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TOPOLOGY OPTIMIZATION AS A DESIGN TOOL - AN INDUSTRIAL EXAMPLE OF SPRAY TANK BRACKET

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Abstract: The paper presents the issues of structure optimization. The introduction discusses the matters important when designing the new structures and the need to develop solutions that are better than the existing ones. In the next part, the focus is on explaining the concept of optimization in terms of mathematics and finally referring to the practical application of optimization in structure designing in example of the bracket using the SolidWorks software which uses the solid isotropic material with penalization (SIMP) method.The results of numerical analyzes present optimization process, which made it possible to obtain a solution that is both lighter and more durable than existing one used in the prototype. The conclusions focus mainly on the observed limitations and problems resulting from applied optimization method.

Key words: *Optimization, Structural optimization, Topology optimization, Agriculture robot, Solid Isotropic Material Penalization (SIMP) method, SolidWorks simulation.*

1. INTRODUCTION

Designing machines is a complex process that requires the designer to have comprehensive knowledge from many different engineering fields. During this process, in an appropriate manner, on the basis of the adopted criteria, certain design features are assigned to the structure that enable the final recording of the construction results in the form of design documentation. The criteria to be considered while designing are relate to various aspects: construction (i.e., the adoption of the correct load transfer system, ensuring adequate strength and stiffness), technological (manufacturing processability, cheapness, availability of materials, ease of assembly) and operational (ensuring functionality, ergonomics, reliability, durability, efficiency, ease of use and repairability). The security issues, which have already been indirectly mentioned and which are in fact one of the most important criteria, should broaden list of aspects. Health and life of users must not be put at risk while operating the device. Aesthetic issues, which also have a significant impact on the purchase of a given structure by a potential customer, are also becoming important from a marketing point of view. While maintaining similar parameters (e.g., efficiency) considered when purchasing products and meeting the same customer needs, the price has the greatest impact on the decision to buy a product, and therefore the possibility of reduction of production costs is quite an important problem that should be taken into account when designing. Reductions of these costs can be achieved, for example, by minimizing the weight of the structure, which additionally reduces the cost of its operation by reducing the energy consumption of the given movements by specific parts, but one should take into account at least sufficient strength, hence the need to find the best result in given conditions is important. Finding the best result under given conditions, assessed in terms of the adopted criteria, is called optimization. The article presents a new approach to structure design (compared to conventional methods) using a shortened and automated process of decomposing material with specific properties in a certain space defined and acceptable by the designer.

The subject matter of the article thus fits in the current trend related to the algorithmization of the process of designing structures using the capabilities of modern computers, which will be sufficiently durable using the minimum amount of material necessary for their production, which is discussed in many articles from related magazines.

2. OPTIMIZATION IN STRUCTURE DESIGN

From the mathematical point of view, according to the classical definition, optimization is the search for the extremes of a function. This means that a minimum or maximum of a function (or in the broader functional context) of many variables should be found for the values of these variables included in a specific set of feasible solutions (decisions). A graphical representation of the mathematical optimization model presents figure 1.

