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Application of a methodology for topological optimization of gears

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Resumo. *The popularization of additive manufacturing in the industry allows the creation of more complex products. In this way, topological optimization, an engineering technique that uses algorithms to determine the best distribution of material in a structure, becomes increasingly common. In view of this, in order to corroborate the use of topological optimization, the creation of methodologies is observed in the literature, however, most are not practical and, not infrequently, are not very instructive. In this sense, this work aims to apply the topological optimization process to minimize the mass of a gear for power transmission, through the engineering software Solidworks. Together, the creation of a workflow necessary for the best efficiency in the development of this type of project will be carried out. For this, topology optimization and generative design were used with the help of Solidworks software, the mass minimization algorithm was adopted, seeking the most appropriate stress distribution, improved aesthetics and the best performance while maintaining the displacements and safety factor (FS) established by current regulatory standards. Thus, firstly, a structure of primitive geometry was modeled in a computer-aided manufacturing software (or CAM, Computer Aided Manufacturing), just detailing the fixation locations, then the simulation was carried out by finite element method (or FEM, Finite Element Method) that takes into account loads, thermal requests and vibration, from this, a topological optimization study was generated based on mass reduction, for which it was defined which parts should not be changed and in sequence the algorithm was applied, obtaining an optimized model. Finally, it was necessary to implement a new design seeking a more suitable functionality and aesthetics in its application. In this logic, the path to obtain a project with low cost and better performance with economy of development time through process automation was discussed. For the aforementioned study, he highlighted the practical application of these techniques when optimizing a cylindrical gear with straight teeth, resulting in a 70% reduction in the mass of the final part. This illustrates the importance of computer modeling to validate the optimization process and determine the best manufacturing method. . Thus, we continue on a path that seeks to advance towards the creation of new technologies that are increasingly optimized.*

Palavras-chave: *Mass Reduction, Static Simulation, ECDR, Additive Manufacturing.*

1. INTRODUCTION

Optimizing structures is extremely important for mechanical engineering, as it is a process that allows more efficient and safer structures to be designed, while at the same time reducing costs and production time. This is especially important in an increasingly competitive market, where reducing costs and maximizing performance are critical factors for success.

In this sense, improving designs is fundamental for mechanical engineering, as it makes it possible to create lighter, more resistant and more economical components and systems. In this logic, we can see the importance of improving components in high-tech applications, such as in the aerospace and automotive industries, and in any area where the performance-mass ratio is crucial to the efficiency of the system. In addition, topological optimization can also help reduce the amount of materials needed to produce a component or system, which can result in significant savings in terms of costs and natural resources.

Structural optimization in mechanical engineering can be achieved through various techniques, such as computer-aided engineering (CAE), finite element method (FEM) simulation and topological optimization, as well as the selection of suitable materials and the appropriate manufacturing process, with the aim of achieving the best system performance.

In view of this, (Filho, 2009) defines CAE as a set of *software* techniques and tools that allow simulations and analysis of industrial projects and processes to be carried out using mathematical and computer models. In this way, this tool allows engineers and designers to analyze the behavior of systems under different conditions, even before physically building

them, enabling a faster, more efficient and cost-effective development process.

Within the CAE process, finite element simulation is the most important way to understand the structure's behavior based on pre-established loads and fixings. In this logic, FEM is a numerical analysis technique used in engineering to solve complex structural, thermal, fluid dynamic and acoustic analysis problems, among others. In short, (Gouri Dhatt, 2012) explains that this method consists of dividing a mathematical model of a system into small elements, such as triangles or quadrilaterals, and calculating the solutions for each element separately, using known mathematical equations. These partial solutions are then combined to form a global solution to the problem.

With information about the structure and the stresses to which the parts of a system are subjected, topological optimization emerges, which according to (Jun Wu, 2021) is a computational design technique that uses optimization algorithms to find the ideal distribution of material in a three-dimensional structural model, with the aim of minimizing the weight or maximizing the stiffness of the structure, subject to performance constraints such as stresses, displacements and safety factors.

This work aims to apply the topological optimization process to minimize the mass of a power transmission gear, using the engineering software *Solidworks*. In conjunction, a *workflow* will be created, which is necessary for the most efficient development of this type of project.

To achieve the desired goal, it will first be necessary to identify the gear's *design* and *non-design* areas, then analyze the stresses and safety factor associated with the structure, validate the optimization process and finally determine the most suitable manufacturing process.

