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METHOD FOR A SOFTWARE-BASED DESIGN CHECK OF ADDITIVELY MANUFACTURED COMPONENTS

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Abstract

Additive manufacturing offers the potential to produce complex structures such as topology-optimized components or lattice structures. However, even these numerically generated structures are subject to manufacturing restrictions. Therefore, compliance with design rules has to be checked to ensure a robust production. For complex structures, this check requires a great effort. Hence, a method for a software-based design check that automatically verifies the compliance with design rules of complex structures has to be developed.

Within the framework of the developed method, the frequently used STL format which is usually applied during preparation of the manufacturing process, is used. This format approximates components using triangles. By systematically linking these triangles, geometrical attributes of components which are relevant for a controlled manufacturing can be identified. Comparing these attributes to a database containing attribute limits of divergent manufacturing conditions allows a design check regarding robust manufacturing processes.

Introduction

Additive manufacturing offers great potential in comparison to conventional manufacturing methods such as milling or turning. One of the potentials mentioned most frequently is “complexity for free”, e.g. [HHD05, Com10, GRS10]. This gives the impression that theoretically any geometry can be produced by additive manufacturing. However, in practice it has been shown that frequent discontinuations occur during manufacturing process or that there are deviations of the produced physical part as a function of the component geometry. For this reason, design guidelines have been developed in recent years providing permissible nominal geometries or qualitative information on how to design specific geometry characteristics [Ada15, KHE15, Tho09, VDI3405-3]. Presently, it is difficult for the designer to get an overview of the various guidelines. A distinction between relevant and non-relevant guidelines is not always clear depending on the present geometry. With the increasing use of topology and shape optimizations, the identification of recurrent geometry features is even more difficult and requires great effort.

Due to this, a method for a software-based design check needs to be developed that automatically inspects the part geometry and compares it to design guidelines. With this design check, it is possible to guarantee a robust manufacturing process with minimum deviations in shape before starting the manufacturing process. The method is developed for parts built by the Laser-Beam-Melting-Process.

State of the Art – Design Guidelines and Design check

In recent years, different guidelines have been developed for designing components by additive manufacturing. These consider different production machines and parameters as well as materials. Some important works for the Laser-Beam-Melting are described in [Tho09, KHE15, Ada15]:

Guidelines on designing overhangs, gaps, boreholes and the potential need for support material is described in the work by [Tho09]. Parameter studies were carried out for different component geometries using the material 316L while also looking for manufacturing restrictions. Based on the results, specimens to specifically cause regarded effects and guidelines were developed.

The research of [KHE15] is aimed at developing design guidelines for lightweight components made of TiAl6V4. Typical lightweight elements such as beams and cavities were taken into account and the results recorded in a table.

[Ada15] developed a method based on so-called standard elements which are geometrical shapes frequently used by designer, such as rectangles or circles. For the defined standard elements, specimens representing typical geometrical characteristics of these standard elements were developed. Using these specimens, parameter studies were performed to identify geometric conditions under which reliable production is not possible. The results were recorded in design rules that each describe a fact that has to be taken into account in the design and manufacturing preprocessing phases.

The variety of developed design guidelines makes it difficult to maintain a corresponding overview of the relevant design features. Complex structures in particular require a great deal of effort and expertise in order to comply with the relevant guidelines. Therefore, in the work by [RE17] algorithms are presented to realize an automatic analysis and assessment of a part’s geometry. The algorithms use the triangulated surface geometry (STL) of a part and are implemented in a web-based platform. They check the geometry of a part by comparing geometrical features with preselected design guidelines which are shown in table 1. With this selection it is possible to check relatively simple part geometries. However, for numerically generated structures such as topology-optimized structures, further guidelines have to be considered. An example of this is the overhang angle which is not included in the selected guidelines. In addition, the component orientation in the building chamber and thereby the building direction of the component are not taken into account, thus neglecting its influence on other guidelines.