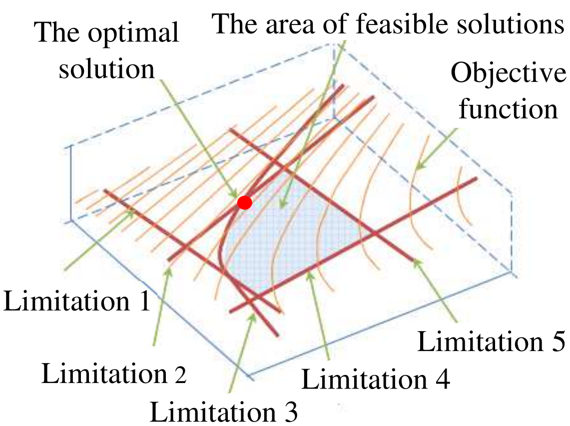


Fig. 1. Graphical representation of the mathematical optimization model

According to Ostwald [1], in real technical issues, both the minimized objective function (functional) and the various constraints imposed on it are defined by means of very complex relations, often with a complex structure and not always with the use of the formalized language of mathematics. Hence, according to the statement "what is simple for humans is difficult for computers and vice versa, what is simple for computers is difficult for humans", on the basis of algorithms developed by distinguished scientists many optimization procedures were created, which by using a computer (and its computing power) were applied to the process of designing machine elements, thus defining the optimization of the structure. It concerns issues related to the appropriate selection of shape parameters (geometric dimensions) and physical properties (mainly mechanical properties) of broadly understood structures, so as to enable them to transfer the load F located somewhere in space to the support in the best possible way - of course in terms of the selected function target (Fig. 2.).

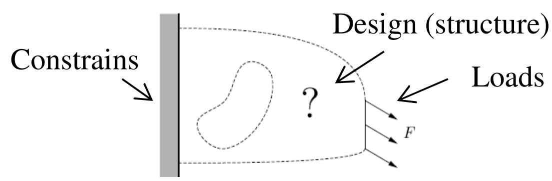


Fig. 2. General problem to be solved in structure optimization [2]

Three basic types can be distinguished while analyzing the literature related to structure optimization (Fig. 3.): size, shape and topological optimization. Assuming that the optimized structure will be a truss, the dimensional optimization is related only to the appropriate selection of the thickness of the cross-sections of its bars, without modifying their spatial position in relation to the original design. In the case of shape optimization, the length and position of the bars and the nodes connecting them in space may change with the same cross-sections of the bars in relation to the original design. However, when the shape optimization concerns only a single truss bar, its cross-section is modified by an appropriate change of the contour over the entire original length unchanged in relation to the design. Topology optimization is the most general form of structure optimization, in the analyzed case, assuming the cross-sectional areas of the truss bars as decision variables, they are assigned the values 1 or 0, which means that the given bars remain in the structure or are completely removed from it.

The analyzed case of a discrete structure (a truss divided into bars connected with each other in nodes) can be easily related to continuous structures which, by using numerical methods, enable their division into discrete elements.

Although there are many different methods for numerical structure optimization, those based on the finite element method (FEM) appear to be the most practical and have become the most common tool for optimization of engineering structures.

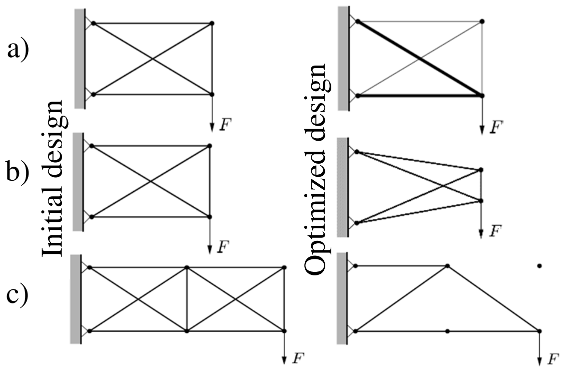


Fig. 3. Types of structure optimization: a) size; b) shape; c) topology [2]

3. TOPOLOGY OPTIMIZATION IN THE SOLIDWORKS ENVIRONMENT

The rest of the article focuses mainly on the practical application of topology optimization, in particular on its Generalized Shape Optimization (GSO) subcategory using the Solid Works software for this purpose, using the method of solid isotropic material with penalization (SIMP). The SIMP method, which operating principle follows a strictly defined algorithm (Fig. 4.), is used to optimize the topology of the isotropic material continuum, in which the optimization is performed within a strictly defined design area Ω discretized into a finite element network called isotropic solid microstructures [3,4]. This means that the considered medium is treated as continuous throughout the design space and, at the same time as discrete, treating each finite element as a material point with separate material properties.