2. MATERIALS AND METHODS

To develop the project, a case study will be used to analyze the process of developing the design and structure of a cylindrical spur gear (ECDR), this type of part is used in power transmission systems. In this logic, the gear chosen is part of a vehicle reduction gearbox, the table 1 indicates the specifications and parameters of the gear to be modeled.

Tabela 1: Gear specifications.

Dados	valor
pressure angle	20°
circular step	6.5 mm
teeth thickness	20 mm
number of teeth	60
Primitive diameter	125 mm
Gear module	2
Nominal shaft diameter	20 mm

The parameters of a spur cylindrical gear play a critical role in the operation of mechanical systems. The proper selection of these parameters is vital to ensure the efficiency, reliability and durability of the system, as well as to avoid problems such as premature wear, noise and mechanical failures. It is therefore essential to choose these parameters when designing and manufacturing gears for specific applications.

2.1 Computational modeling

First, it was necessary to model a primitive gear in *computer aided design* (CAD), using the involute curves responsible for the tooth profile. this design is made in such a way that the structure presents simple polygonal geometries. For this, the tool and automatic creation of machine elements from the *Solidworks* software will be used.

Next, the determination of the *design* and *non-design* areas is made, that is, the regions in which topological optimizations can and cannot be performed, such as the fixation regions and the regions of force application as determined by (Kapil Gupta, 2017). An example of this process is shown in figure 1.

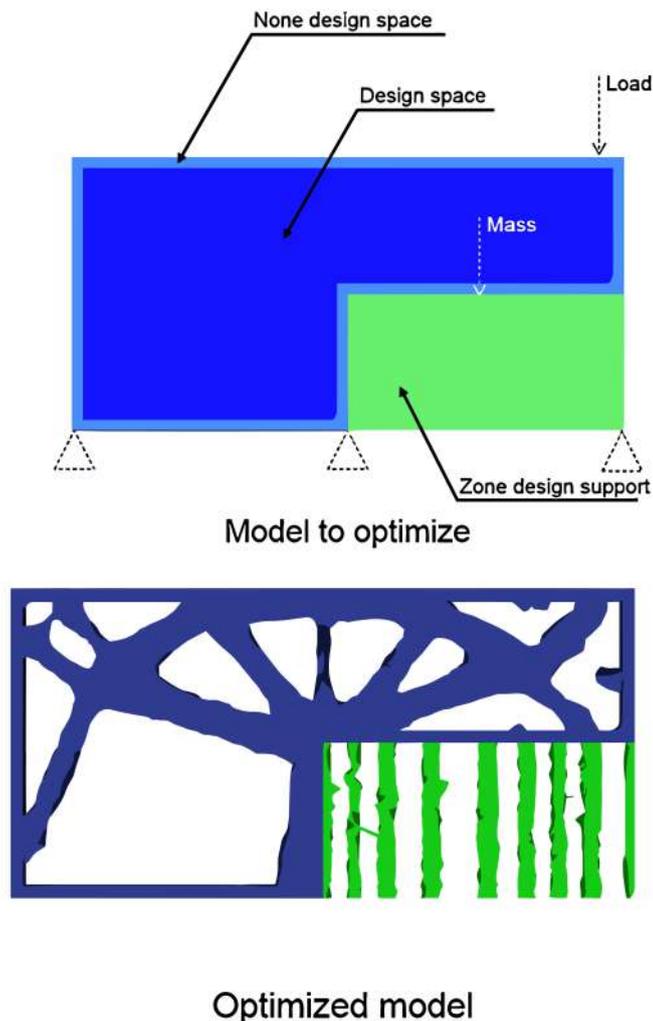


Figura 1: Design and non-design areas.
Source: Nicolas Gardan (2015)

A balance is struck between none-design areas, where material concentration is maximized to meet performance requirements, and design areas, where material is minimized to reduce weight. This results in more efficient designs with a better relationship between weight and performance, being particularly valuable in sectors such as aerospace, automotive and structural engineering, where weight reduction is a critical consideration.

Correctly selecting design and non-design areas in topology optimization is crucial to avoid problems such as inadequate performance, excess weight, material inefficiency, manufacturing complexity, validation difficulties, sensitivity to model errors and additional engineering costs. Inadequate selection can lead to designs that fail to meet performance requirements, increase production costs, make manufacturing more complex and compromise structural validation, resulting in potential project failures and delays. It is therefore essential that engineers carefully consider the definition of these areas from the start of the topology optimization process.

