An integrated approach of topological optimization with parametric validation and response surfaces, using ANSYS®

A B Bodog[1,2] and G Grebenişan[1]

[1]University of Oradea, Managerial and Technological Engineering Faculty, Industrial Engineering Department, 1- Universitatii street, CP-410087, Oradea, România

[2]Email: bodog.bianca@gmail.com

Abstract. In industrial engineering practice, the use of cutting tools, or those of plastic deformation (dies), is known, involves high costs of materials, and requires, at the same time, conditions of high resistance to deformation. The reduction of the mass of the parts, ie the reduction of the costs with the materials, from the composition of the tools, at the same time with the constant maintenance, or, if possible, with the increase of the rigidity, which, in turn, is identical with the decrease of the metallic materials. when trying to optimize the shape of mechanical parts. To evaluate and to study the behavior of a plate material, also, elastic deformation of a tool component part, a specialized Computer Aided Engineering (CAE) software, Ansys Academic R22, was used. The load was applied to the holes contour of the plate to simulate "action" which determines the generation of permanent plate deformation.The boundary conditions, i.e. the fixed supports, are materialized in the lateral face of the piece and the upper edge of the opposite face. Both the applied load and the limit conditions simulate real situations from industrial practice.

1. Introduction

Optimization is the activity that achieves the best results in certain given circumstances. The purpose of this study, as is the case of the two types of optimization, parameterized and topological, which we use in this combined analysis, is to find approaches to minimize costs and efforts to achieve a feasible goal, respectively to obtain results proposed with maximizing the desired benefits. Economic development, in particular, we refer here to the processing industrial practice in the mechanical field, have registered, in the last decades, remarkable advances in terms of technological advancement, and the emergence and proliferation, at the same time, of various optimization techniques and algorithms. immediate applicability, have led to the efficiency of methods for solving different types of problems of mathematical programming, shape optimization, or parameterized optimization. All these positive developments have generated techniques, methods, algorithms that have led to the emergence of another branch of goal-based optimization, namely gave rise to structural optimization, which is aimed at solving optimal problems of efficient use of materials to create structures. reliable, made of components with valid characteristics according to the projects and which allow modifications of the geometric parameters, in the conditions of reducing the consumption of expensive materials, for tools, modification of the state variables so that the solution found is the optimal one, which admits the fulfillment of at least a criterion (objective function) and which must satisfy a set of functional and cost requirements (constraints) [1], [2]. Topological optimization of mechanical structures is a process of determining the most efficient geometric shape of the part. The optimized shape of the part results from the application of optimization criteria [3]. Structural optimization has been divided into three categories which are based on the variables involved. Optimization, in general, in the case of projects or the sizing of the components of a project, cross-sections or equivalent cross-sectional characteristic dimensions (cross-thickness) are taken into account as state variables, while in shape optimization, topological optimization, or parameterized, parameters and variables are directly responsible for the structural changes of the initial geometry of the part. Topological optimization often uses variables that bring dimensional or topological changes to the part, as a result of the distribution of deformation resistance, remaining, highlighted by the analysis of the Static Structural system [2].

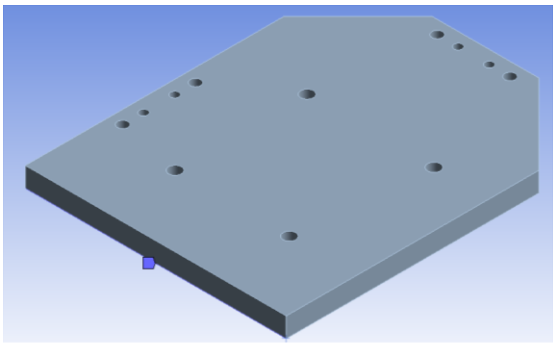
In this article we focused on the development of a combined analysis, in order to optimize the topology of an active plate in the composition of a plastic deformation mold, with the validation of the geometry obtained after optimization. Using Ansys Academic Release R22, the entire structural analysis-topological optimization-geometry validation-parametric optimization procedure was performed through the Design of Experiments (DOE) module. The behavior of the part in a Static Structural system was analyzed (the results being Total deformation and Equivalent Stress von Misses) and the life of the part, respectively the safety factor). With the necessary settings for re-configuring the part, in the SpaceClaim CAD system, specialized software, component of ANSYS, an approximate, technological sketch was obtained, the dimensions of which were modified by the Structural Optimization system, so as to respect the loading conditions. boundary conditions. The geometry obtained, following the optimization, was the starting point in the structural analysis for validating the state variables of the pre-optimization system, establishing and defining the output variables (parameters) (in SpaceClaim-output variables (parameters), being linear dimensions), respectively in Mechanical Model (output parameters: part mass and Total deformation). These parameters (input and output parameters) are used to find the design points space in order to generate a Response Surfaces, and to optimize the project, based on Candidate Points, so that, following the analytical determinations, could make the decision on the proposed issue: what is the best design point for getting the best project? (under the conditions: lightest (minimum mass); most rigid (minimum compliance and total deformation less than the maximum initial value, before optimization obtained) [4] [5].The final model resulting from the iterative optimization process must meet the conditions and restrictions imposed on the operation of the final product. Among the existing methods of structure optimization that are used so far are topological optimization and topographic optimization. By using topological optimization, it is possible to reduce the volume of the material and increase the rigidity of the optimized model.