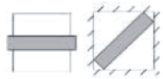
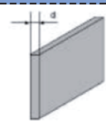
Restriction or guideline	Figure	Description
Part dimensions		
Part dimensions		The part has to fit into the build chamber of the generating machine. If necessary, the part must be oriented appropriately.
Walls and gaps		
Wall thicknesses		Wall thicknesses should not be below a certain limit to ensure a reliable and clean generation. The limit can depend on the orientation (angle to the build platform).
Gap dimensions		In order to avoid powder accumulations, merging of opposite areas within the part and facilitating removal of powder in the post-processing, gap dimensions should not fall below certain limits.
Cylinders and boreholes		
Cylinder diameters		The diameter of cylindrical structures should not be below a certain limit for a reliable and clean generation process.
Borehole diameters		In order to avoid powder adhesion, borehole diameters should not fall below a certain diameter.

Table 1: Selected guidelines for an automated design check by [RE17] (example figures by [KHE15])

Methodology for a software-based design check

Given the described deficits in the state of the art, a method has to be developed that allows a software-based, automatic check of the component shape. The method should be applicable to complex geometries and take into account the part orientation in the building chamber. Furthermore, the production machine, parameter set and type of material should be considered as well. The method developed is shown in figure 1.

To reach this goal, i.e. the development of a software-based, automatic design check, the frequently employed STL data format is examined in more detail in order to check whether all necessary geometric properties of a component can be reliably recorded before starting the production process. An analysis of existing design guidelines to identify the most important ones with a relevant influence on the manufacturing process and the manufactured part quality is carried out as well. The results of these two steps are integrated into the identification of geometric features in order to be able to examine specific geometric structures. In addition, a database containing the permissible geometric limit values is created based on the identified guidelines. The design check can be realized by comparing geometric attributes with corresponding limit values from the database.

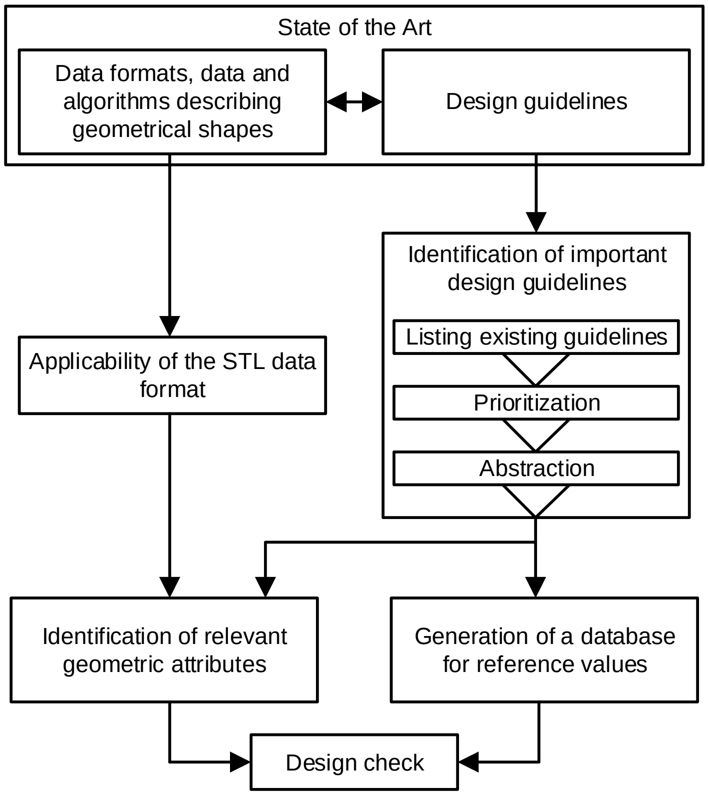


Figure 1: Methodology for realizing a software-based design check.

The individual steps of the method and the results achieved are described in more detail in the following chapters.

Applicability of the STL data format for the software-based design check

The automated design check requires information about the part geometry to be manufactured as a virtual model. For this purpose, different data formats are available for the various phases from designing up to manufacturing. A closer look at the process chain shows that the STL data format is generally available between the CAD and the pre-processing steps (figure 2). This data format offers the possibility to describe the geometric shape of the component independently of specific programs.