2.2 Computer simulation

In order to carry out the finite element simulation, it was necessary to determine the material chosen for the part being analyzed. Figure 2 shows a list of the most common materials used in the production of ECDs. It is important to note that the choice of material must be based on the application of the gear within the machine, and also the manufacturing process carried out in the production of the geometry obtained at the end of the process, since by selecting materials that suit the chosen manufacturing process, the savings in the manufacture of the part will be extremely relevant.

			Properties	Applications
Cast iron	Gray iron		Good machinability, sound dampening properties, good resistance to wear, low impact strength	Large-size mill gears; moderate power-rating applications; low shock applications; and machine tools
	Ductile iron		Fair to good machinability, sound dampening properties, better impact and fatigue strength than gray iron	Transportation; railroad and military vehicles; girth gears for mills
Plain carbon steels	Carburizing gear steels	Low-carbon steels (1010, 1015, 1020, 1021, 1022, 1025)	Excellent machinability, good combination of strength and ductility, heat treatable, can be case carburized	Low to medium duty applications
		Through-hardening gear steels	Medium-carbon steel (1035, 1040, 1045)	Good machinability
		High-carbon steel (1060)	High strength and durability	High-power rating applications
Alloy steels	Carburizing steel	Nickel–chrome–molybdenum carburizing steel (SAE8620)	Good wear characteristics/ high wear resistance	Automotive transmissions; farm machineries; earth movers
		20MnCr5 (SAE5120)	Case-hardening imparts hard case with good wearing properties and tough core	Automobile gear boxes; heavy-duty transmission gears; hoisting; and cranes
	Through-hardening gear steels	Chrome–molybdenum alloy steel (4140)	High toughness, good torsional strength, good fatigue strength	Differential systems of automobiles; and tractors

Figura 2: Most common materials in the production of ECDR's.
Source: (Kapil Gupta, 2017) p. 21

In this sense, it was necessary to determine the support areas of the part, this fixation can be chosen according to how the studied structure is coupled with the other components of the system, the most common options found in the *software* used are shown in figure 3.

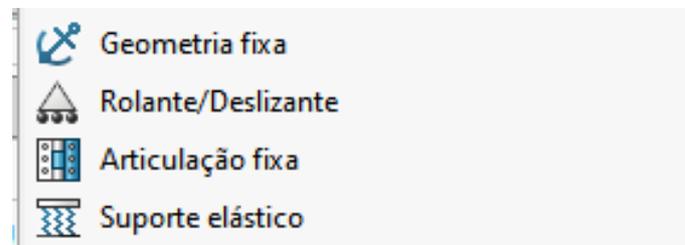


Figura 3: Fixation types.
Source: Autor (2023)

In possession of the aforementioned information, it was necessary to establish the loads applied to the part and where these loads will be used. For this, the modeling of (Kapil Gupta, 2017) was used, which details the way in which the contact between the ECDRs takes place and where these loads are carried out, the value referring to the load depends on its application and the calculation referring to the value of the force can be found in the (Norton, 2011).

The next step is the creation of the mesh used in the simulation, this mesh was chosen according to the type of surface of the part, and the refinement of the mesh is of crucial importance for the future topological optimization (M.P. Bendsoe, 2004), since the more refined the mesh, the better the results of the resulting surface at the end of the process.

Finally, for the application of the FEM, an adaptive mesh process was chosen, which can be of type p or h.

2.3 Topological optimization

After obtaining the static simulation results, it was necessary to analyze the plots of stresses and the factor of safety associated with the structure and from this result it was possible to define whether topological optimization was necessary. For this purpose, (Norton, 2011) indicates that the minimum safety factor in a projected structure, in which all the material data is not known, must be 5.

Finally, the topology study was carried out and, for this, the preserved areas and the desired mass reduction percentage were determined, in addition, for the case analyzed, symmetry is essential, so defining the symmetry planes for the project study is important to obtain an acceptable final result. The application of topological optimization is an iterative process, so the flowchart in figure 4 shows how the entire process cycle is done to reach the final result.

