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Article

Application of Advanced Design Methods of “Design for Additive Manufacturing” (DfAM) to the Process of Development of Components for Mobile Machines

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Abstract: The solved research problem is oriented to the implementation of advanced methods of component design and their sophisticated use in the ever-advancing additive manufacturing. Based on the stated objectives, the research was divided into several parts. Initially, the methods and principles of design in additive manufacturing were evaluated and investigated, from which the intent was subsequently defined and the DfAM method in the component design and development process was determined. The given design method, namely topology optimization (TO), was applied to multiple development and production cycles of additive manufacturing parts to validate the research conclusions. In this paper, the procedure for a specific part or component assembly is shown. By evaluating the developed design procedure using the TO method included in the design process, the conclusions are positive in terms of both time savings and properties of the designed part such as strength and weight parameters. The given findings need to be further developed by implementing on specific product lines for increasing the efficiency of the developed design methodology.

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1. Introduction

Additive manufacturing (AM) technologies have developed intensively over the past decades and are now an essential part of efficient industrial production. 3D-printing no longer serves only as a technology for prototype or small batch production. As a manufacturing technology, the type of 3D-printing not only affects the design of the component along with the material used, but also the development time, functionality, safety, reliability, durability, efficiency, ecological footprint and recyclability [1]. The working principles of various 3D-printing technologies have enabled the emergence of new methods and procedures for component design. The design of a part is no longer adapted only to traditional manufacturing methods, but also to its application and functionality. It is important that research and development for AM continues to come up with innovative and sophisticated component design methods corresponding to current design advances, due to the increasing number of input requirements for part design and manufacturing [2, 3].

Manufacturing technology, operating costs, waste management, etc. are limiting factors that influence the component design process, even if they are not directly related to its functionality. Currently, the final design is a compromise that takes into account all specific factors of the product life cycle [4]. Traditional manufacturing technologies are one of the limiting factors that has a significant impact on product design. Their technological design principles do not always achieve the optimum part properties for a given application. Modern AM (Design for Additive Manufacturing - DfAM) technologies make it possible to implement an innovative component design process. The design of a design is determined only by the application and the specific requirements of the designer

for the component [5]. Based on the new knowledge and understanding of the capabilities of DfAM, the following construction methods were introduced [6]:

- Topology Optimization (TO),
- Generative Design (GD),
- Multiscale Structure Design (MSD),
- Multimaterial Design (MD),
- Parts Consolidation (PC),
- Design for Mass Customization (DfMC),
- Lattice Structures (LS),
- Thermal Issues in Design (TliD).

Among the above-mentioned design methods, TO is used in the research due to the ever-increasing development of that type of DfAM, especially in the automotive industry but also in other industries. The principles of TO have been known for several decades. The method provides optimal designs of components that are very complex in terms of geometry and are not manufacturable or difficult to manufacture by traditional manufacturing methods (chip machining, casting). It was with the advent of additive manufacturing technologies that it began to be applied to a greater extent in the component design process [7-9]. Currently, TO is implemented in the development of components that have the optimum strength, mass and dynamic parameters for a specific function. The resulting design is characterized by organic shapes that are only manufacturable by 3D-printing [10, 11]. The above method of construction (TO) is a set of mathematical iterations that work on the principle of removing and distributing material in a defined space of the original shape of the part [12]. The optimization is based on predefined conditions - load, functional elements of the part that must be preserved (contact surfaces, holes, etc.), links, limiting space (original shape of the part). Often TO is confused with the GD method. The main difference is that TO upgrades the design of an existing component and the GD method creates a new component with an optimal design. The optimization itself is preceded by a strength check of the part using the finite element method. The strength check results in stress and strain maps that serve as input to the optimization process (Figure 1) [13].

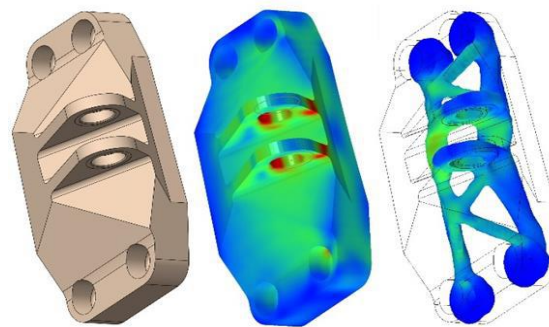


Figure 1. Topology optimization of the part [14].

Today, there are several innovative CAD software on the market that allow designers to use the full production potential and capabilities of additive manufacturing technologies, many of which include TO tools. One of them is the *3DExperience* software, whose licenses are available at the research institute of the Faculty of Mechanical Engineering. The software includes two optimization modules:

- Structural Generative Design (SGD) – mass optimization,
- Flow Generative Design (FGD) – shape optimization with respect to pressure losses.

In the SGD module, the optimization process can be based on different strategies. The TO strategies used are:

1. maximize the stiffness for a given part weight,
2. minimize the weight while respecting the constraints,
3. maximize the value of the lowest natural frequency for a given weight of the part.

