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Mass reduction method for topology optimisation of a Ti6Al4V part for additive manufacturing

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Abstract
Additive manufacturing and topology optimization provide new possibilities to produce complex parts. They can be used separately but with joint applications as a mutually reinforcing solution in component development tasks. The results obtained using the design software can be refined even further depending on the specific goal set. This paper deals with mass reduction with stiffness-based topology optimization of a structural component. The effect of different design spaces, load cases, and design parameters were examined. Then, the new part was validated with FEA simulation. After the validation, the part was prepared for 3D metal printing. Based on the research results, we present a methodology that can be used as a solution considering the software's limitations and the development of the specific component. Applying the methodology developed in the research makes it possible to achieve mass minimization on other parts with a similar method.

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1. Introduction

In recent years, additive manufacturing or 3D printing has been mainly used for polymers (Ficzere, 2022; Alzyod, 2023) and metals. Several methods are also used for the 3D printing of metals (Armstrong, 2022.), among which selective laser melting (SLM), also known as laser powder bed fusion (LPBF), is presented in our research.

In comparison with traditional manufacturing processes, additive manufacturing technology builds up the components layer by layer, so the freedom of design and construction is greater than traditional solutions. As a result, additive manufacturing processes are becoming more and more widespread. However, especially in the case of metal materials, the construction and operation of the infrastructure and the raw materials have high costs (Calignano, 2023). For this reason, the application of the technology is economical in cases where not traditional construction is manufactured, but constructions that provide additional benefits can be created by utilizing new design methodologies. This additive-specific design is called Design for Additive Manufacturing (DfAM) (Djokikj, 2023), and this intensively developing field uses new solutions such as reinforcement learning (Venugopal, 2023; Jang, 2022).

During the development of vehicle components, processes and methods that provide an individual solution to a specific task are becoming more common. These processes include generative design and the 3D printing technology (Chauhan, 2020). Combining these methods, new part solutions can be developed which did not exist before (Walton, 2017).

The application of generative design is a useful solution in product optimization in additive manufacturing (AM) (Yi, 2021). The most common reason for applying topology optimization and generative design is the creation of new parts that can be designed with less material and weight (Liu, 2018). The demand for weight reduction (Dhokia, 2017). In vehicles is the most important (Ahmed, 2022). It is also significant in the aircraft industry (Zhu, 2021), but it is used in the building industry (Salta, 2020), in some medical applications (Rajput, 2021), as well as in many other areas (Djokikj, 2021). As a result of the rapid spread of 3D printing, technology has also appeared in component manufacturing. Using additive manufacturing can replace previous part designs with new design solutions, which is also greatly aided by generative design (Khan, 2018). It is often used where production needs customized components, complex and smaller parts and a shorter lead time (Kaushal, 2021). A particularly prominent area in the vehicle industry is competitive sports (Kumar, 2022; Mesicek, 2019).

Topology optimization (TO) and generative design (GD) are additive-specific design procedures now closely connected with additive manufacturing technology. The main question of both design methodologies is where to put raw materials depending on what boundary conditions must be met. While topological optimization is a more straightforward procedure that provides one type of output, generative design is a more complex procedure that simultaneously considers several boundary conditions and provides several design solutions (Vlah, 2020). For example, in the design of the part, it is possible to consider that the support used during printing is minimal (Zhu, 2021.), which can reduce the amount and time of post-processes, thus increasing the economy of the process. The field of use related to the research focuses on parts of automotive (Junk, 2022) and aircraft (Hanush, 2022), where the strength-to-weight ratio must be as high as possible; therefore, a titanium alloy is very often applied.

These new design methods are not only able to create new component constructions taking into account strength aspects. Still, they are also suitable for considering thermal (Venugopal, 2023) and fluid mechanic phenomena (Ling, 2023).

These design methods can be used not only in the case of additive manufacturing but also in traditional processes (Gupta, 2022). However, the combined use of additive manufacturing and additive-specific design provides advantages that allow more efficient use of the possibilities.