2. Information about the part

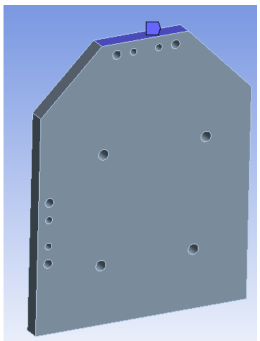
The plate made for the case study has a thickness of 19 mm and is made of structural steel. Limit and loading conditions are specified as follows: on each hole is applied a force of 1100N, 1120N. And the fixed support is placed on the face and the edge marked in Figure 1.

Table 1. The geometry dimensions and the part material

Direction	Measured value (mm)	Volume calc. (mm^3)	The material
x	250	1520000	Structural Steel
y	19		
z	320		



a). Fixed support-edge



b). Fixed support-face

Figure.1 Fixed supports

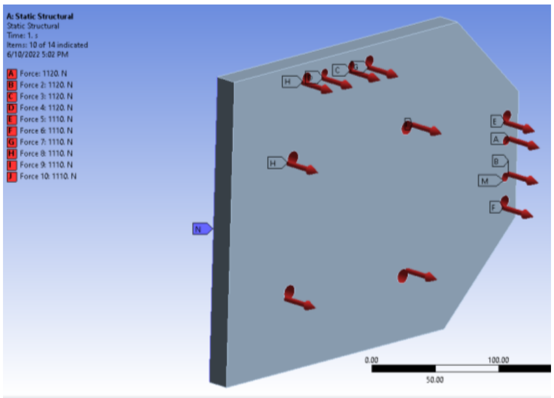


Figure 2. Forces applied on the plate

In the optimization process, the geometry of the model is taken over and discretized into finite elements by using Ansys R22. The model is discretized into 14670 nodes and 8021 finite elements.

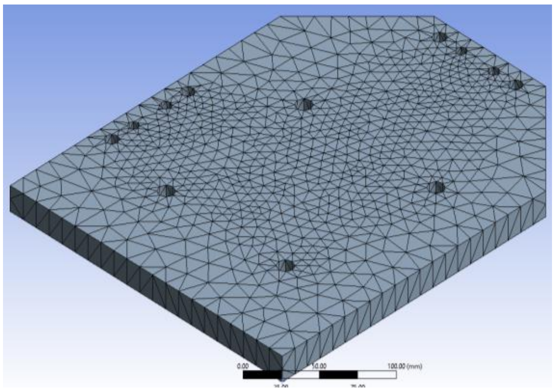
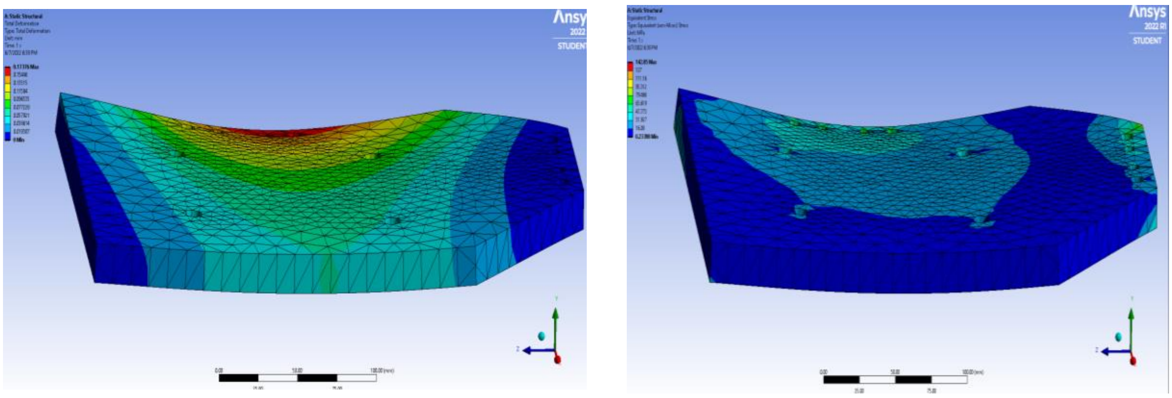