For strategies 1 and 3, it is necessary to define the desired weight of the optimized part. The disadvantage of these strategies (especially strategy 1) is that the predefined desired weight may not be the lowest possible weight of the component at which the strength requirements are satisfied. Optimization by strategy 2 requires the determination of a limiting factor, such as:

- maximum allowable stress,
- maximum allowable deformation,
- maximum/minimum wall thickness,
- manufacturing technology.

In this strategy, the material is removed as long as the optimization conditions of the TO are met. A schematic representation of the whole optimization process is shown in Figure 2 [15].

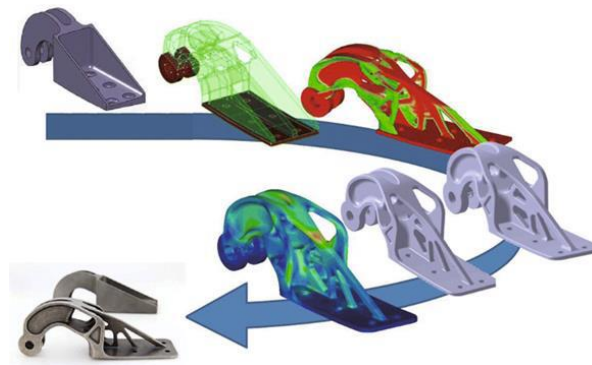


Figure 2. Topology optimization process [16].

The aim of the research activity is to develop, apply and evaluate the effectiveness of an innovative methodology for the design of mobile machine components intended for AM in comparison with traditional design procedures, based on the acquired know-ledge in the field of AM and DfAM methods. The specific aim is to minimize the time required not only to reduce the product development stage but also to manufacture it efficiently, especially for geometrically shape-intensive components, often with the requirement to reduce their weight while maintaining the required strength parameters. To achieve the final result of the research, the following sub-objectives are specified:

1. to develop a sophisticated design methodology for the construction of mobile machine parts intended for AM based on the current state of the art,
2. application of the proposed design methodology for shape and weight optimization,
3. validation of the proposed component manufacturing methodology by evaluating its effectiveness.

2. Materials and Methods

2.1. Traditional method of component designing

To evaluate the effectiveness of the new construction methodology, it is necessary to define the traditional construction procedures. The construction procedure used in companies specialized in the development of mobile machines serves as a comparative benchmark.

2.1.1. Design process by traditional design method

In companies using CAD software in the development of component construction, whose modules and tools do not use the principles of innovative construction methods, the development of

the component construction is an iterative process, consisting of two, maximum three iterations of the design solution. The two-iteration development process of the component construction is composed of the following operations:

1. problem analysis:
 - application site (available footprint),
 - function,
 - load cases,
 - weight and strength requirements;
2. first iteration of the design solution:
 - material selection,
 - design of the structure,
 - design validation by strength,
 - analysis of strength check results – failure to meet strength requirements;
3. second iteration of the design solution:
 - analysis of the original design and strength check,
 - modification of the design,
 - validation of the new design by strength check,
 - analysis of strength check results – meeting strength requirements;
4. postprocessing:
 - analysis of tolerance chain,
 - manufacturability analysis,
 - optimization of the final design for production.

The development of the design of a new component, from the given production line, presented in the research consists of two iterations of the design solution, which, based on the data obtained, takes one designer two weeks, i.e. 75 hours.

2.1.2. Applying the traditional method of designing to research

From the traditional design approach, the first iteration was implemented on the electric motor mounts. The assembly of the brackets and the electric motor is shown in Figure 3.

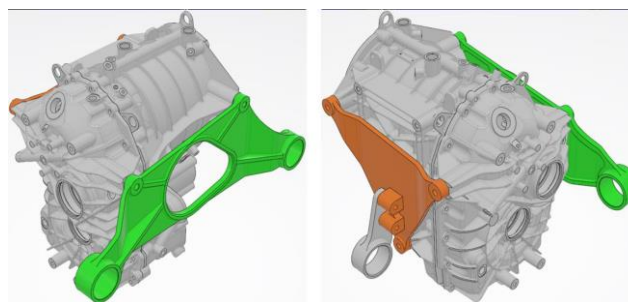


Figure 3. First iteration of the design solution for electric motor holders.

The weight of the front bracket is 1.9 kg and the weight of the rear bracket is 1.124 kg. However, this design did not meet the strength requirements. The material used was aluminum alloy EN AW-7022 with a yield strength of 370 MPa. In some loading situations, the maximum stress values were 476 MPa and 481 MPa for the front and rear brackets, respectively.

The traditional design method no longer proposed a second iteration of the design that would take into account the strength test results of the first iteration. Instead, the decision was taken to apply CAD software to the development of the components, which includes modules and tools that use the principles of innovative design methods. The TO method in the SGD module of the *3DEXperience* software was used to develop the component design. The whole procedure serves as a template for the development of a sophisticated design methodology for shape and weight optimization of mobile machine components, which is described in detail in the following section of the research.