Many types of software are used for design on the market today, with different advantages and disadvantages (Junk, 2021), which, based on our own experience, only become apparent when used. Accordingly, we used various software for design, one of which we will present as a tool in this article.

With the use of the software, the experience emerged that the created design can be used as just one possible solution. Still, by changing the software parameters and even multiple iterations, it is possible to create a construction that is even more suitable for the goals. Since we did not find a systematic study on this in the literature, questions arose about filling this gap in knowledge, and answers need to be sought.

Therefore, in the presented research, our goal was to develop a methodology in case an additive-specific design for a metal part is purposefully designed for this test, considering the associated boundary conditions and SLM manufacturability simultaneously to reach the minimal mass of the part.

The real challenge here is that in the case of software, it is not possible to create the final construction in a fully automated way. Here, we present a solution to the difficulties in managing CAD models, the limitations of converting surface models and body models, and the problems of working together and interoperability with other software.

2. Methods

The experimental part was designed to investigate the capabilities of the software. The main objective of this study was mass minimising. The manufacturing equipment we planned the production on is an EOS M100 SLM machine. In Figure 1., the flowchart diagram of the optimisation can be seen.

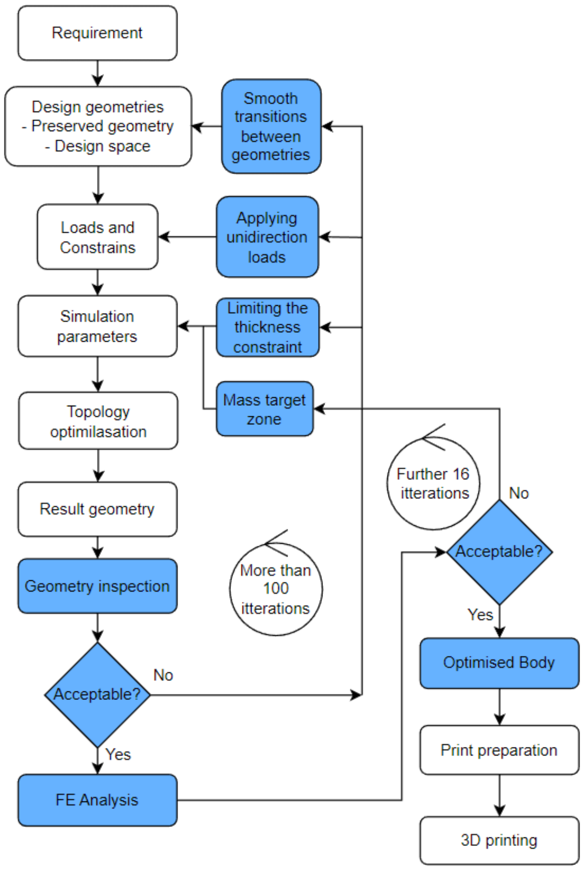


Fig. 1. The optimisation flowchart

The first step of defining the optimisation process is the CAD modelling of the design geometries. These geometries have a significant impact on the simulation results. The design geometries are shown in Figure 2.-3. and are defined as independent bodies.

Two bodies belonging to the preserved geometries were marked in Figure 2. These volumes will be part of the result body and will not change during optimisation. The first preserved geometries serve as base plate for the future part.

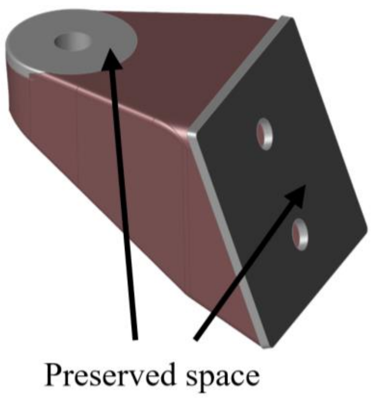


Fig. 2. Design geometries: the preserved geometry

In Figure 3, the design space can be seen where the material reorganisation can happen. The design space must be created considering the accessibility of parts. The software with a different colour highlights this body. All presented simulations used the same design geometries.