The most important parameter defined at the beginning of the analysis is the size of the available mass m_0, which is determined by the reduction factor α of the original mass m (with density ρ and modulus of elasticity E) completely filling the area Ω with a known volume V, hence, according to [5]:

$$\begin{cases} m_0 = \alpha \cdot m \\ m = V \cdot \rho \end{cases} \quad (1)$$

where $\alpha \epsilon (0,1)$.

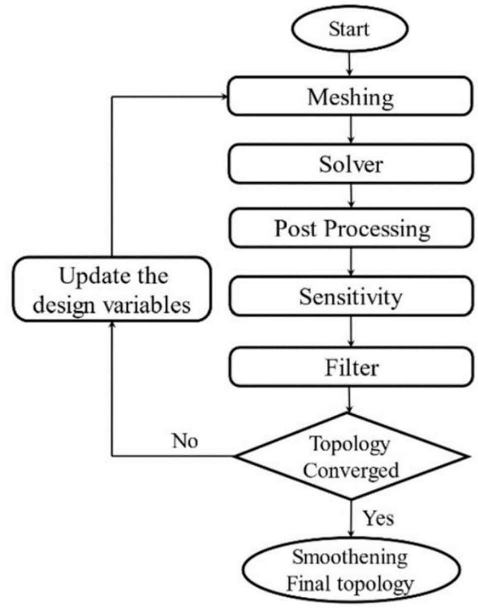


Fig. 4. Scheme of topology optimization using the SIMP method [4]

At the beginning of the analysis, a random distribution of the material is dealt with, in which two areas can be distinguished: with the density of the material accepted for analysis and with a density of 0 (Fig. 5. a). To ensure the possibility of obtaining a solution, it is necessary to change the nature of the considered problem to a continuous one, therefore, in the next step, homogenization of the available mass m_0 is used, resulting in homogenization of the entire considered area Ω, filling it with diluted material with a constant density ρ_0 (Fig. 5. b). Then the optimization algorithm in the next j-th calculation steps (successive iterations) eliminates the material from some space elements and transfers it to others (Fig. 5. c). The elements from which the material has been eliminated are in fact filled with a very flaccid material, so in the final stage of the optimization process, the material contained in these elements becomes relatively weak enough that from the physical point of view it can be treated as non-existent [5]. Assuming the density threshold value for which a given element will be treated as negligible, it is possible to finally (binary) present the solution of the optimized structure (Fig. 5. d).

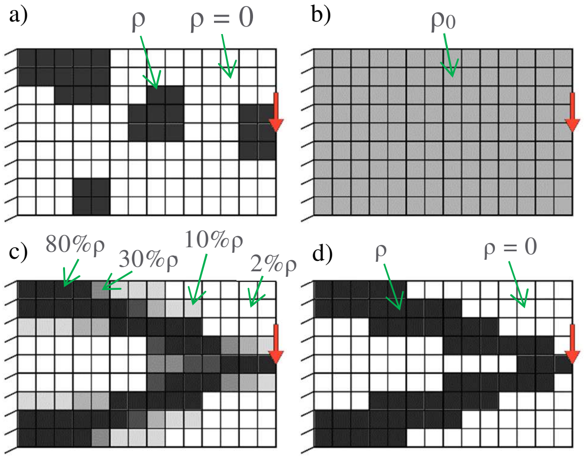


Fig. 5. Successive steps of topology optimization using the SIMP method for a 2-dimensional problem: a) random mass distribution; b) homogenization; c) mass transfer between elements in successive iteration steps; d) final result - optimal topology

In the SIMP method, a properly defined updated Young's modulus was used in individual elements (E_e), linking its value with the value of the adopted density of individual elements ρ_e expressed as a percentage of the density of the original mass and the penalty factor p, therefore, according to [6]:

$$E_e(\rho_e)=\rho_e^p \cdot E \quad (2)$$

where: e - number of the next finite element, e = 1, 2, ... n (n - number of elements in the project domain).

