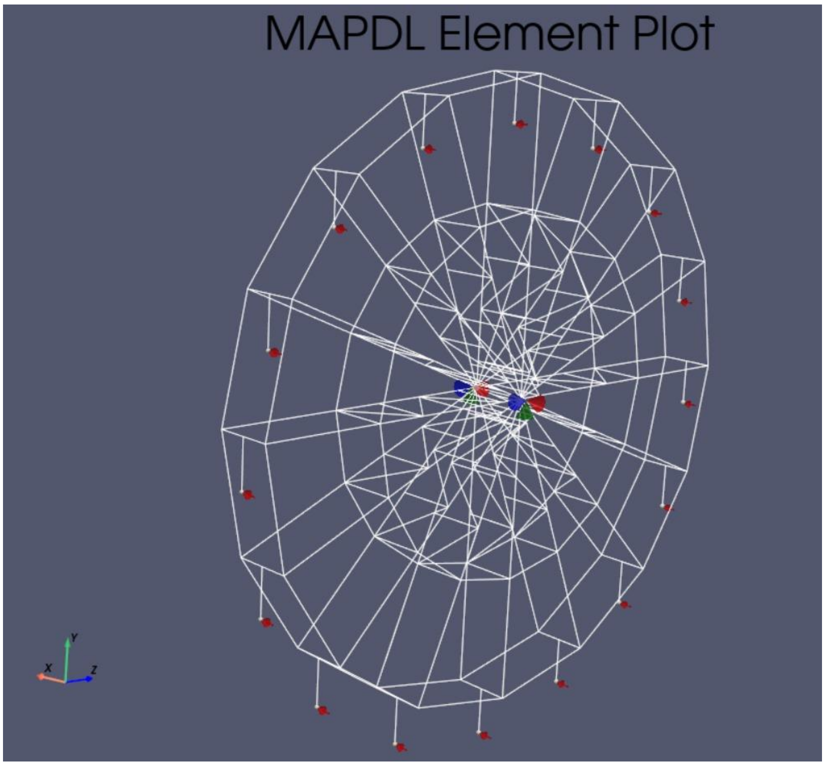


Figure 4. Complete modeling of the Ferris wheel.

The modal analysis is performed to identify the natural frequencies of the Ferris wheel, avoiding resonance and potential structural failures. This analysis considers the first twelve vibration modes of the structure, using the Lanczos method for mode extraction, which is efficient for large systems. A sparse equation solver is employed to solve the associated linear equations. The analysis also accounts for pre-existing stresses in the structure before executing the modal analysis, as well as gravitational acceleration in the Y-axis. This approach ensures robust and accurate modeling of the Ferris wheel, contributing to the safety and efficiency of the structure throughout its lifespan.

4 Results

The adaptation of the GA to the present study proved to be functional and efficient, allowing up to 10,000 simulations in each optimization process autonomously, without the need for operator intervention. This level of automation ensures that the optimization process occurs continuously and accurately, according to the established objectives. The finite element model resulted in a Ferris wheel composed of 260 nodes and 467 elements. The results of three optimum configurations are presented in Tab. 2.

Table 2. Optimum results.

Parameters	Configuration 1	Configuration 2	Configuration 3
Max. stress [MPa]	245.22	286.69	253.40
Max. displacement [mm]	23.30	84.29	26.23
Total mass [ton]	37.867	37.405	37.135
Safety Factor	1.43	1.22	1.38

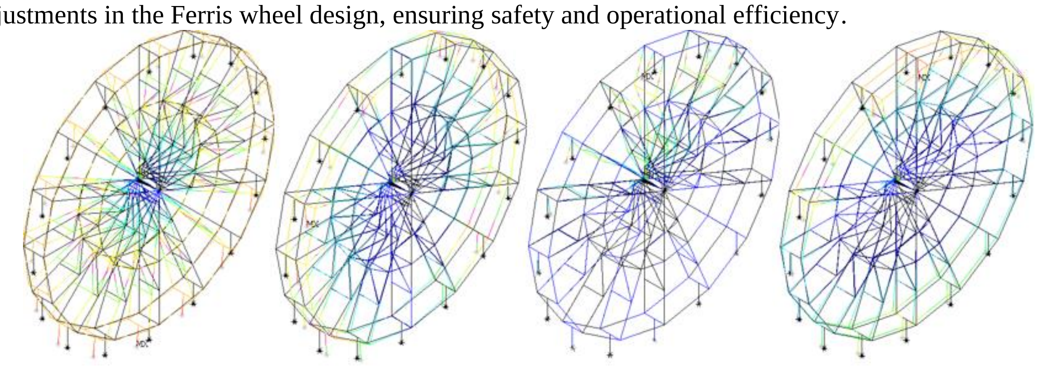
In comparison to other optimal results, Configuration 3 has the lowest total mass while also presenting a reasonable safety factor. According to the NBR 15926-2 [1] standard, the safety factor adopted for this study is

1.35. Therefore, the obtained safety factor is within the expected range. It is noted that in Configuration 1, the total mass of the structure is 700 kg higher compared to Configuration 3, while in Configuration 2, the safety factor is lower than the standard's requirement, which reinforces the choice of Configuration 3. Configuration 3 is selected from the GA optimization, being the most suitable for the study's objectives, and is analyzed by a dynamic analysis of the structure, with its parameters specified in Tab. 3.