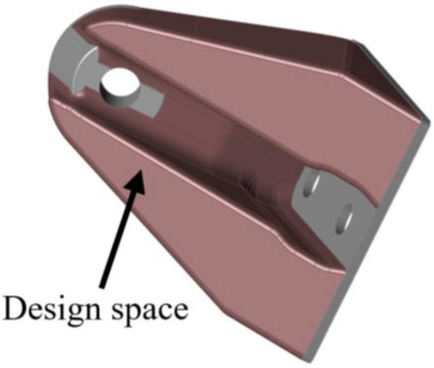


Fig. 3. Design geometries: the design space

The applied fixed constraints are shown in Figure 4. The part is fixed on the surface of the holes of the flat plate due to the applied fixturing.

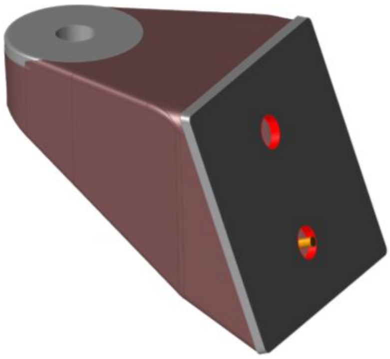


Fig. 4. The applied fixed constraints

The location of the applied load and the possible direction is shown in the following Figure 5. Single force is the expected load of the future part with a magnitude of 1000 Newtons. In this study, only single forces with different directions but the same magnitudes were used because the real load directions are unknown.

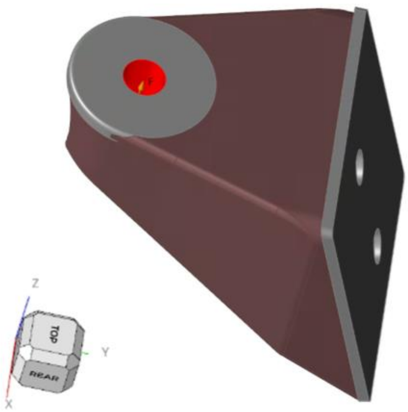


Fig. 5. The applied force directions

The single forces are parallel with the axis on the coordinate system's axis. For example, "Force Z" is parallel with the coordinate system "Z" axis, and further. In the case of the "Y" axis, the force vector is also parallel but in the opposite direction. The coordinate system and the directions of the forces are presented in Figure 5.

A further symmetrical constraint was added (Figure 6.). This is an additional plane, which is a geometric condition where the future part needs to be symmetrical to stand against various force directions. The plane of symmetry is defined by the centre points of the three holes.

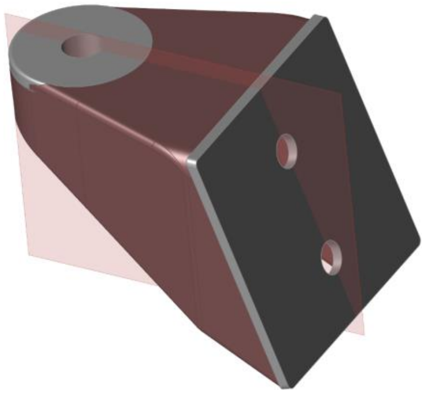


Fig. 6. Symmetry constraint

The optimisation method is stiffness-based topology optimisation. This method was used to reach the mass minimum of the future part. All the used parameters of topology optimisation are organised in Table 1. The first of the investigated parameters is the mass target parameter. The mass target is the usable material quantity the software can reshape. The 80% mass target value means that 80% of the design space mass is rearrangeable.