The use of the penalty factor reduces the impact of elements with intermediate densities in subsequent iterations and directs the analysis to the final solution. Many studies, including [4,6], show that the value of the penalty coefficient equal to 3 in engineering applications allows to obtain satisfactory calculation results (Fig. 6.). Reducing the Young's modulus of a given element e also reduces its stiffness. The global stiffness matrix calculated in the next j-th iteration steps is the sum of the stiffnesses of individual elements and is determined from the formula [6]:

$$K^j=\sum_{e=1}^{n}[\rho_{min}+(1-\rho_{min})\rho_e^p]K_e \quad (3)$$

where: K_e - element e stiffness matrix; ρ_{min} - minimum relative density adopted in the analysis.

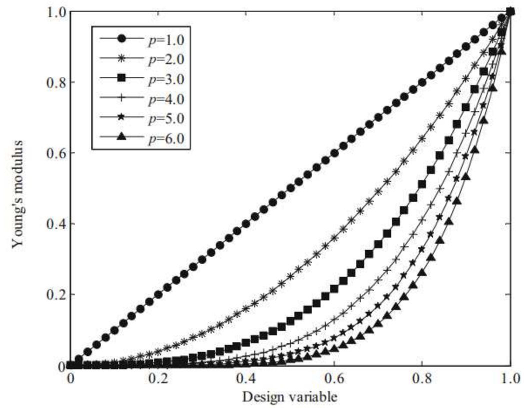


Fig. 6. SIMP interpolation curves with different penalty factors [7]

The SIMP method is a gradient method of searching for an optimal solution, which can be mathematically expressed as the search for an ideal distribution of full and empty elements (Fig. 5. d), so as to minimize the global compliance, which is equal to the sum of the elastic energies or stresses. Due to the fact that compliance is defined as the inverse of stiffness, minimizing global compliance C is equivalent to maximizing global stiffness [8-10], hence, according to [6]:

$$\min C(\rho)=\sum_{e=1}^{n}\rho_e^p[u_e]^T[K_e]\,[u_e] \quad (4)$$

where: $[u_e]$ - nodal displacement vector of element e.

At the same time, for the next steps of the analysis, while searching for the minimum value of the compliance functional, the relation between the available mass declared at the beginning is maintained [6]:

$$\sum_{e=1}^{n}\{V_e\}^T\rho_e \leq m_0 \quad (5)$$

where: V_e - volume of element e.

During successive quasi-static calculations in which the global stiffness matrix is modulated with the vector of relative densities, the optimization algorithm performs a sensitivity analysis to assess the effect of changing the material density on the defined objective function and to maximize the stiffness. The sensitivity analysis is expressed as the derivative of the objective function with respect to the material density, hence according to [6]:

$$\frac{dC}{d\rho_e} = -p(\rho_e)^{p-1}[u_e]^T[K_e][u_e] \quad (6)$$

During the sensitivity analysis, elements weighted with low material density factors eventually lose their structural significance and are eliminated in subsequent iterations. When the sensitivity for each element is calculated independently, without taking into account the connection between the elements, the result may be a discontinuity in the material and a lack of connection between the volume and the main geometry (the so-called checkerboard effect). In order to limit the checkerboard effect, the filtering process uses the element influence radius and averages the sensitivity of each element within its influence area [11]. Optimization iterations continue until the objective function changes converge and the iterations meet the convergence criteria.

4. EXAMPLE OF TOPOLOGY OPTIMIZATION OF A FIELD ROBOT SPRAY TANK BRACKET

As an example of using topology optimization as a design tool in the SolidWorks Simulation environment, it was decided to optimize the existing bracket (Fig. 7.), thus enabling the development of a new version, better in selected aspects.