Figure 3. Mesh discretization

Using Ansys-Workbench features (a Static Structural Analysis was accomplished) and obtained the following results: the maximum of total deformation value, plastic deformation, is of 0.173 mm, and the maximum equivalent stress value is 142.85 MPa, Figure 4.



a)- Total deformation (mm) b)-The von Mises Equivalent Stress (MPa)

Figure 4. Static Structural Analysis Results

3. **Topological optimization**

The main goal of topological optimization is to solve the PDE problem and find the best solution to rational and efficient use of the material of the plate in the given loading state. In this process, the geometry of the plate is discretized in finite elements. The system Structural Optimization was connected over the Solution tab of Static Structural Analysis System:

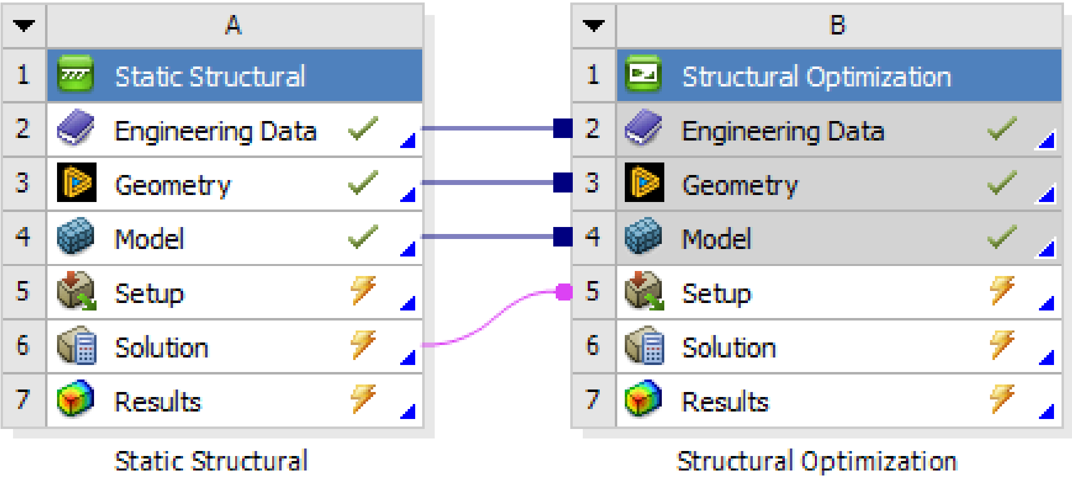


Figure 5. Structural Optimization

3.1 Defining the problem of shape optimization

If we can consider a known limited domain $\Omega \subset R^d$ (where d $\epsilon\{2,3\}$). To solve the PDE problem, that is, to provide an optimal solution for the mathematical model, means to find a subspace ω ⊂ Ω that minimizes the objective function J, which is function of ω. One can create an equation of general form [7]:

$$\min_{\omega \epsilon U_{ad}} J(\omega) \quad (1)$$

where Uad is the subdomain reunion of admissible forms between subdomains belonging of Ω. The optimization procedure may contains constraints, defined by user. The objective function, J, as function of ω by solving an equation (PDE), or a system of PDE equation. It is obvious that establishing the cost function, J, also the set of admissible subdomains values (including constraints) is obviously important.