Table 1. Varied parameters of the simulations

Simulation setup number	Mass targets (%)	Fz (N)	Fx (N)	Fy (N)
S1	80	1000	0	0
S2	60.5	1000	0	0
S3	50	1000	0	0
S4	40.5	1000	0	0
S5	29.5	1000	0	0
S6	20.5	1000	0	0
S7	15.5	1000	0	0
S8	10	1000	0	0
S9	11	1000	0	0
S10	12	1000	0	0
S11	20	0	1000	0
S12	17	0	1000	0
S13	14	0	1000	0
S14	23	0	0	1000
S15	15	0	0	1000
S16	13	0	0	1000

The last important, but in this case fixed parameter was the thickness constraint. It was constant during the optimisation simulations, and the preset value was 3 mm. This parameter controls the minimum wall thickness of the topology-optimised body. The 3 mm value came from the SLM manufacturing technology. This technology requires support structures between the build platform and the printed part. The future part must also withstand the loads of the removability process.

3. Results and discussion

The first phase is all about the preparation. The problematic transitions (e.g. sharp edges) between the preserved geometries and design space were developed with iterations. Every iteration gives one result. The results must be checked; if any type of problematic geometric appears, it must be corrected. This is a time-consuming process, but it is necessary to get usable topology-optimised results. The topology optimisation can begin after only the design space is developed. This phase was finished after approximately 100 iterations.

Usage of complex force vectors was analysed but was found to be insufficient. Force vector with more than two direction components often lead to failed simulations. These simulations further increased the number of iterations in the case of this study.

The development phase contains sixteen iteration that were made to achieve the best possible result. The result bodies are shown in Figures 7.-11. The results in these figures were created using the same "Force Z" and different mass target settings. These figures show that the software decreased material quantity from left to right as the mass target parameter was reduced (except in Figure 11).