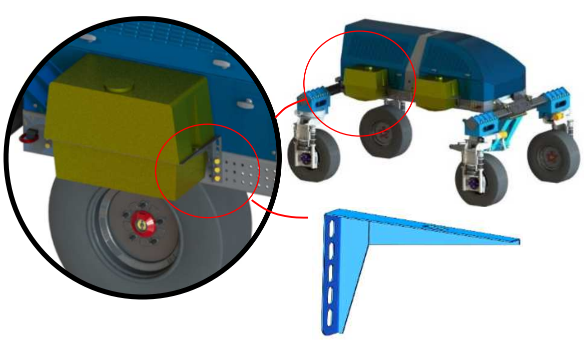


Fig. 7. Selected element - Agrorob intelligent platform bracket, subjected to topology optimization analysis

Based on the overall dimensions of the existing solution geometry, the simulation has declared the permissible design space for the new version of the bracket, taking into account (as in the original bracket) the possibility of fixing it with elongated holes. Then, the defined space was discretized into a network of finite elements, which were given specific mechanical parameters by assigning them to the material: S355J0 steel (Table 1). In the next step, certain boundary conditions were defined: support in the form of a stationary geometry of the internal surfaces of all elongated holes and the load applied to the upper surface of the support (Fig. 8.), on which a 60-liter tank rests in the form of a force of 425 N, which results from the assumed maximum accelerations affecting the vehicle while moving.

Table 1

Main strength properties of S355J0 steel

Property	Value
Modulus of elasticity	2.1e+11 N/m^2
Poisson ratio	0.28
Shear stress factor	7.9e+10
Specific mass	7800
Tensile strength	4.5e+8
Yield point	275 MPa

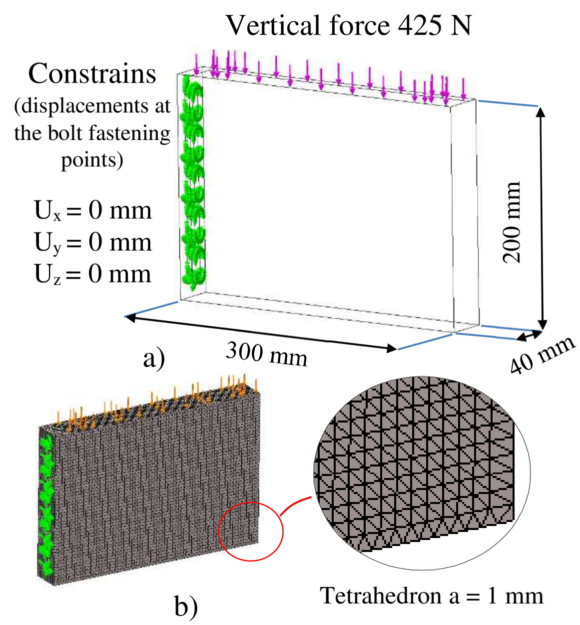
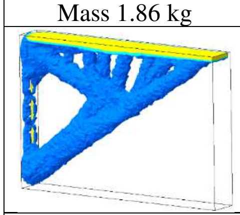
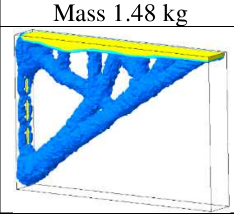
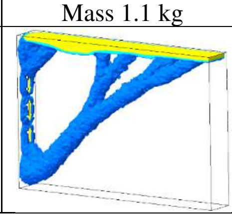
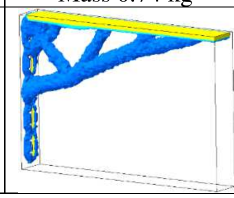
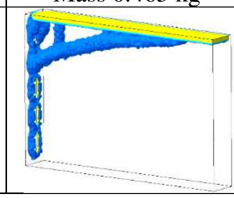
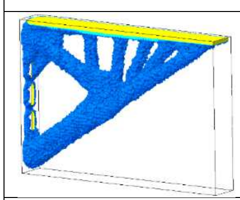
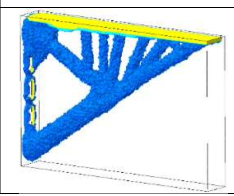
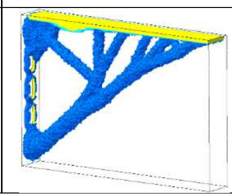
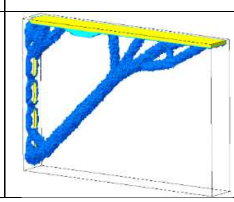
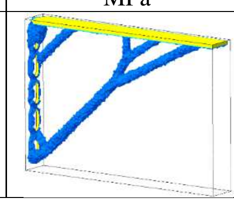
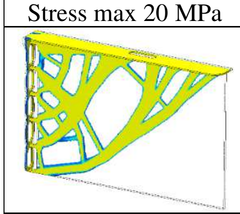
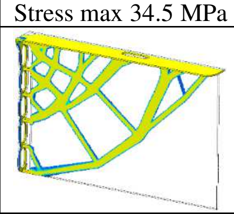
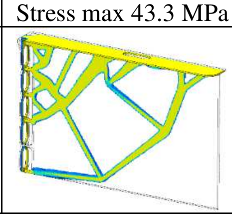
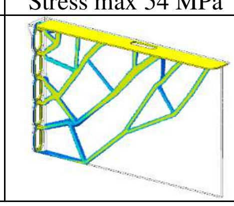
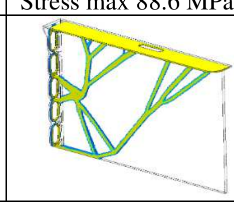