2.2. TO designing procedure

The proposed procedure for the development of the design of the electric motor mounts using the TO method in the SGD module of the *3DExperience* software consists of five main stages:

1. pre-preparation for TO,
2. TO,
3. postprocessing,
4. validation of the final design,
5. preparation for production.

2.2.1. Pre-preparation for TO

Part of the TO pre-preparation is the creation of the shape of the object for optimization, definition of its functional elements, creation of the *Body* (volume in CAD software) of the optimization object, creation and assignment of the material profile.

2.2.1.1. Object shape creation for optimization

The first thing to do is to create an optimization object. The object can be either an existing component or the maximum allowed building volume, the so-called semi-finished product. In this case, the existing components, i.e. the first iterations of the design of the electric motor holders, did not meet the strength requirements. Therefore, the holder blanks were created. The semi-finished volume is the maximum allowable build volume that the future component can occupy. The design of the blank is designed to avoid collision with the frame, interior and other components of the passenger car. The designs of the holder blanks and their comparison with the first iterations of the bracket design are shown in Figures 4 and 5. The individual semi-holders were created as separate *Bodies*.

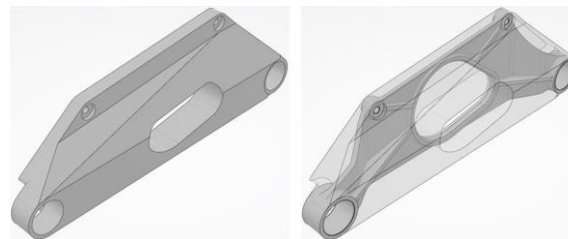


Figure 4. Object for optimization - front holder blank.

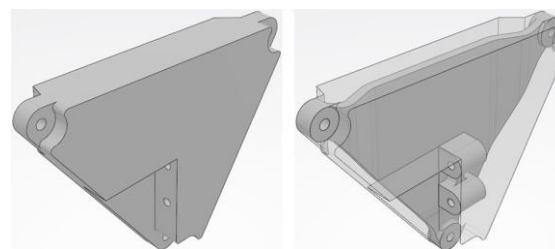


Figure 5. Object for optimization - rear holder blank.

2.2.1.2. Defining the functional elements of an object for optimization

Functional elements are those parts of the optimization object volume that are to be preserved after TO. The individual functional elements have been created as separate *Bodies*. The shape of the *Body* of the functional elements has a significant impact on the quality of the *mesh* and thus on the progress of the individual simulations that are part of the TO. Therefore, the shapes of the *Bodies* of the functional elements were designed to follow the contour of the shape of the semi-finished product with a certain distance.

In the case of the front bracket, the following object functional elements were retained for optimization (Figure 6):

- through-holes and recesses for screws (marked in yellow),
- the holes for the silent blocks (shown in orange).

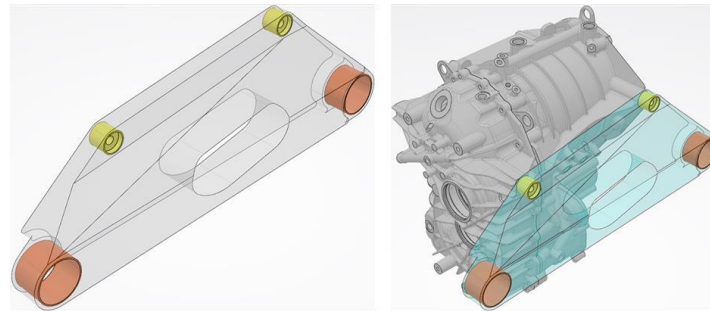


Figure 6. Functional elements for optimization - front holder blank.

In the case of the rear bracket, the following functional elements of the optimization object were retained (Figure 7):

- through-holes for screws (marked in yellow),
- the threaded holes for the rear arm attachment (shown in orange).

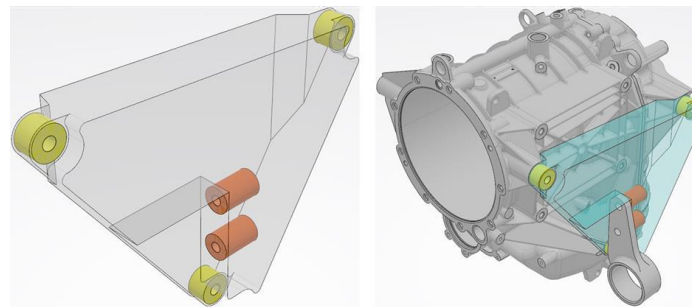


Figure 7. Functional elements of the object for optimization - rear holder blank.

2.2.1.3. Creating the Body object for optimization

By linking the *Body* of the blank with the *Body* of the functional elements, the *Body* of the optimization object is created, which was used in the next steps of the optimization process. The *Partition Design Space* function is used to create the *Body* object for optimization.