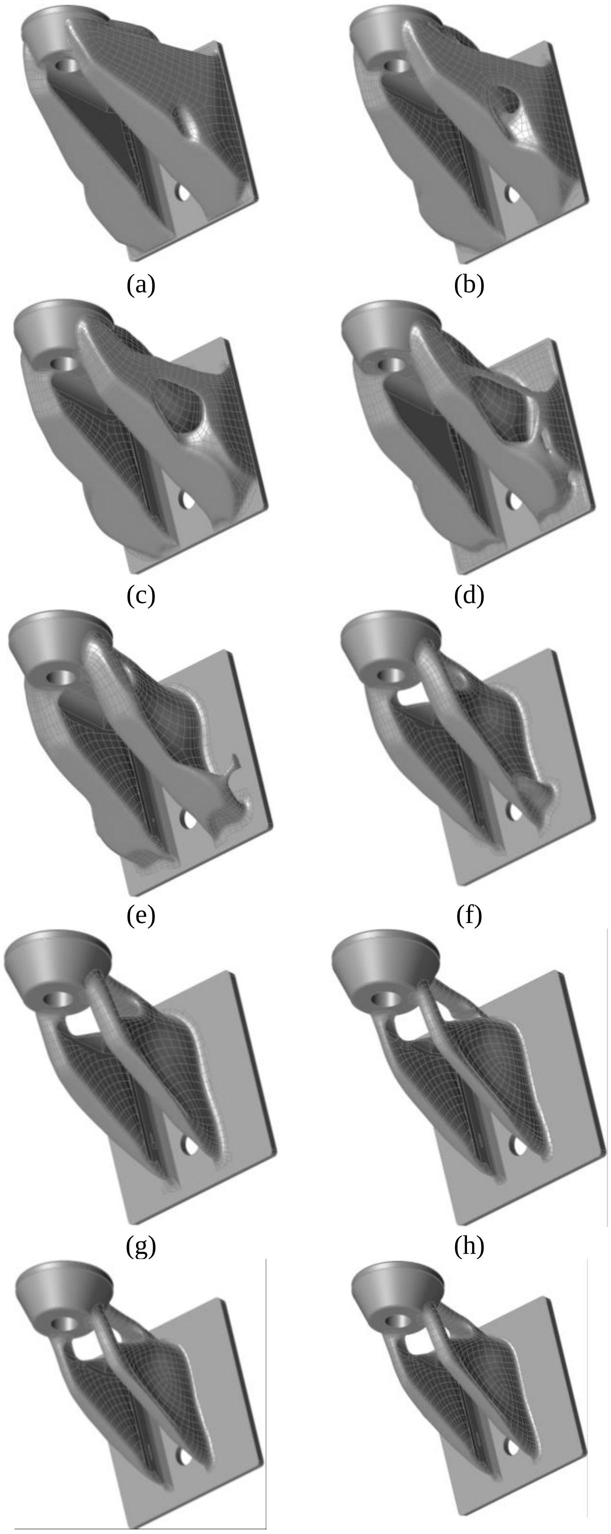

(a) (b) (c) (d) (e) (f) (g) (h) (j) (k)

Fig. 11. Result body of simulation S1 (a), S2 (b), S3 (c), S4 (d), S5 (e), S6 (f), S7 (g), S8 (h), S9 (j), S10 (k)

The result bodies in Figures 12 were created using the same "Force X" and different mass target settings.

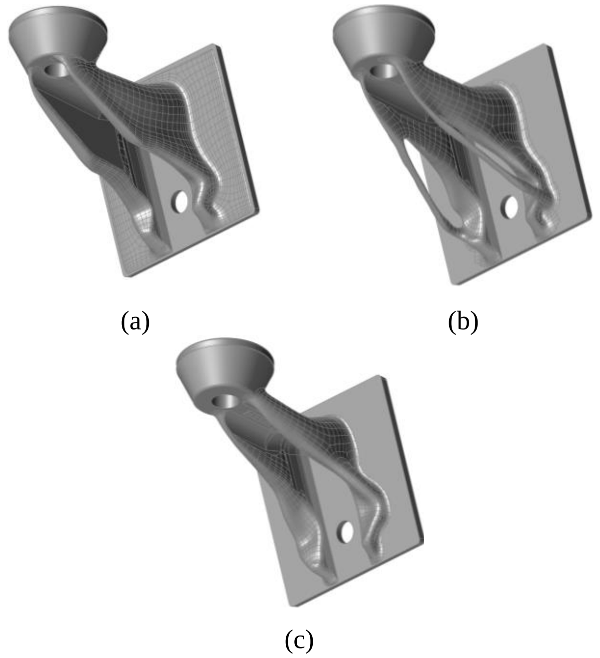


Fig. 12. Result body of simulation S11 (a), S12 (b), S13 (c)

The result bodies in Figures 13 were created using the same "Force Y" and different mass target settings.

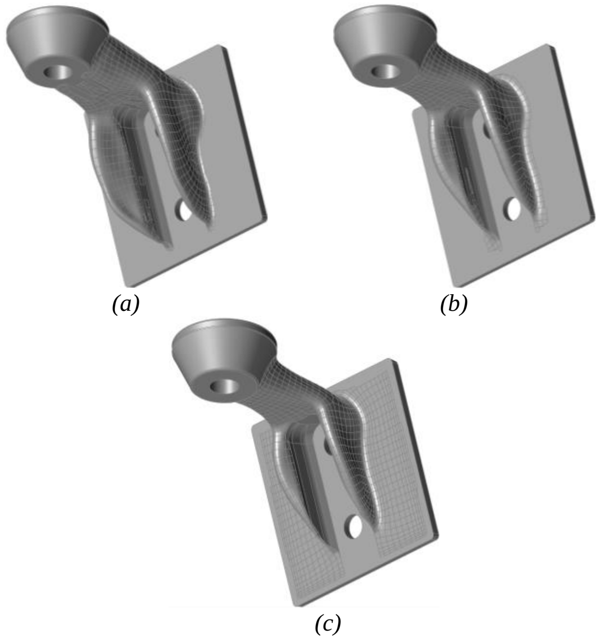


Fig. 13. Result body of simulation S14 (a), S15 (b), S16 (c)

After a successful topology optimisation, a visual inspection is performed to detect possible geometric errors (e.g. thin parts). After the visual confirmation is finished and the result looks acceptable, a validation Finite Element Method (or FEM) analysis is the next step. An FEM analysis of the optimised body is performed to determine whether the resulting body can withstand the specified load or whether further mass reduction is possible.