Fig. 8. The adopted analysis conditions: a) the space in which the target solution will be located and the boundary conditions (element support and the given load); b) discretized analysis space into a finite element network

For the simulation conditions defined in this way, the next step was to adopt the objective function consisting in determining the best stiffness of the bracket for the declared available mass of the element. Subsequent analyzes for the adopted mass reduction factor α from 90% to 97.5% maximally filling the allowable design area, made it possible to determine the optimal shapes (Table 2; points a-e). Analyzing the results, it can be concluded that for such declared conditions - assuming only the maximization of stiffness, the analysis allows to generate the optimal shape even with a mass reduction of over 99%. However, such a solution will not meet the strength conditions, hence the first important conclusion is that such maximization or minimization cannot be performed without any limitations, hence there is a need to introduce an additional criterion for assessing the structure. The criteria that are usually used as constraints in design optimization problems are mainly stresses and displacements, therefore the subsequent results (Table 2; points f-j) also take into account the allowable reduced stress that may occur in a single finite element of 0.8 R_e (yield stress).

Table 2

The shape of the bracket structure for the assumed objective function and constraints

<table>
<tr><td colspan="5">Objective function: best stiffness to mass ratio. Adopted limitation: mass reduction</td></tr>
<tr><td>a)
Weight reduction
90%
Mass 1.86 kg</td><td>b)
Weight reduction
92%
Mass 1.48 kg</td><td>c)
Weight reduction
94%
Mass 1.1 kg</td><td>d)
Weight reduction
96%
Mass 0.74 kg</td><td>e)
Weight reduction
97.5%
Mass 0.465 kg</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Objective function: best rigidity. Adopted limitations: weight reduction and maximum stress 0.8 R_e</td></tr>
<tr><td>f)
Weight reduction
90%
Mass 1.86 kg
Stress max 1 MPa</td><td>g)
Weight reduction
92%
Mass 1.49 kg
Stress max 1.4 MPa</td><td>h)
Weight reduction
94%
Mass 1.1 kg
Stress max 24.5 MPa</td><td>i)
Weight reduction
96%
Mass 0.74 kg
Stress max 54.9 MPa</td><td>j)
Weight reduction
97.5%
Mass 0.465 kg
Stress max 123.3 MPa</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Objective function: best rigidity. Adopted limitations: mass reduction, maximum thickness of elements 4 mm, maximum stress 0.8 R_e</td></tr>
<tr><td>k)
Weight reduction
45%
Mass 0.569 kg
Stress max 20 MPa</td><td>l)
Weight reduction
60%
Mass 0.417 kg
Stress max 34.5 MPa</td><td>m)
Weight reduction
63%
Mass 0.379 kg
Stress max 43.3 MPa</td><td>n)
Weight reduction
72%
Mass 0.285 kg
Stress max 54 MPa</td><td>o)
Weight reduction
74%
Mass 0.266 kg
Stress max 88.6 MPa</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
</table>