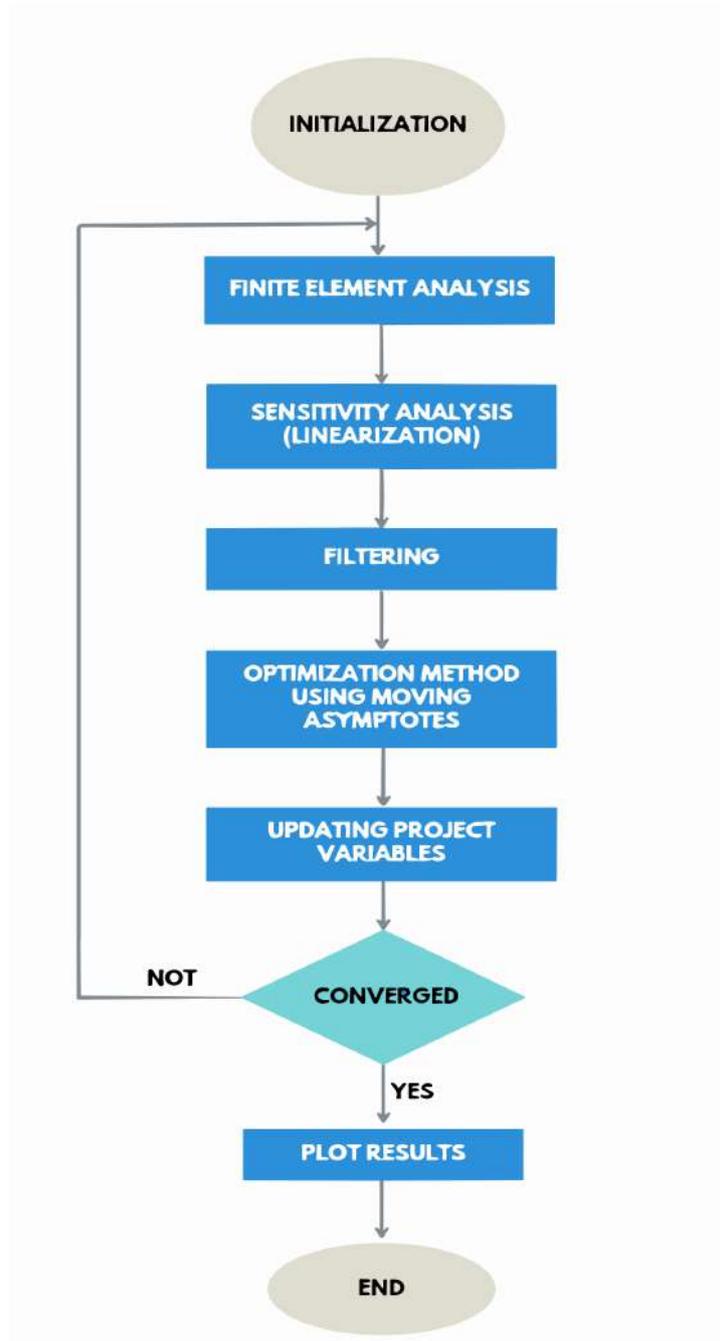


Figura 4: flowchart.
Source: (Palma, 2018)

The last step is to validate the mass removal process, performing a new static simulation with the new geometry obtained and then the new stresses and safety factors associated with the regions of the studied structure can be observed, if it does not meet the specifications, the optimization is redone with new parameters.

3. RESULTS AND DISCUSSION

Firstly, using the *toolbox* tool from *solidworks* an ECDR was created, in this utility it is only possible to insert the desired parameters and a piece with simple geometry is automatically generated in which an 18mm coupling axis was chosen, as it is the most common diameter in the industry, in addition to using (Gears, 2021) to determine all the parameters necessary to create the CAD modelling. The modeling carried out can be seen in figure 5.