To visualize the mass reduction process systematically, Figure 14 illustrates the mass targets and the simulated masses of the bodies in a diagram. Each point in the diagram means a simulation. Using multiple FEM analyses, it was possible to determine the mass range to build the desired part. This method can determine the mass range in the first round, which can be further refined in the second step. This range was between 30 g and 40 g (equal to mass target values between 10% and 20%). In the case of X and Y force directions the-further designs were already looked for within this range by changing the target mass more finely. The best results (S10, S13 and S16) were accepted as the one with the lowest mass that passed finite element analysis.

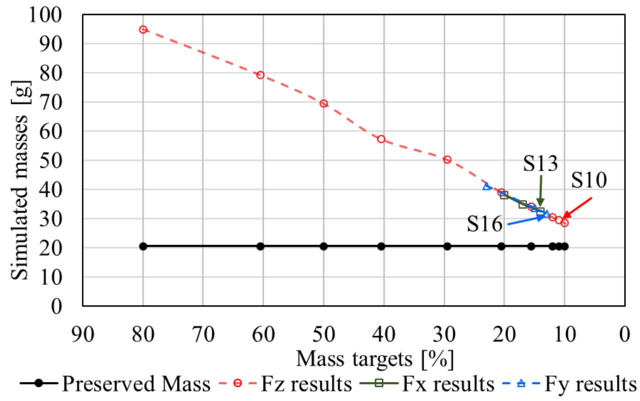


Fig. 14. Masses throughout the optimization

The best-optimized results applying different forces are shown in Figure 15.

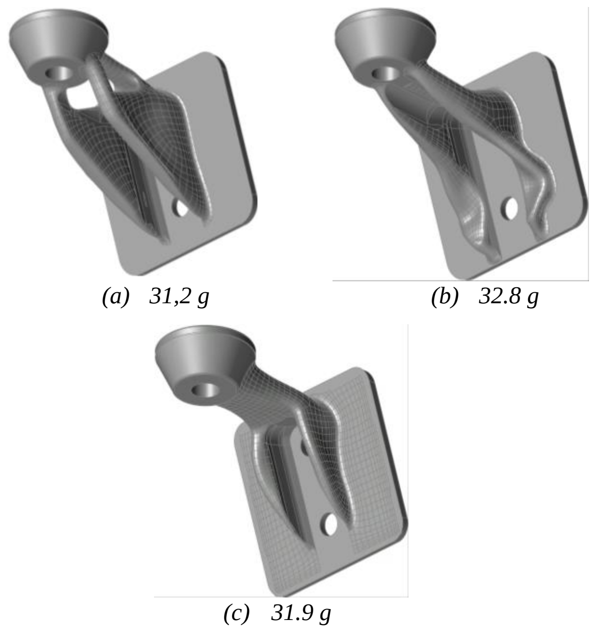


Fig. 15. The best results of the optimised parts S10 (a), S13 (b), and S16 (c)

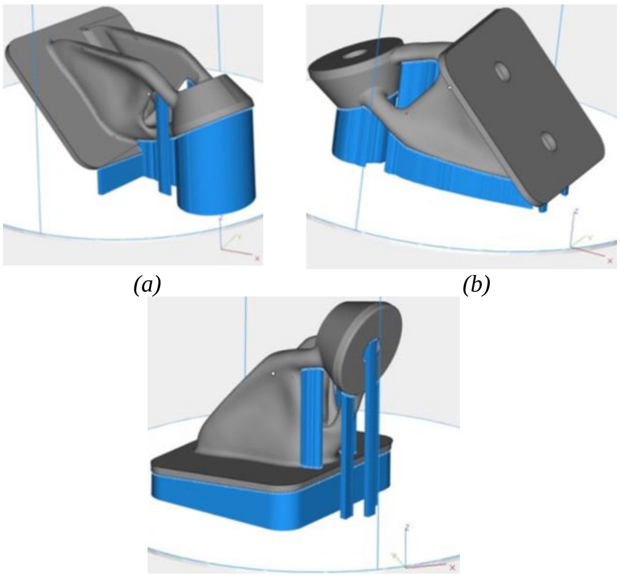
The optimization process was made only with one force in each case, but in FEA, each result body was tested with all three load cases. Due to minimizing the part's mass, S10 optimization was chosen to be manufactured. Before manufacturing the base plate 1 mm radius fillet was modified to be 5 mm.