The optimal design of a given part (structural part) is often not intuitive and usually involves complex and space-limited shapes. Topology optimization algorithms do not take into account aspects such as aesthetics and design in terms of technology, violating common design principles (such as, for example, uniformity of thickness, use of standardized elements).

Therefore, the use of optimization topology works best for machine elements produced by incremental production processes (stereolithography, selective laser sintering, melt deposition, etc.) or also to some extent by casting and metal forming.

The serial production of the manufactured elements is also an important aspect. In the case of unit production, the use of foundry production methods and the need to make the mold beforehand may turn out to be much more expensive than making parts from ready-made semi-finished products in the form of profiles, plates and sheets as well as parts made by traditional machining methods. Moreover, such semi-finished products are produced in mass quantities under certain specific - controlled conditions, which affects the ability to accurately determine their strength. Therefore, the subsequent results (Table 2; points k-o) take into account technological limitations, which consisted in the possibility of placing the material in a space with a maximum thickness of 4 mm - imposing a bracket made of sheets of standard thicknesses ready on the market. In this way, a solution of the weight of 0.266 kg was obtained (table 2; point o), which made it possible to design the final version of the bracket (Fig. 9.), the mass of which is 0.320 kg and is 31% smaller and 17% more durable than the original bracket (comparing values of maximum stresses determined by quasisatic analysis for the same boundary conditions).

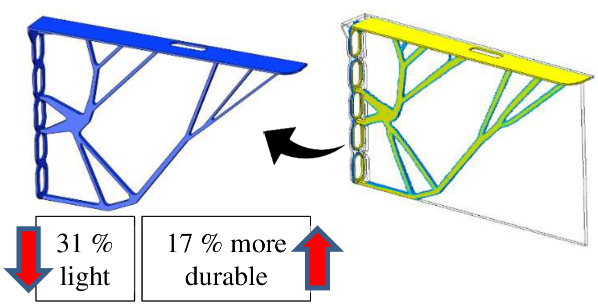


Fig. 9. Final version of the bracket

5. CONCLUSION

Topological optimization seems to be a great tool that allows designers to quickly design structures that are optimal in selected aspects. This article presents the results of the optimization of the virtual model of the spray tank bracket of the intelligent platform by the SIMP method, using the SolidWorks software. As a result of a series of simulations, the final bracket was both significantly lighter and more durable than the original version. The obtained solution is better than the original one, but due to the adopted analysis conditions, it does not mean that it is optimal. The computational solver used by the analysis in the SolidWorks environment is typically linear, in which the maximum value of the force that can act on the structure was used as an estimate of the acting load. In fact, the bracket is attached to the vehicle, on which dynamic loads act and vary in time and direction, therefore it is reasonable to take into account the dynamic properties of the entire structure using a non-linear analysis that also takes into account the decrease in material strength due to fatigue (Wohler curve). Moreover, the analyzed bracket has several possibilities of mounting to the robot's frame (for simplification all longitudinal holes were immobilized in the analysis), such a situation influences the change of the boundary conditions of the simulation, which results in obtaining different results of the analysis and obtaining other final structures.