2.2.1.4. Create and assign a material profile to the optimization object

In order for a material profile to be usable for a TO, three parameters need to be defined:

- density – ρ ,
- Young's modulus – E ,
- Poisson's number – μ .

Aluminum alloy AlSi10Mg, which is suitable for fabrication by additive manufacturing using DMLS or SLM technologies, was selected for the structural design of electric motor mounts by TO method. Its parameters are:

- density: $\rho=2650 \text{ kg.m}^{-3}$,
- Young's modulus: $E=66 \text{ GPa}$,
- Poisson's number: $\mu=0.325$,
- yield stress: $Re=260 \text{ MPa}$.

2.2.2. TO

The TO process in the SGD module of the 3DEXperience CAD software consists of the following sequential steps:

1. defining the TO strategy,
2. definition of the optimization object and its functional elements,
3. definition of force loads, constraints and their assignment to load cases (*Load Cases*),
4. *mesh* creation,
5. initial strength check of the optimization object,
6. definition of optimization conditions,
7. TO,
8. concept generation,
9. strength check of the generated concepts.

2.2.2.1. TO strategy

In the SGD module, TO can follow three different strategies as mentioned earlier (Chapter 1):

1. maximize the stiffness with respect to the specified component mass,
2. minimize the weight while respecting the constraints,
3. maximize the value of the lowest natural frequency for a given component weight.

In the development of the electric motor mounts, the objective was set to achieve the lowest possible weight at which the components meet the strength requirements. Therefore, the strategy TO no. 2 *Minimize the weight while respecting the specified constraints* was chosen.

2.2.2.2. Object to be optimized and its functional elements

The user selects from the list of all available *Bodies* whose internal structure contains partitions, i.e. the *Body* of the Optimization Object. In the next step, it is necessary to select which volumes of the optimization object are to be preserved and which are to be optimized. The software also informs the user of the masses of the individual volumes. The total weight of the front bracket blank is 12.776 kg, of which the weight of the functional volumes is 0.188 kg (1.46 %) and the weight of the optimized volume is 12.589 kg (98.54 %). The total weight of the rear bracket blank is 6.668 kg, of which the weight of the functional volumes is 0.198 kg (2.96 %) and the weight of the optimized volume is 6.471 kg (97.04 %).

2.2.2.3. Definition of load situations

The loads acting on the components were obtained from measurements performed on a real vehicle during thirty load situations. The individual load situations represent conditions that may occur during vehicle handling, driving or collision. The measured forces were in the silentblocks (Figure 8 position 1,2 and 3) through which the electric motor with brackets is attached to the vehicle frame. These forces are then applied to the inner circumference of the front bracket hubs and the rear arm hubs, from which the force effects are transferred to the rear bracket. All thirty load situations are represented in the software by load cases. A load case consists of the applied force effects (force, moment, ...) and the constraints.

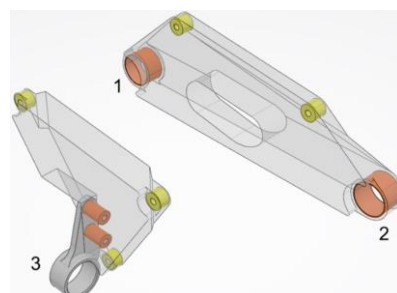


Figure 8. Hubs for the silentblocks of the front holder blank (1, 2) of the rear arm (3).

For the front holder, the load case includes (Figure 9a):

- two forces (*Force* type) - reactions from the silentblocks acting on the holder hubs;
- six linkages - representing the attachment of the holder to the electric motor by two bolts:
 - two rotational links (*Rotate* type),
 - four sliding links (*Slide* type).

For the rear holder, the load case includes (Figure 9b):

- one force (*Remote Force* type) - the reaction from the silentblock acting on the rear holder hub;
- nine links - representing the attachment of the holder to the electric motor by three bolts:
 - three rotating links (*Rotate* type),
 - six sliding links (*Slide* type).

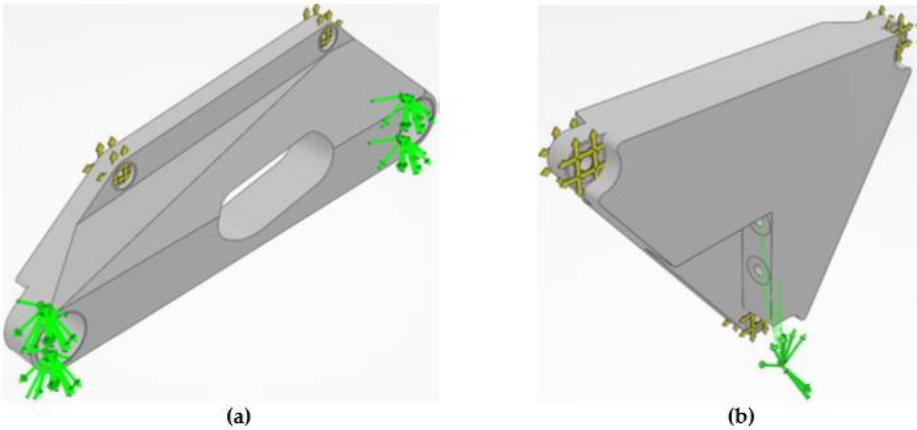


Figure 9. Schematic representation of all 30 load cases of the blanks: **(a)** front holder, **(b)** rear holder.