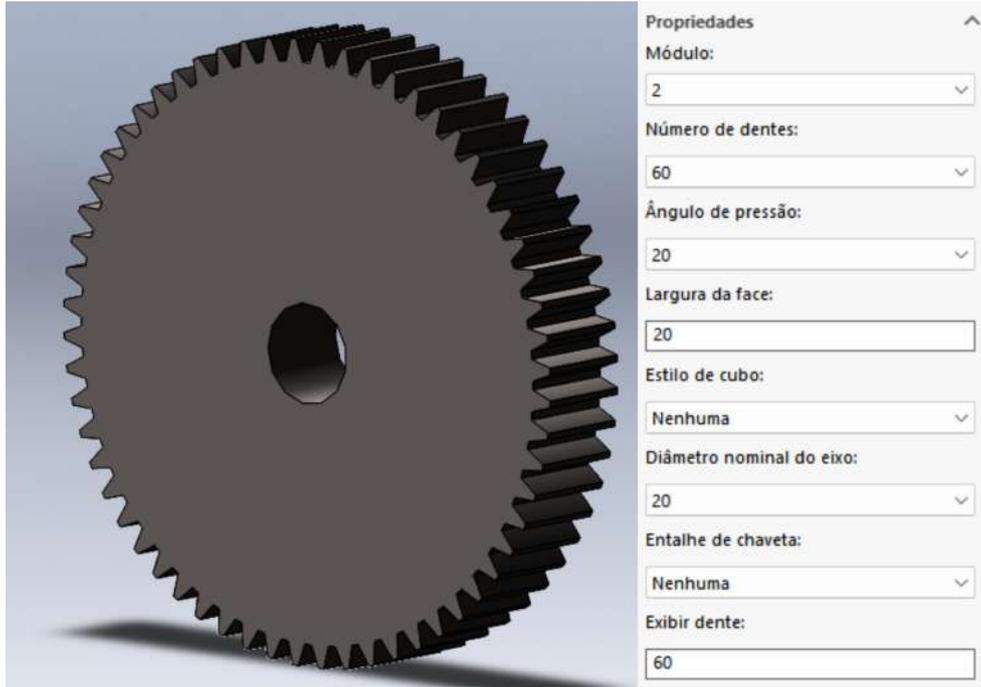


Figura 5: Parameters and model used.
Source: Autor (2023)

Once the study model has been defined, it is necessary to define the *design* and non-*design* areas, for this it was defined that the areas of structure fixation and the areas of application of requests must always be preserved, in figure 6 it can be seen in purple the parts that will not be optimized so that the operation of the mechanism is not affected.

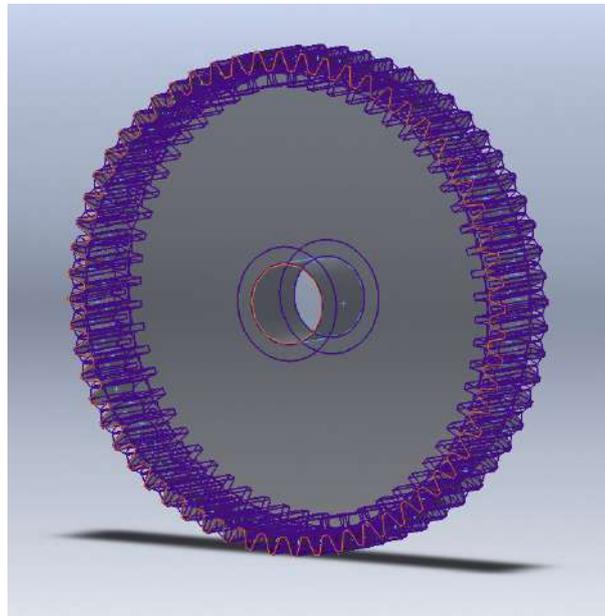


Figura 6: preserved areas.
Source: Autor (2023)

To carry out the static simulation, it was necessary to determine what material the analyzed component is made of, from the table 1 and ISO 53:1998 (Gears, 2021) the material chosen was drawn steel AISI 1045, which has a high machinability and is normally used for high power systems. the properties used are arranged in the table 2.

Tabela 2: gear specs

Property	Value
elastic modulus	205 Gpa
Poisson Coefficient	0,29
shear modulus	80 Gpa
tensile strength	625 Mpa
flow limit	530 Mpa

For the FEM simulation to be performed, it is appropriate to apply the gear connections, the type of coupling chosen was fixed geometry, this type of constraint defines the translational degrees of freedom as zero, in addition to not having to refer to the geometry, the location chosen as fixed can be seen in green in figure 7. Another important factor to obtain good results in the simulation is to determine the value and type of load and where it will be applied in the structure, in relation to the former, it can be found in the ISO 53:1998 standard (Gears, 2021) as for the latter, it was determined by (Kapil Gupta, 2017), in figure 7 one can observe the types of values and where the loads were applied.