Topology optimization methods drastically reduce engineering costs associated with new parts and product development by significantly reducing design process time. The automated process is capable of designing much better parts in a fraction of the time as an experienced team of designers could do. It should be noted, that Topological Optimization is only a numerical tool the use of which requires caution and experience.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Ostwald, M. *Fundamentals of structure optimization in system design.* (in Polish) PP, Poznań, 2016.

[2] Christensen, P.W., Klarbring, A. *An Introduction to Structural Optimization*. Springer 2009, https://doi.org/10.1007/978-1-4020-8666-3.

[3] Patyk, R., Kułakowska, A. *Topological optimization of the structure on the example of a universal joint shaft yoke. Buses. Technology, Exploitation, Transport Systems (in Polish)*. Instytut Naukowo-Wydawniczy "SPATIUM" Radom. Pp. 380-385. Ed. 5. 2012.

[4] Dara, A., Bahubalendruni, M., Mertens, A. *Does Topology Optimization Exist in Nature?* Natl. Acad. Sci. Lett. 45, 69–73, 2022, https://doi.org/10.1007/s40009-021-01050-1.

[5] Kutyłowski, R. *Optimization of material continuum topology* (*in Polish*). *Publishing House of the Wrocław University of Technology, Wrocław*, 2004.

[6] Solid Works helpdesk: Topology optimization using the SIMP method. Available at https://help.solidworks.com/HelpProducts .aspx (accessed 07.2022).

[7] Zhao, Q., Zhang, H., Zhang, T., Hua, Q., Yuan, L., Wang, W. *An Efficient Strategy for Non-probabilistic Reliability-Based Multi-material Topology Optimization with Evidence Theory.* Acta Mechanica Solida Sinica, 32(6), 2019, https://doi.org/10.1007/ s10338-019-00121-7.

[8] Antonova, V., Alekseev, S., Tarasov, A., Scheglova, N., Klyavin, O., Borovkov, A. *Analysis and use of SIMP method in optimization of a car hood design.* Internat. Sci. Conf. on Energy, Environmental and Construction Engineering, E3S Web of Conferences 140, 04017, 2019, https://doi.org/10.1051/e3sconf/20 1914004017.

[9] Rouhi, M. *Topology optimization of continuum structures using element exchange method.* A Thesis Submitted to the Faculty of Mississippi State University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Aerospace Engineering in the Department of Aerospace Engineering, Mississippi State, May, 2009.

[10] Sigmund, O. *Design of Material Structures using Topology Optimization*. Department of Mechanical Engineering/Solid Mechanics Technical University of Denmark. Lyngby, Denmark, 2005.

[11] Abbey, T. *Topology optimization*. available at https://www.digitalengineering247.com/article/ topology-optimization (accessed 07.2022).

OPTIMIZAREA TOPOLOGIEI CA INSTRUMENT DE PROIECTARE - UN EXEMPLU INDUSTRIAL DE SUPORT DE REZERVOR DE PULVERIZARE

Lucrarea prezintă problemele optimizării structurii. Introducerea discută aspectele importante la proiectarea noilor structuri şi necesitatea de a dezvolta soluţii mai bune decât cele existente. În partea următoare, accentul este pus pe explicarea conceptului de optimizare în termeni de matematică şi, în final, se face referire la aplicarea practică a optimizării în proiectarea structurii. Este prezentată utilizarea practică a optimizării topologiei pentru proiectarea structurii suportului rezervorului de pulverizare a robotului agricol utilizând software-ul Solid-Works în care softul de calcul utilizează metoda materialului izotrop solid cu penalizare (SIMP). Rezultatele analizelor numerice prezintă procesul de optimizare, care a făcut posibilă obţinerea unei soluţii mai uşoare şi mai durabile decât cea existentă utilizată în prototip. Concluziile se concentrează în principal pe limitările şi problemele observate rezultate din metoda de optimizare aplicată, a cărei utilizare poate avea ca rezultat obţinerea unei soluţii care nu trebuie să fie acceptabilă din cauza altor cerinţe.

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