Mathematical theorists usually propose common objective functions (this is because of their valuable properties, rather than their fidelity for solving the PDE problem or, generaly for the applications), while real the applications expects complicated and not realy common approaches, for this reason the objective functions are no quite simple nor very approachable. A few examples of such constraints can be: maximum admissible local stress, the safety factor, service life, minimum curvature radii, cooling of the molded / injected part in a shorter or longer time than that given, etc. Some of them are even difficult to solve or difficult to be affordable mathematically, in a common way (as example can be given here the constraints related to the casting process) and can make it impossible to solve or require to solve additional complex problems [8], [9].

3.2 Objective functions

Compliance, is the measure of rigidity, in the sense of the following sentence from physics: "The inverse of the stiffness defines the compliance of the elastic element."

$$J(\omega) = \int_{\Omega} \chi(x) Ac(u): e(u) dx = \int_{\Omega} A^{-1}\sigma: dx = \int_{\partial\Omega} f \cdot u dx = c(\omega) \quad (2)$$

Cost function belonging on stress [7]:

$$J(\omega) = \int_{\Omega} |\sigma|^p \quad (3)$$

or the equivalent Von Mises stress. In this study, we used the distribution of the Von Mises stresses, which can be analyzed in the ANSYS-Mechanical Model, [10], [11].

The optimized range (surface, volume of a part) is discretized with finite elements and then the conditions are applied to the limit and loads. By topological optimization, it is desired to determine the optimal shape with percent of retaining 50% in the initial volume, shown in Figure 6, where, a certain stage of the process of material retain, from the area of resistance to deformation (von Mises equivalent stress), is presented:

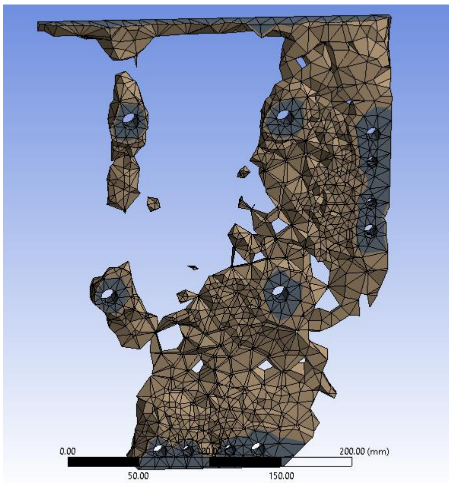


Figure 6. Topology density
(almost final stage)

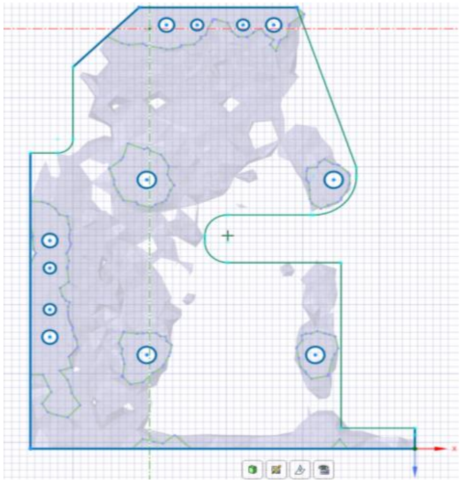


Figure 7. Sketch of the optimization plate
(green colour line)

In Mechanical mode, the Mesh command is executed, through this command a simple discretization with 36094 nodes and 7204 finite elements is obtained.

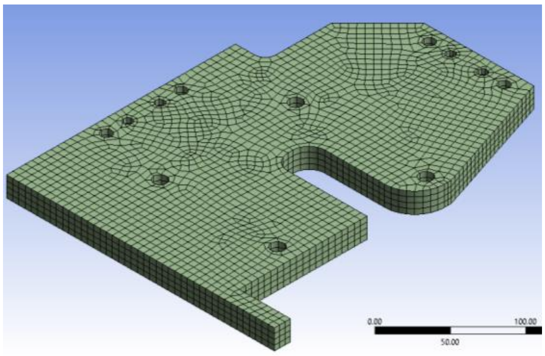


Figure 8. Mesh structure

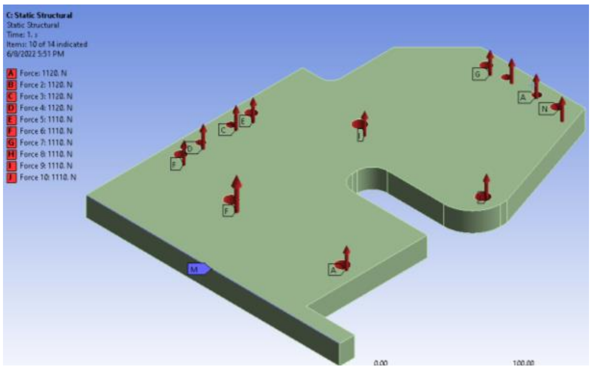


Figure 9. Limit and load condition

After the optimization procedure is accomplished, the upper solution value by total deformation is 0.198 (mm). Upper value of equivalent stress, after the optimization accomplished, 216.22 (Mpa).