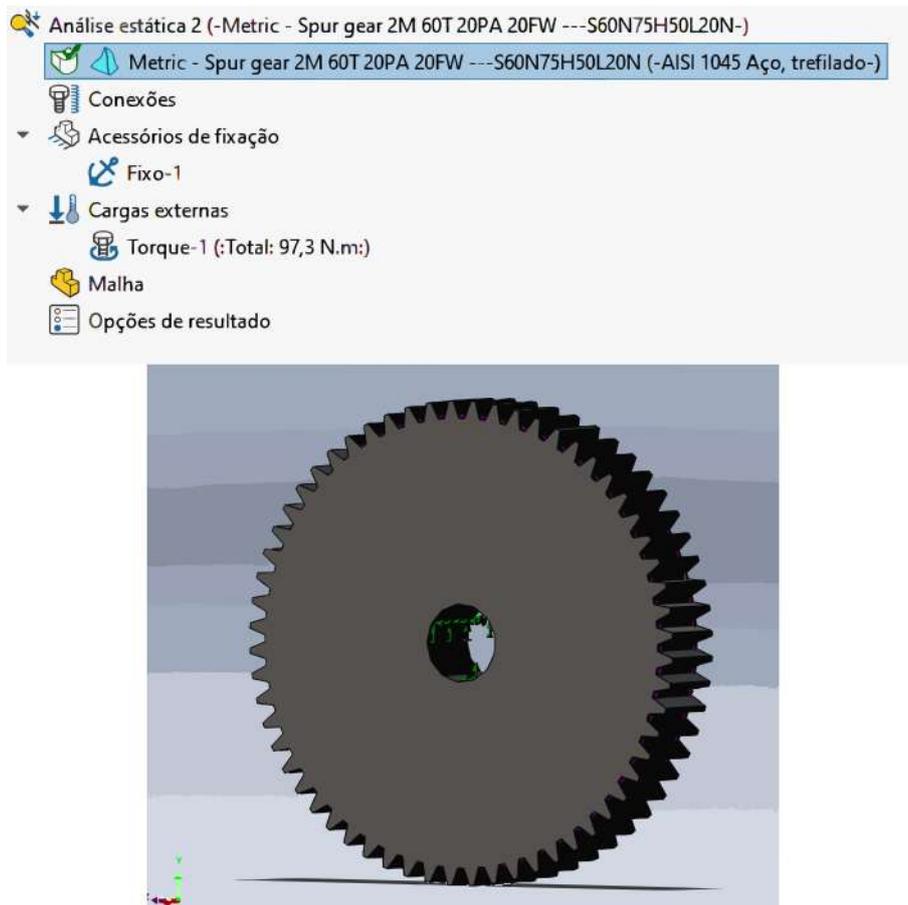


Figura 7: Fixed areas and loads.
Source: Autor (2023)

As the optimization process depends directly on the chosen mesh, the highest possible refinement and a convergence to the h-type mesh will be chosen, the concept of the h method is to use the smallest elements in regions with many errors. After running the study and estimating the errors, the software automatically refines the mesh to improve the results until reaching a precision defined as 98% in up to 5 iterations, in figure 8 you can see the mesh and the values for performing the convergence.

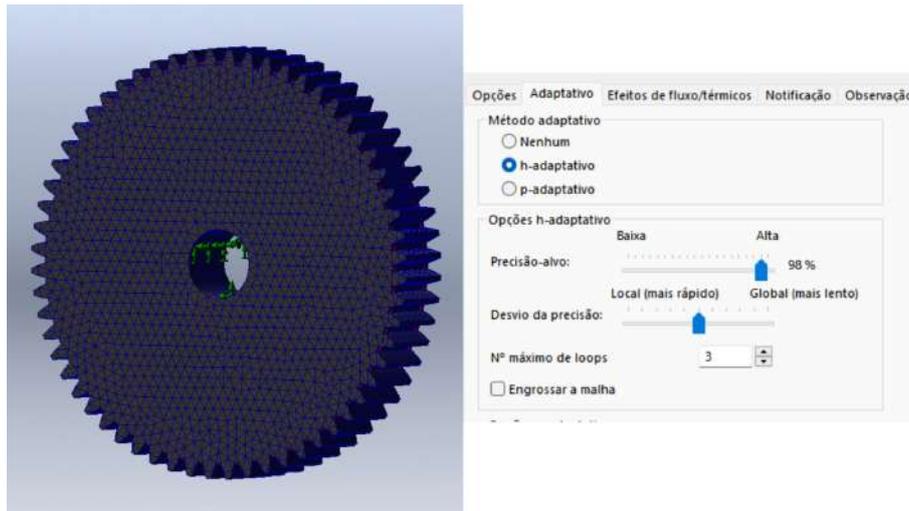


Figura 8: Mesh and shape adaptive.
Source: Autor (2023)

Shortly after creating the mesh, the static analysis began and the plotting of stresses and the safety factor was observed, in the image 9 it was possible to observe that the maximum stress does not reach the yield strength of the material and that the safety factor obtained is 39,24. In this sense, topological optimization can bring about a mass reduction without compromising system operation.