After selecting the component with the lowest weight, the printing orientations were checked in the preparatory software for the printing equipment.

The applied EOS M100 3D printing equipment has a 100 mm diameter cylindrical working space. This is where the part needs to be placed.

The possibilities of the part's orientation were examined, and three of the obtained results are presented below. The three possible printing orientations can be seen in Figure 16. The printing orientation determines the printing time, the amount of support to be applied, the amount of post-processing, and the resulting internal stresses, so it is essential to analyse them before printing.

Orientation B provides the smallest support volume, with upward connecting surfaces. It has the benefit that the joining surface should not be further machined. This is also the direction with the shortest printing time because of the smallest printing height. The other two printing directions have tall, thin support parts and more support volumes. These tall and thin supports are often not buildable and should be avoided. With this, the design and print orientation points were determined. Based on the preparation, the next step is the 3D printing and then the evaluation of the part, which is realised in the following research phase.



(a) *(b)*

(c)

Fig. 16. Investigated printing orientations orientation A (a), orientation B (b), orientation C (c)

Approximately 120 iterations were made for the S10 result part which means huge amount of time spent with simulation. The optimization process time must be decreased. For this purpose, changes in the original methodology were made. These changes are highlighted in the flowchart with blue background in Figure 1. Summarising the developed methodology is as follows:

- Defining the preserved geometries with every necessary feature (e.g. fillets, chamfers, holes).
- Creating design space geometries most carefully, considering the geometry requirements (smooth transitions, riveting process, symmetry, thread machinability).
- Defining constraints of the future part.
- Defining the possible loads on the specific spots. If multiple loads or multiple directions are expected, the most important load should be used as the load of the optimization.
- Defining the simulation parameters (thickness constraint parameter, symmetry planes, manufacturing constraints).
- Topology optimisation
- Geometry inspection (the generated results are checked for unnecessary geometry deformations). A further iteration is in order if any geometric error is in the result.
- Simulating in the first step, the rough determination of the target weight per cent range, where the simulation also gives a meaningful result (simulation gives results close to the required safety factor). Refined designs are defined in smaller steps within the range in the second step. In the case of force Z, the acceptable result occurred in 10 iterations. The mass target zone is determined. This can be used to fasten to optimisation in other load cases. Applying the mass target zone (10-20 %), an acceptable solution occurred in the X and Y directions with 6 iterations.
- Selection of suitable results in all force directions the lowest mass was chosen.
- Determination of orientation that takes printability aspects into account before printing.

4. Summary and conclusion

As a result of the research, instead of a simple simulation run, an iteration method was developed, which can be used to minimize the mass of the component taking into account the specific boundary conditions. Our hypothesis presented in the introduction section, according to which the results can be further improved by appropriately modifying the parameters and process of the simulation software, was confirmed.

Based on the research results, the following conclusions can be drawn:

- A methodology has been developed that can be used to reduce the weight of specific components, considering the limitations and possibilities of topological optimisation software and taking printability into account.
- For the presented part, designs depending on the load direction were developed, and after the analysis, the part for printing was determined.

- Design space has a huge impact on the optimisation outcome. To achieve a good optimisation result, it is essential to design it in the most considerate way.
- By considering the remaining volumes, there is an additional possibility to reduce the weight. The base plate must be redesigned to achieve further mass reduction.
- Based on the printability test, the printing orientation B was determined. To validate the process, the component evaluation after printing is also required in the next step.

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