2.2.2.4. Creating a mesh

Based on the results obtained from the analysis of the *mesh* influence on the progression and outcome of the TO, a quadratic *mesh* configuration with a default number of elements (*Automatically deducated quadratic mesh option*) was used for both holders. The quadratic *mesh* network with default number of elements of the front holder is shown in Figure 10a and that of the rear holder in Figure 10b. The shapes of the *Body* function elements were designed to follow the contours of the shape of the blank with some distance to avoid certain qualitative errors of the *mesh*.

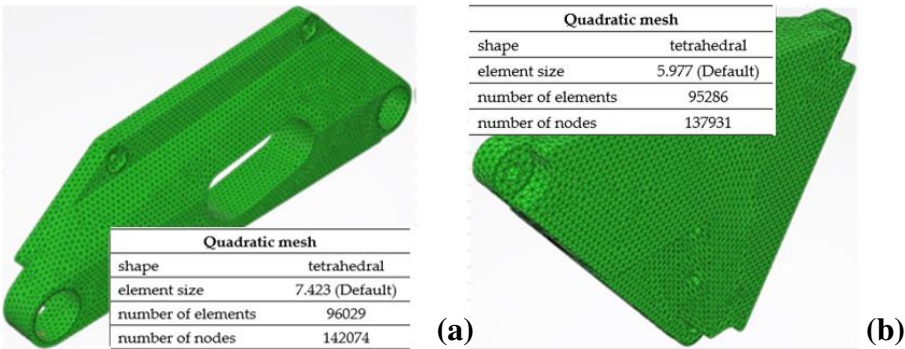


Figure 10. Network of a quadratic mesh with default number of elements: **(a)** front holder blank, **(b)** rear holder blank.

2.2.2.5. Initial strength check of the object for optimization

The initial strength check is used to demonstrate the optimization potential of the object to be optimized. Its result serves as input to the TO. Based on the stress map, the material is removed or reorganized in the blank volume. The value of the maximum stress from the input strength check must be lower than the value of the allowable stress in the optimization condition. For the purpose of evaluation and analysis, 30 stress situations with strength control were performed.

After analyzing the results of the input strength control, it was decided that the parts will be optimized only for the ten most unfavorable-greater load situations. This accelerated the entire development process. The most unfavorable load situations did not develop only on the basis of voltage values, but also on the basis of the sizes of the individual components of the acting forces.

2.2.2.6. Definition of optimization conditions

A single optimization condition, i.e. the maximum allowable stress, was defined for the TO of the electric motor holders. In order to be able to run the optimization process at all, it is necessary that the value of the maximum allowable stress is greater than the stress values obtained during the initial strength check of the semi-finished product. On the other hand, it should not be greater than the yield strength or ultimate strength of the material used. On the basis of consultations with companies using additive SLM technology for the production of dynamically stressed mobile machine components made of aluminum alloy AlSi10Mg, it was found that the maximum stress value (reduced *Von Mises stress*) of the static strength analysis should be in the range of 90 MPa - 110 MPa. Compliance with this condition will achieve the required service life of the components. A maximum allowable stress value of 100 MPa was set as the optimization condition for the TO of both motor holders.

2.2.2.7. TO

The TO of the front mount lasted 3 hours and 2 minutes. The optimization converged to a solution that satisfied the optimization conditions after 120 iteration cycles were performed. The results of the TO of the front holder are shown in Figure 11. The software evaluated the failure to meet the optimization requirement for two *load cases*. The stress values exceeded the maximum allowable stress value by 0.5%. However, after analyzing the results, it was concluded that the optimization condition was satisfied in all ten load cases. The achieved mass of the front bracket concept was 1.574 kg (Figure 11 labeled as *Mass - Design Space.1: Final Value*), i.e. 12.3% of the weight of the holder.

Name	Load Case	Original Value	Final Value	Bounds
Minimize Mass		6.298kg	1.387kg	
Stress Constraint.1	4	135.525MPa	✓ 39.611MPa	100MPa
Stress Constraint.1	6	136.787MPa	✓ 73.745MPa	100MPa
Stress Constraint.1	10	47.294MPa	! 100.529MPa	100MPa
Stress Constraint.1	11	48.13MPa	✓ 89.942MPa	100MPa
Stress Constraint.1	17	47.014MPa	✓ 85.549MPa	100MPa
Stress Constraint.1	18	48.175MPa	✓ 78.671MPa	100MPa
Stress Constraint.1	20	160.278MPa	✓ 48.296MPa	100MPa
Stress Constraint.1	21	181.554MPa	✓ 57.599MPa	100MPa
Stress Constraint.1	25	301.943MPa	! 100.44MPa	100MPa
Stress Constraint.1	26	323.868MPa	✓ 95.523MPa	100MPa
Mass - Design Space.1		6.485kg	1.574kg	

Figure 11. Results of TO front holder blank.