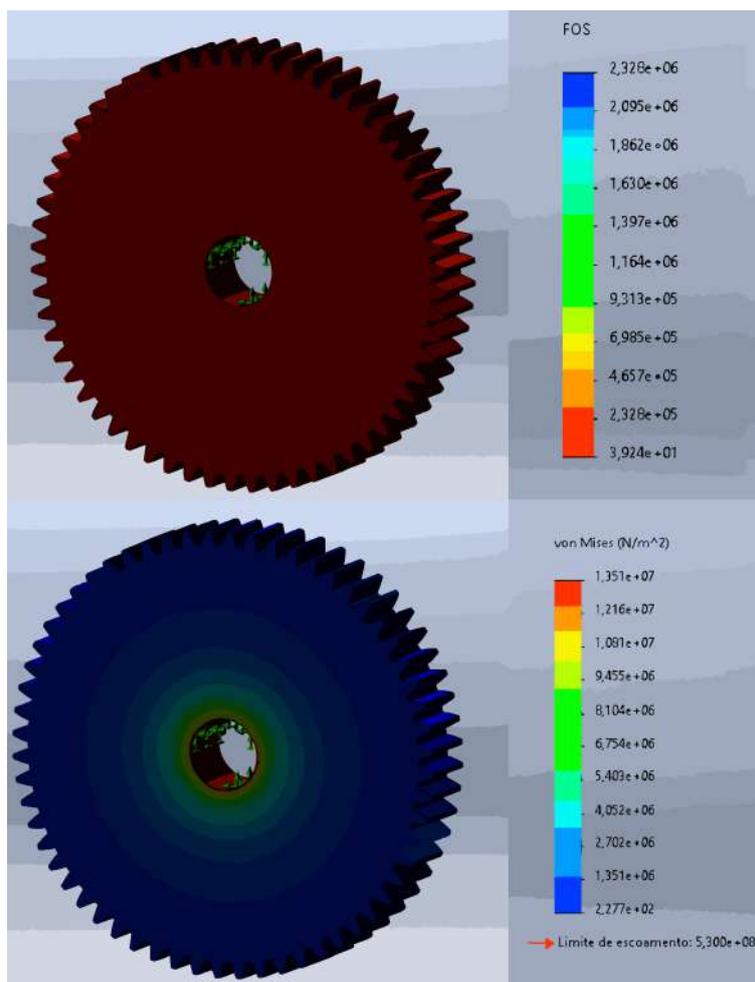


Figura 9: Factor of safety and stresses.
Source: Autor (2023)

To improve the mass distribution of the part, the mass minimization parameter was chosen, that is, to obtain the

smallest possible mass, with the restriction of the safety factor greater than 5, after defining the necessary symmetry planes for the structure, the topology study process was carried out, the result is shown in figure 10.