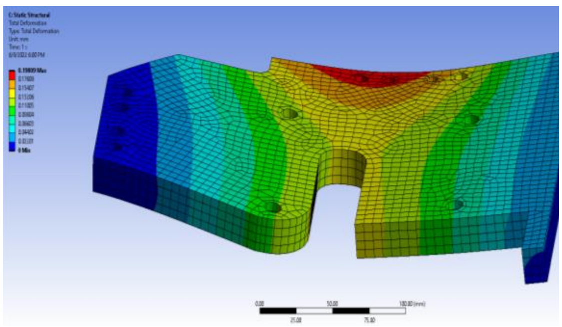


Figure 10. The total deformation

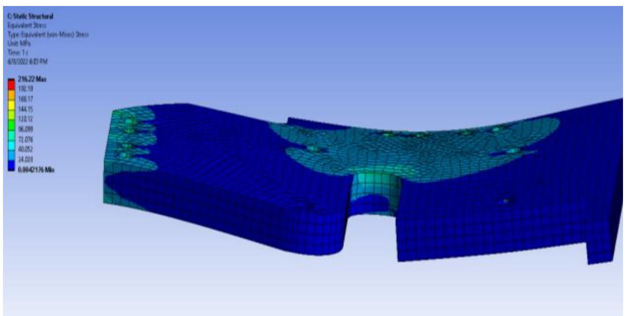
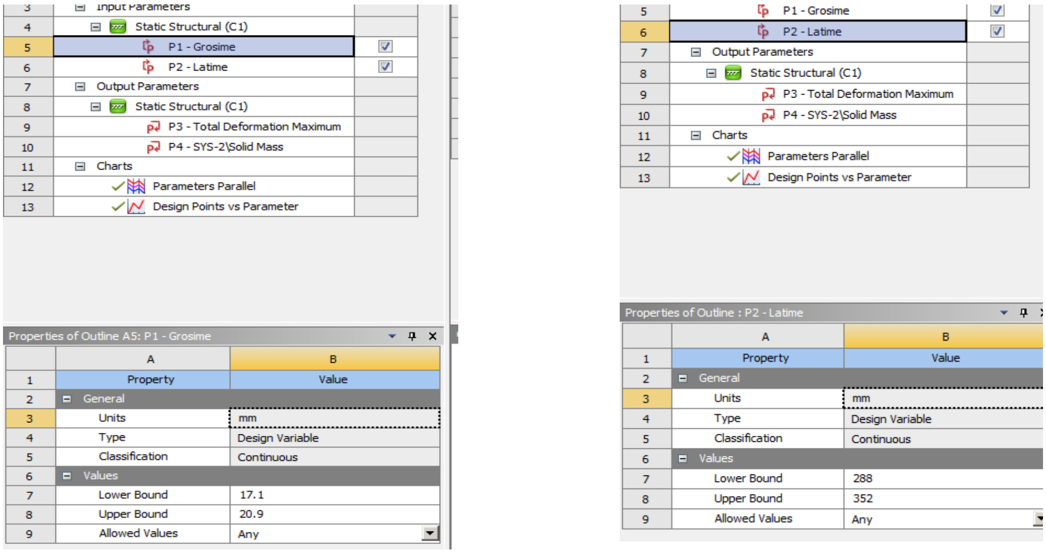


Figure 11. The von Misses- quivalent stress

4. **Parametric optimization**

4.1 Parameters Set

After the finite element analysis and topological optimization has been done, parametric optimization is performed. The start point for this optimization is the values for the input variables (parameters) and output parameters. Input variables (parameters): the plate thickness (19mm, with inferior and superior limits established by user) and the width (250mm, where the inferior and superior limits are established by user). Output parameters are the maximum of total deformation and minimum of mass [6], [12].



a. Input variables (parameters) -thickness b. Input variables (parameters)- width

Figure 12. Setting lower and upper bounds of the input parameters

4.2 Response surfaces

Response surfaces are, according to properties and features, functions defined by the nature of the output parameters which, in turn, are defined as a function of the Input variables (parameters). Constructed using DOE, these response surfaces approximate values of output variables, Figure 13.