The TO of the rear holder lasted 1 hour and 32 minutes. In this case, the optimization converged to a solution that satisfied the optimization conditions after only 52 iteration cycles had been performed. The results of the TO of the rear holder are shown in Figure 12. The optimization

condition was satisfied in all *load cases*. The achieved mass of the rear bracket was 0.806 kg (Figure 12 labeled as *Mass - Design Space.1: Final Value*), i.e. 12.1% of the mass of the holder.

Name	Load Case	Original Value	Final Value	Bounds
Minimize Mass		3.237kg	0.608kg	
Stress Constraint.1	10	240.582MPa	✓ 92.69MPa	↓ 100MPa
Stress Constraint.1	11	257.925MPa	✓ 99.924MPa	↓ 100MPa
Stress Constraint.1	14	21.405MPa	✓ 55.628MPa	↓ 100MPa
Stress Constraint.1	15	31.633MPa	✓ 59.08MPa	↓ 100MPa
Stress Constraint.1	18	24.941MPa	✓ 51.558MPa	↓ 100MPa
Stress Constraint.1	19	43.965MPa	✓ 60.978MPa	↓ 100MPa
Stress Constraint.1	23	126.749MPa	✓ 48.742MPa	↓ 100MPa
Stress Constraint.1	24	141.755MPa	✓ 55.049MPa	↓ 100MPa
Stress Constraint.1	25	264.076MPa	✓ 99.929MPa	↓ 100MPa
Stress Constraint.1	26	252.131MPa	✓ 93.855MPa	↓ 100MPa
Mass - Design Space.1		3.435kg	0.806kg	

Figure 12. Results of the TO rear holder blank.

2.2.2.8. Concept generation

The concept generation process is used to materialize the results of the TO. The *Cutting Value* (CV) parameter has the greatest influence on the generated shape. It is an informative parameter whose value describes the amount of mass retained after the optimization process. By changing the parameter, material is removed or added with respect to the TO result. Two concepts have been generated for the two holders. One concept was generated with a CV parameter such that its mass is closest to the mass of the concept after the last iteration of the TO (Figure 11 and 12 labeled as *Mass - Design Space.1: Final Value*, respectively). The CV value of the front holder and the rear holder was set to 55 and 53, respectively. The second concept was generated with a higher CV parameter value (CV value: front bracket - 90, rear bracket - 80). The generation of two concepts with different CV parameter value allows to analyze the influence of the parameter on the weight, design concept and strength of the generated concepts. From Figures 13 and 14, it can be seen that the weight of the generated concepts with the CV parameter, where the weight is closest to the weight after the last iteration of TO, is larger than that shown in Figures 11 and 12, respectively. This is because the software adds material at certain locations in order to generate a concept with a nice continuous shape without defects.

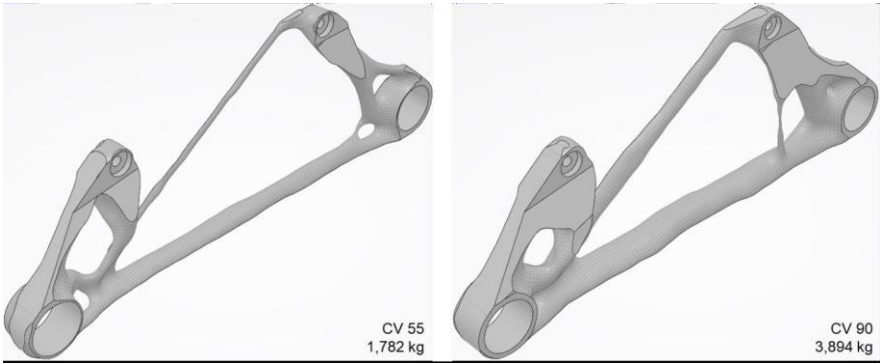


Figure 13. Front holder concepts generated.

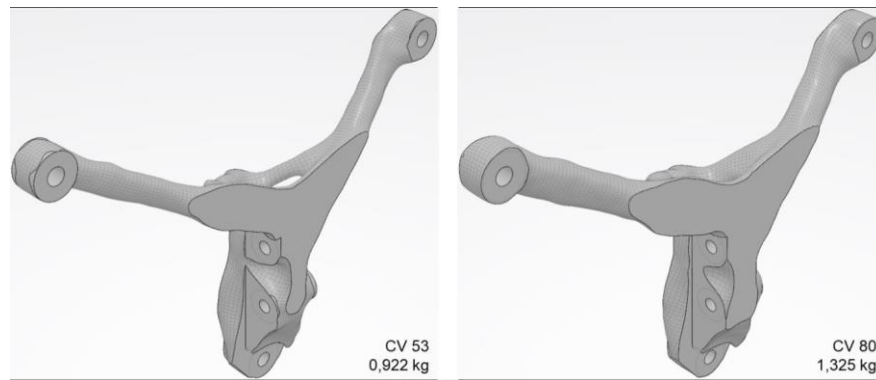


Figure 14. Rear holder concepts generated.