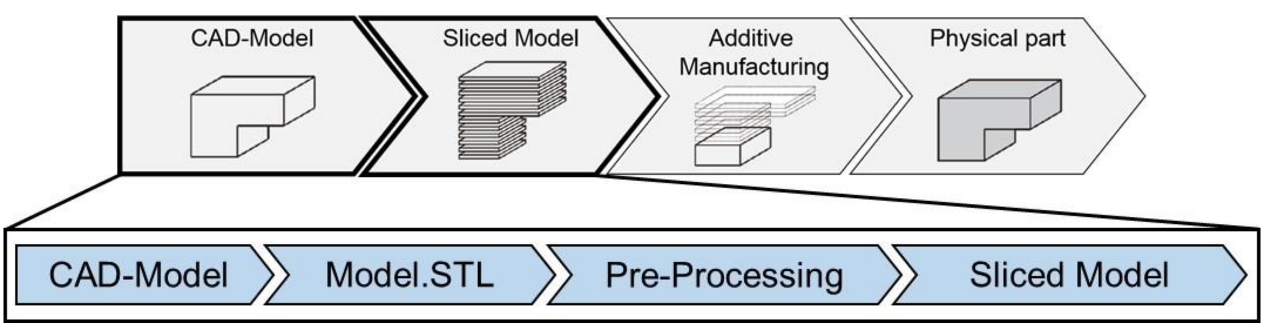


Figure 2: Process chain started by the CAD-Model to the manufactured, physical part [TL18].

The STL data format approximates the part geometry using triangles. Each triangle contains the following information:

- Position of each corner point relative to a coordinate system.
- Orientation of the triangle surface which is represented by a normal vector always pointing away from the component surface.

Figure 3 schematically illustrates the approximation of a component and a triangle with the described information.

With the information about position and orientation of the triangles it is possible to get further information about the part geometry (figure 4). Linking triangles offers the possibility to obtain geometric information such as distances (b, l, h), angles (α, β) and area sizes (A). With these, typical geometric features can be determined such as wall thickness or gap width, orientation of a surface in space or the cross-sectional area.

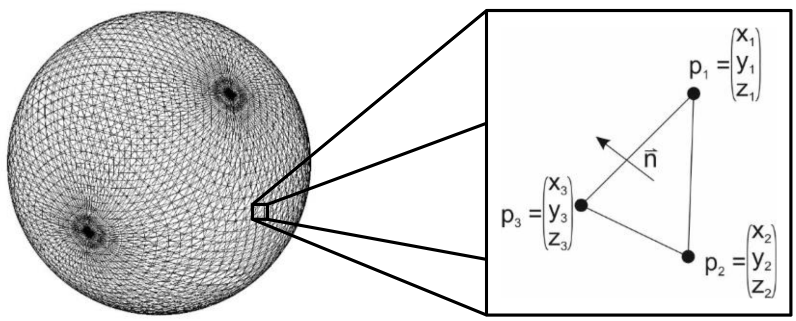


Figure 3: Ball approximated with triangles, showing one exemplary triangle with information about position und orientation in space.

Consequently, the STL data format offers the possibility to obtain the necessary geometrical information of a component independent of a specific software, thus providing the basis for an automated design check.

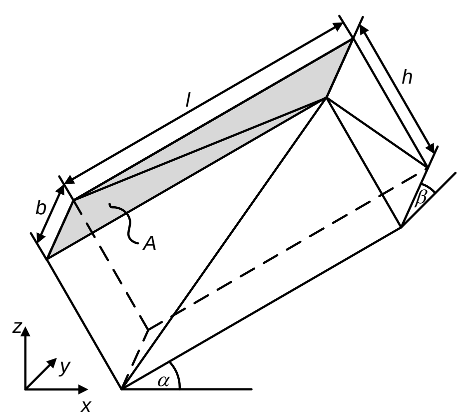


Figure 4: Identification of geometric information of the part geometry by systematically linking triangles [TL18].

Identification of the most important design-guidelines

The shape of a component has to meet various design guidelines to ensure a robust additive manufacturing process. For an overview of the different design guidelines, a table was created listing the guidelines of research by [Ada15, KHE15, Tho09]. As a result, about 100 guidelines were identified with information on the design of components using the Laser-Beam-Melting-Process. With regard to a software-based design check, it is questionable if this large number of guidelines can be checked within a reasonable time. Consequently, the number of considered guidelines has to be reduced. For this purpose, a procedure is developed that identifies the most important guidelines for a software-based automated design check. This procedure is shown in figure 5.