Any type of response area (graphics) is generated by the different algorithms. The following algorithm variants can be selected by the user: Genetic Aggregation (default); Full second-Degree Polynomials; Kriging; Neural Network; Sparse Mesh (Grid).

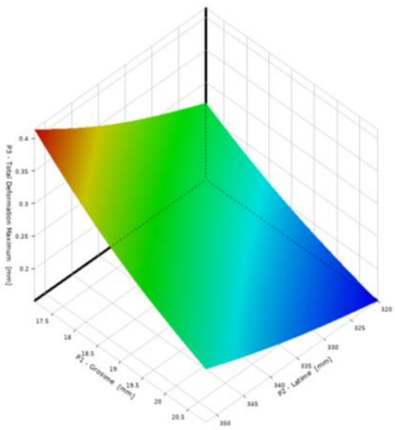


Figure 13. The Response surface (plate thickness 19 mm)

4.3 Candidate points

After the optimization goals are declared and three candidate points are determined too, the Table panel in the Optimization system shows the candidate points. These candidate points may be inserted as a start for a new design or verification points. The options affordable depends on the type of current optimization, Figure 14:

Table of Schematic D4: Optimization , Candidate Points

	A	B	C	D	E	F	G	H
1	Reference	Name	P1 - Grosime (mm)	P2 - Latime (mm)	P3 - Total Deformation Maximum (mm)		P4 - SYS-2\Solid Mass (kg)	
2					Parameter Value	Variation from Reference	Parameter Value	Variation from Reference
3	◉	Candidate Point 1	19.29	320.15	★★★ 0.18998	0.00%	✕✕ 8.6216	0.00%
4	○	Candidate Point 2	19.503	321.9	★★★ 0.18827	-0.90%	✕✕ 8.7438	1.42%
5	○	Candidate Point 3	19.639	323.59	★★★ 0.18858	-0.74%	✕✕ 8.8308	2.43%
*		*New Custom Candidate Point*	*19*	*336*				

Figure 14. Candidate points

The local sensitivity graphs allow the analysis and visualization of the continuous effect of input variables (parameters) over the output variables. At the level of the response area (surface), the sensibility graphs is "functions" with a single parameter, Figure 15. This means that the Design of Experiments determines the modification of the output parameters taking into account the modification of the independent inputs, at the current input parameter value.

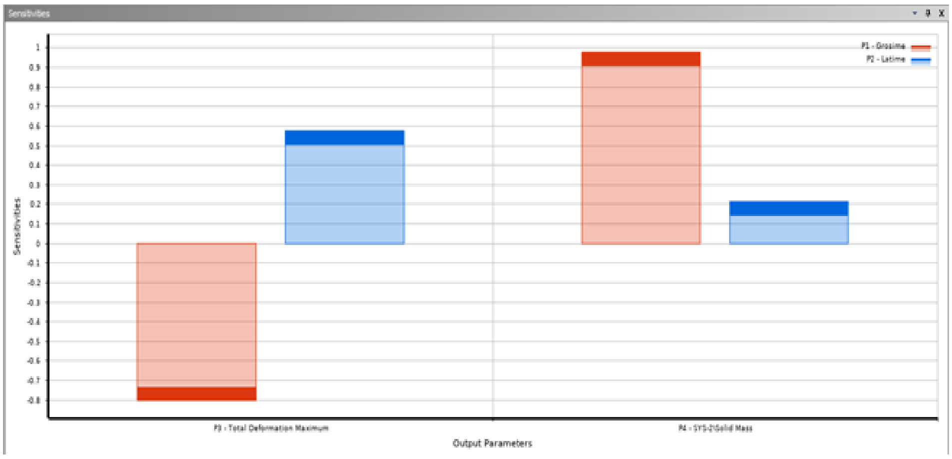


Figure 15. The local sensitivity of output parameters on inut variables (parameters)

The greater the changes in the values of output variables (parameters), the more significant gets the role of the input variables (parameters) is. Such as, the sensitivities of a single parameter are local sensitivities [12].