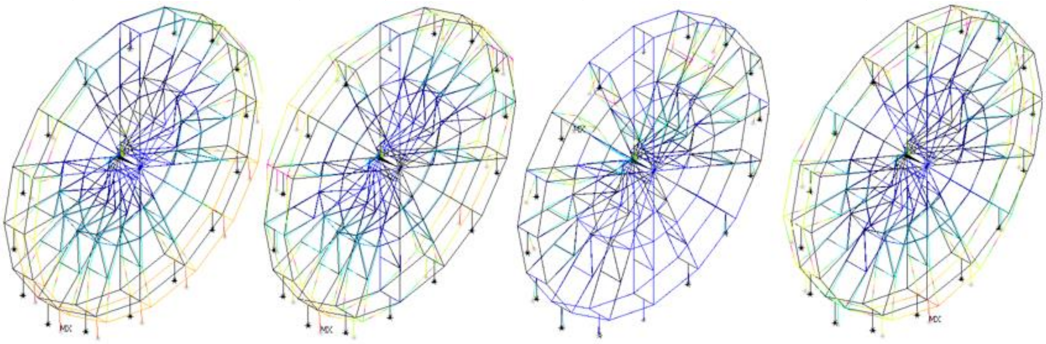
Table 3. Selected Ferris Wheel configuration from GA optimization.

Parameter	R_{ext} [m]	R_{int} [m]	L_{gap} [m]	M_{gond} [ton]	L_{gond} [m]	L_{rod} [m]	$L_{cg,gond}$[m]
Value	10.0	0.4	0.5	1000	2.5	1.8	1.618

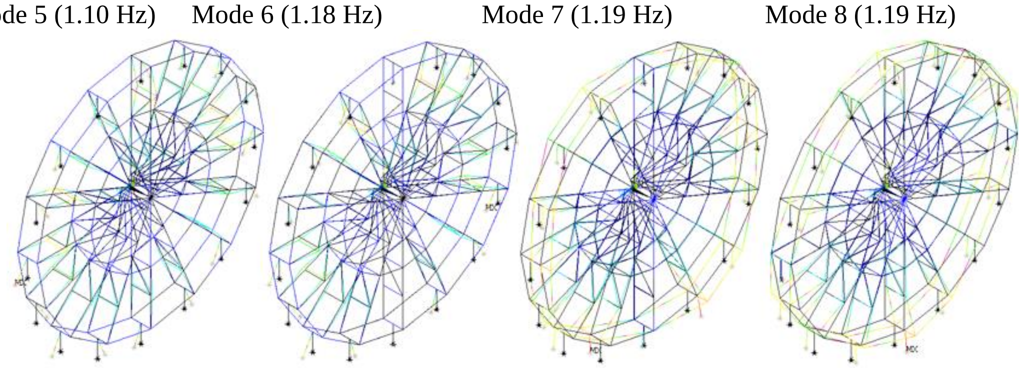
The results of the modal analysis, presented in Fig. 5, indicate that the natural frequencies of the first twelve vibration modes range from 0.06 Hz to 1.33 Hz. Among these modes, it was observed that: in the first mode, the deformation resembles a rotation around the X-axis, which is consistent with the operational movement of the Ferris wheel; in the third and seventh modes, large deformations occur in the spokes, indicating critical points that need attention to prevent structural failures. The data obtained provide a solid foundation for future improvements and adjustments in the Ferris wheel design, ensuring safety and operational efficiency.



Mode 1 (0.06 Hz) Mode 2 (0.99 Hz) Mode 3 (1.01 Hz) Mode 4 (1.02 Hz)



Mode 5 (1.10 Hz) Mode 6 (1.18 Hz) Mode 7 (1.19 Hz) Mode 8 (1.19 Hz)



Mode 9 (1.27 Hz) Mode 10 (1.33 Hz) Mode 11 (1.33 Hz) Mode 12 (1.33 Hz)

Figure 5 – Ferris wheel vibration modes.

5 Conclusion

This research successfully achieved the proposed objectives, significantly contributing to bridging the gap in academic studies related to the design and simulation of forces in Ferris wheels, especially in Brazil. The adaptation of the GA to the Ferris wheel design, integrated with the Python program, proved effective in optimizing the design, reducing the total mass of the structure and ensuring an adequate safety factor to prevent possible failures.

The finite element modeling proved to be suitable for the problem, with the use of element types and the iterative process employed, facilitating the repetitive creation of the analysis model during GA processing. The configuration of the Ferris wheel resulting from the optimization proved to be efficient, presenting a reduced mass and a satisfactory safety factor.

The modal analysis was essential to evaluate the integrity of the structure, indicating the need to avoid operating the Ferris wheel when subjected to the resulting natural frequencies, especially in the third and seventh modes, where high deformation in the spokes was observed, which could lead to structural failures and cause serious accidents.

As a future development of this research, it is proposed to enhance the interaction of the GA with new structural configurations, as well as to improve the graphical interface. Additionally, further automation of finite element modeling is sought, particularly in the creation of the spokes, allowing for the generation of spokes with different numbers of trusses, aiming to design Ferris wheels of much larger dimensions compared to the project studied in this research. The action of the wind will also be included to add important information in the evaluation of resulting stresses and the overturning of the structure.

This ongoing technological development will not only enable the creation of safer and more efficient Ferris wheels but will also elevate the standard of amusement park designs in Brazil, strengthening the country's position as an innovation hub in this sector.

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