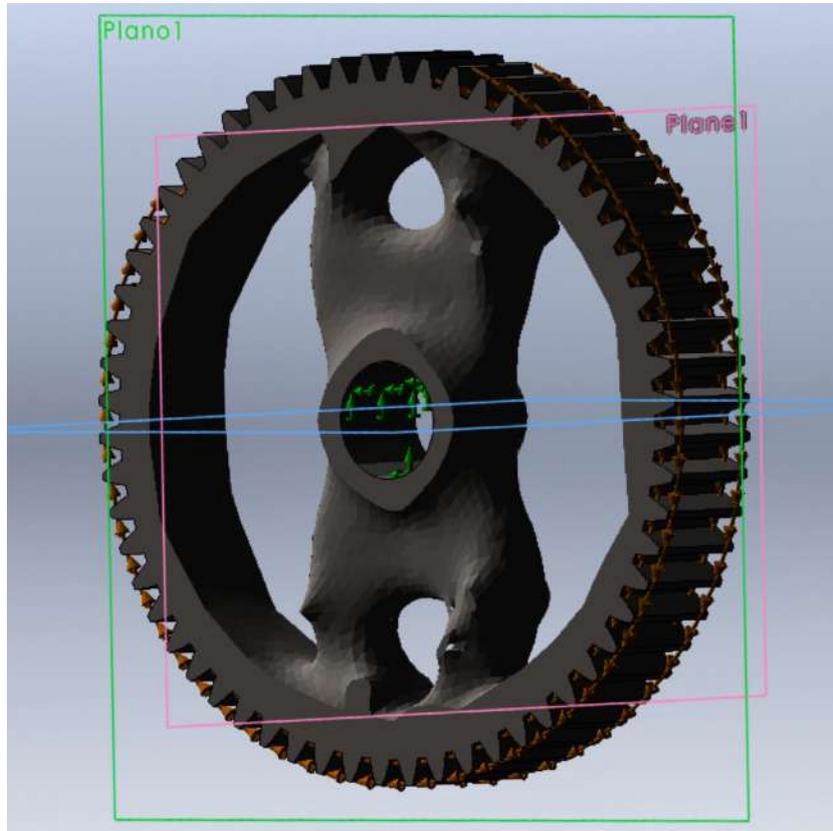


Figura 10: Topological optimization.
Source: Autor (2023)

In possession of the optimized model, it is important to validate the new geometry, for this a new static simulation was performed with the same values applied to the previous structure, this validation was carried out by observing whether the maximum stresses and the safety factor are within the desired limit, the validation results can be seen in figure 11.

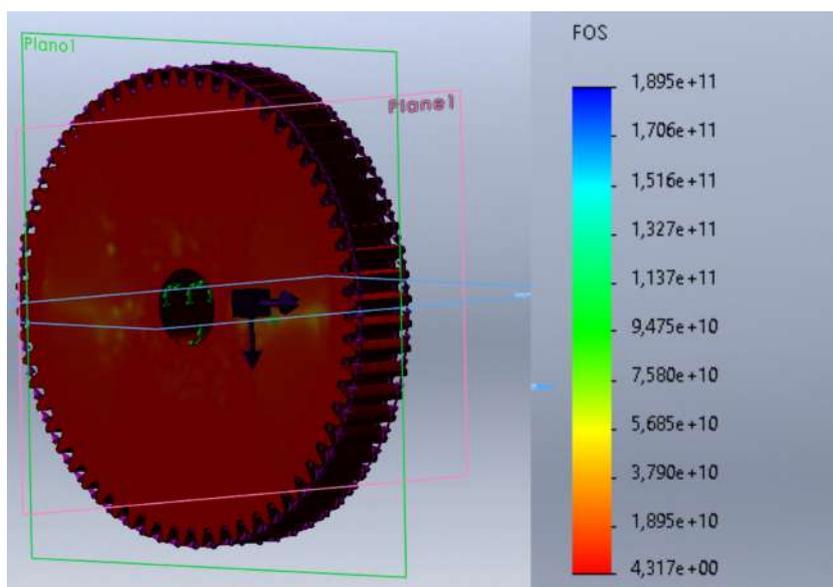


Figura 11: Topological optimization.
Source: Autor (2023)

After being approved in the validation process, it was observed that the mass of the structure was reduced by 70% and

the safety factor became 4.31. It is also seen that the new geometry is now organic and complex for the most common manufacturing methods. In this logic, additive manufacturing is a great option for part construction, as it is indicated for complex organic geometries.

The path to be taken to optimize a part must always take into account where it will be applied, prioritizing the application of the part, for example, the gear model used has a great lack of symmetry, so this characteristic must be prioritized in the process, as well as the places where the mass removals will be made and the places that should not be modified, all this depends on the application and the location of the part.

It is important to note that the geometry obtained in this process can vary according to the desired application or even the required design, other manufacturing processes can be applied leaving the surfaces more polygonal in order to use some processes and more economical machinery, topological optimization shows where the mass of a part can be removed, the final design is an option of the designer.

It is also important to know which parts can or should be optimized in a large system, since fatigue and vibration analysis also needs to be carried out after the final geometry has been obtained. This can be applied in a future project seeking to develop a generative design with the aid of topological optimization.

4. CONCLUSIONS

Therefore, structural optimization is a fundamental tool for mechanical engineering, allowing to create lighter, stronger and more economical components and systems, in addition to reducing costs and production time. The optimization process can be achieved through several techniques, such as computer-aided engineering, finite element method simulation and topological optimization. The case study presented in this text, which involves the optimization of a cylindrical spur gear for power transmission, achieved the desired results by reducing the mass of the final part by 70% and consequently the amount of raw material required for its production, this case study illustrates the practical application of these techniques and highlights the importance of computational modeling to validate the optimization process and determine the most appropriate manufacturing process. In the context of an increasingly competitive market, structural optimization is an essential tool to ensure the efficiency and safety of mechanical systems, while seeking to reduce costs and environmental impacts.

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