2.2.2.9. Robustness check of generated concepts

The strength check of the generated raw front and rear holder concepts for all ten load cases was used to validate the strength of their design and the accuracy of the TO results.

The raw generated front bracket concept with CV 55 did not meet the strength requirements for all *load cases* (two *load cases*). However, after analyzing the results, it was concluded that with minor modifications to the design in *postprocessing*, these relatively high stresses could be avoided. The strength checks proved the accuracy of the TO results. The generated concepts are suitable for use as templates for the final design of components within the *postprocessing*.

2.2.3. Postprocessing -- creation of the final design

In *postprocessing*, the complicated design of the generated and validated concepts is reconstructed, and functional elements are implemented in the final design.

The SGD module has functions and tools for the reconstruction of complex geometry using *NURBS* surfaces [17]. These are general surfaces whose geometry is controlled by control points. Such surfaces can be connected to each other to form larger units, thus creating the final design of the component. The individual design elements of the concepts are modeled as separate planar entities by the *IMA - Tube drawing* and *IMA - Cylinder* functions. The final design of the front and rear holder was obtained by trimming the blanks with the final *NURBS-flat Split* function and implementing the functional elements into the trimmed volume by *Boolean operations* (Figure 15 and Figure 16).

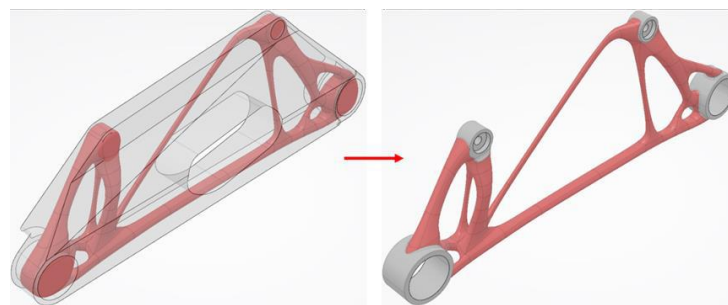


Figure 15. Trimming of the front holder blank with the final *NURBS*-plate and implementation of the functional elements.

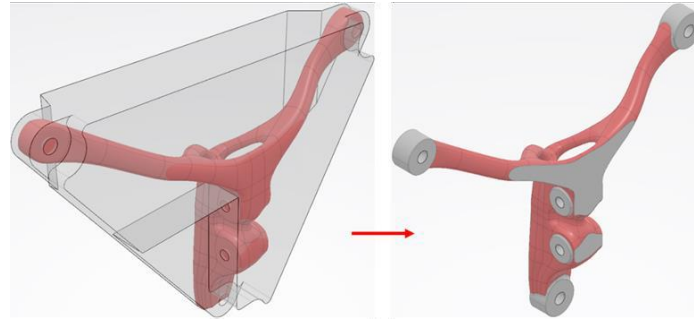


Figure 16. Trimming of the rear holder blank with the final NURBS-plate and implementation of the functional elements.

2.2.4. Validation of the final design

To validate the correctness of the final design of the front and rear holder, strength tests were performed for all thirty loading situations. A linear mesh with an element size of 2 mm was used for the front holder and a linear *mesh* with an element size of 1.5 mm was used for the rear holder. These are the same *mesh* configurations that were used in the validation of the generated bracket concepts (Chapter 2.2.2.9). The strength tests proved the correctness of the front and rear electric motor bracket design. In neither load case do the stresses (*Von Mises* type) exceed the maximum allowable stress value of 100 MPa. All the conditions imposed on the design of the bracket construction have been fulfilled.

2.2.5. Final design - preparation for 3D-printing

The weight of the final design of the optimized front holder is 1.714 kg. A detailed view of the front holder design of the electric motor is shown in Figure 17. The weight of the final design of the rear holder is 0.783 kg. A detailed view of the rear electric motor holder design is shown in Figure 18. The electric motor assembly with optimized front and rear holder is shown in Figure 19.



Figure 17. Final design of the optimized front electric motor holder.

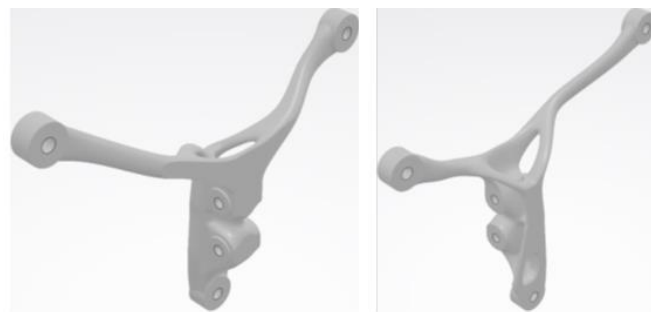


Figure 18. Final design of the optimized rear electric motor holder.