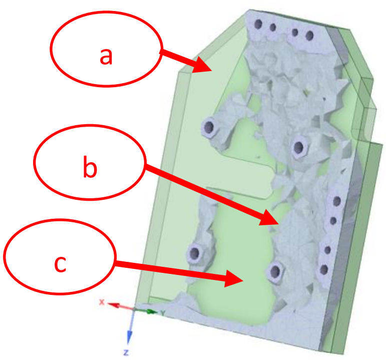


Figure 16. Three geometry models:
a- initial geometry (light green colour),
b-topological optimization (unprocessed, roughly state, gray color),
c- topological and parameterized optimization (middle plane, full green colour)

5. Conclusion

The main goal of topological optimization is to solve the PDE problem and find the best solution to rational and efficient use of the material of the plate in the given loading state. Areas that contribute less to functionality and support higher values of stress are excluded from the initial geometry through changes in the geometry of the part respecting the distribution of equivalent stress with the purpose to minimize the mass. The plate presented for the case study has a thickness of 19 mm and the material is Structural Steel. To get an optimal plate, was needed to observe the performance of the plate material when forces act on it and observe which areas are more affected, and this goal was reached after a Static Structural analysis results were accomplished, by the Finite Element Method (FEM) . To obtain an optimal solution, by parameterized or topological optimization, for a part of the tool construction, of any type, it is essential to be able to define the objective function (in the case of this paper minimizing the mass of material, necessary to ensure the operating conditions, respectively ensuring that the maximum of total deformation is not exceeded).

Usually, topological optimization is made before geometrical optimization. After the objective function has been defined and the restrictions have been established, the optimization procedure analyzes the results for von Mises equivalent stress, in discretized mesh and eliminates, from close to close, iteratively, elements that are not necessary for the proposed purpose, and the values corresponding to the finite elements are large, or the largest. The distribution of the material is related to boundary conditions, load direction, or a system of loads. Static structural analysis revealed that the maximum value of the total deformation is 0.173 mm. Also, the maximum value of the von Mises equivalent stress is 142.85 MPa. After the optimization procedure is accomplished, the upper value of the Total deformation is 0.198 mm. The upper value of equivalent stress, after optimization, is 216.22 MPa.The three candidate points obtained are shown in Figure 14. The first candidate point has the most insignificant variation from the reference (0.00%), and the candidate point # 2 has the weakest behavior, having the most unfavorable variations compared to the other two in the reference.Based on this analysis, after analyzing the results, the geometry of the plate changed, and its functionality was not affected.

References

[1] https://en.wikipedia.org/wiki/Elasticity_(physics), accessed on April-Mai-June 2022.
[2] G. M. Kakandikar et al., 2018, Sheet Metal Forming Optimization. Bioinspired Approaches, Taylor & Francis Group
[3] I. L. Scurtu, et al., Optimizarea topologică a structurilor în inginerie,
[4] H L Huei, 2017, Finite Element Simulations with ANSYS Workbench 17, SDC Publications
[5] C Xiaolin, et al., 2018, Finite Element Modeling and Simulation with ANSYS Workbench, Second Edition CRC Press
[6] D C Negrău, G Grebenişan, C Gherghea, 2019, An optimization approach by Finite Element Analysis, using Design of Experiments and Response Surfaces- a survey
[7] G. I. N. Rozvany, T. Lewiński, 2014, Topology Optimization in Structural and Continuum Mechanics, International Centre for Mechanical Sciences, Courses and Lectures, Vol. 549
[8] Luca Esposito, 2013, Topological Optimization Strategies In Multi-Physics Problems, PhD Thesis, University of Naples Federico II.
[9] R. H. Myers, et al., 2016, Response Surface Methodology, Process And Product Optimization Using Designed Experiments, Fourth Edition, John Wiley & Sons
[10] X. Huang, Y.M. Xie, 2010, Evolutionary Topology Optimization Of Continuum Structures, John Wiley &Sons
[11] J Antony, 2003, Design of Experiments for Engineers and Scientists, Elsevier Science & Technology Books
[12] https://www.ansys.com/resource-center/webinar/combining-parametric-modeling-with-design-exploration, accessed on April-Mai-June 2022.