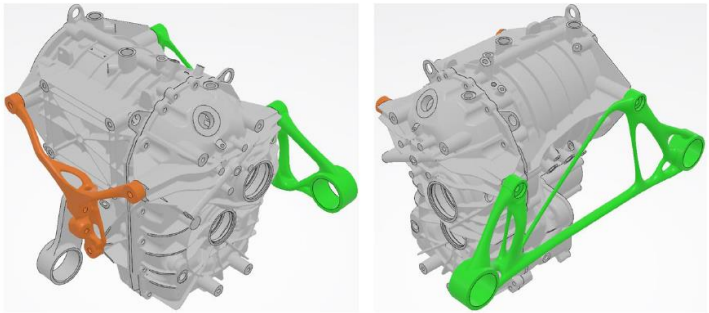


Figure 19. Electric motor with optimized holders.

Before the actual additive manufacturing with SLM technology, it is necessary to perform 3D-printing and cooling simulation of the component. This will highlight the behavior of the components throughout the manufacturing process. Based on the results, manufacturing inaccuracies can be predicted, which can be eliminated by changing the design (so called component pre-deforming) or eliminated in the manufacturing finishing operations. Areas that are prone to deformation during 3D-printing or during cooling after the manufacturing process shall be reinforced with supports. These supports are then removed mechanically or by vibration. Additional material shall be applied to functional surfaces which are subject to high demands in terms of precision and roughness. Precision chip machining is used to remove the additive and thus achieve the required precision and roughness of the functional surfaces.

3. Results

Table 1 shows the duration times for each stage of the development of the electric motor bracket design by the TO method using the *3DExperience* software. These are the times that can be achieved with ideal inputs, ideal operation of the software and ideal outputs from the optimization process. However, real-world use has shown that it is often necessary to rework the inputs (blanks, partitions) to improve the input strength optimization results, and it is often necessary to change the optimization conditions to ensure that the optimization process is working properly and thus obtain usable concepts of the optimized parts. This nature of the software and the TO method itself is accounted for by the reliability coefficient $k_{se} \langle 1.3 \rangle$. The coefficient interval was defined based on the experience gained by applying the method and software to the development of several components. The comparison of the development time of the electric motor brackets with the TO method and the development time with traditional design methods is shown in Table 2.

Table 1. Development time of electric motor holders by TO method.

Development time of electric motor holders by topological optimization method			
Stages	Job description	Front holder	Rear holder
		Time (h)	
pre-preparation for topological optimization	<ul style="list-style-type: none">- creating an object for optimization- creation of functional elements of the optimization object- creation of a material profile and assignment to the optimization object	3	3
topological optimization	<ul style="list-style-type: none">- defining the optimisation strategy- defining the object for optimisation- defining the functional elements of the optimisation object	0.25	0.25

	- definition of force loads and constraints and their assignment to load cases	2	2
	- creating a MESH		
	- Initial strength check of the object for optimization		
	- definition of optimization conditions	3	1,5
	- topological optimization		
postprocessing	- generation of concepts	1	1
	- strength check of generated concepts		
	- reconstruction of the complex geometry of the generated and validated concept through NURBS surfaces	4	4
	- implementation of functional elements of the final design		
validation of the final design	- strength check of the final component design	1	1
preparation for production	- allowances for finishing after 3D-printing	1	1
total development time under ideal conditions (rounded to whole hours)		15	14
method reliability coefficient k_s		3	
total development time under realistic conditions		46	41

Table 2. Comparison of design methods for the development of electric motor holders.

Comparison of design methods						
Method of construction	Development time (h)				Weight of holders (kg)	
	Front holder	Rear holder	Front holder	Rear holder	Front holder	Rear holder
traditional	75				1,9	1,124
topological optimization	Ideal conditions		Real conditions		1,714	0,783
	15	14	46	41		
savings when using the topological optimization method	80%	82%	39%	45%	10%	30%

It is clear that the implementation of the TO method into the process of designing the optimal design of electric motor holders has significantly reduced the development time. A weight saving was also achieved compared to the first iteration of the design of the electric motor holders, which additionally did not undergo a strength check.

4. Discussion

The application of the proposed design methodology in practice confirmed its effectiveness at the component development stage. Its implementation in the component design process demonstrated significant savings in development time and component weight. The principles of TO have been known for a long time, but the method has not been used in practice on a large scale. This is due to the relative difficulty of operating optimization software, its reliability and the lack of trained and experienced personnel. In order to ensure the efficiency and reliability of the implementation of optimization software in the development of new components, it is necessary to develop variants of the design methodology that will be tailored for the design process of a specific product line.

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