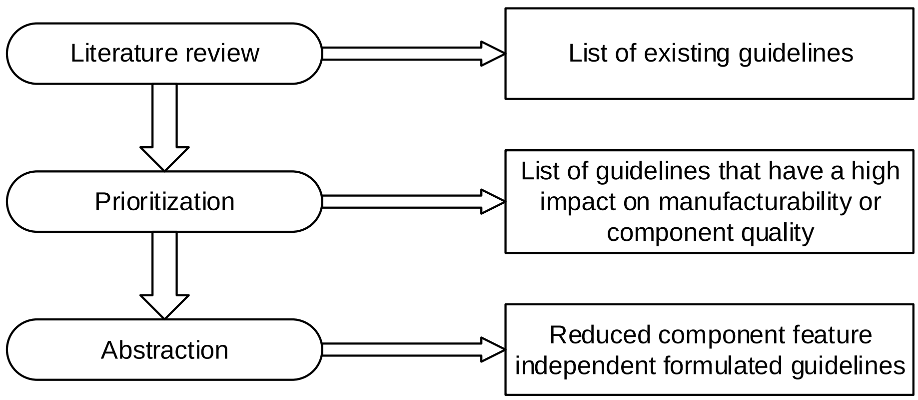


Figure 5: Procedure to identify important guidelines for a software-based automated design check.

The identified guidelines of the literature review are prioritized in a second step. The prioritization is done by dividing the guidelines into four priority levels defined by the criteria presented in table 2 [TL18, LTM+18].

Priority	**Definition**
1	Risks for manufacturing process or later component function
2	Loss in component quality
3	Determination by the user without influence on manufacturability or component quality
4	Already contained in other guidelines

Table 2: Priority level and criteria for the performed reduction of design guidelines

Priority level 1 contains guidelines which, if not complied with endanger the manufacturing process and the construction process is likely to be aborted. Furthermore, this priority level includes guidelines, such as e.g. minimum wall thickness or maximum overhang length, which must be considered for the later function of the component, so that it can fulfill its intended task.

The second priority level contains guidelines with an influence on the manufactured component quality. If these guidelines are not adhered to, the component may be manufactured and fulfill its intended task, but will show deteriorations in quality. These deteriorations can be corrected by post-processing. Exemplary guidelines taking into account these deteriorations refer to e.g. the reduction of the stair stepping effect or material adhesions.

Priority level 3 contains guidelines without any influence on the manufacturing process or the quality of the produced physical component. These guidelines often give hints on specific design features without quantifiable indications, such as providing openings to remove powder in cavities or freely choosing the position of the part in the building room.

Comparable or identical guidelines, which are named by different authors and are already assigned to a prioritization level 1 to 3, are assigned to priority level 4. A typical guideline example is the use of a minimum gap size that exists in all considered references.

With regard to a robust additive manufacturing process, priority levels 1 and 2 are most important. After prioritization, 25 guidelines with a high impact on the manufacturing process or the component functionality and the component quality of the manufactured component are identified.

In a subsequent abstraction, the guidelines are examined for similarities. In particular, the causes for shape deviation are regarded. Also, the general validity of the described guidelines is checked for various geometries, not just the ones specified in the guideline. As a result, further guidelines of a more general character, including one or more of the previous guidelines were developed, e.g. a guideline describing the permissible change of the cross-sectional in building direction.

The abstraction yields nine guidelines that must be checked by an automated software-based design check. These guidelines have priority level 1 and are listed in table 3.

Guideline	**Feature name**
1	Minimum wall thickness
2	Minimum gap size
3	Minimum inner radii
4	Maximum inner radii without support material
5	Minimum outer radii
6	Variation of cross sectional area
7	Maximum cross sectional area
8	Maximum overhang length without support material
9	Minimum overhang angle without support material

Table 3: Identified priority level 1 guidelines for an automated, software based design check

The geometric attributes of the identified guidelines in table 3, include only distances, areas, angles and radii. With respect to the STL data format used, all of these geometric attributes can be identified.

Generation of a database for reference values

The identified design guidelines determine which geometric attributes of the virtual part geometry are to be checked. In order to check whether the guidelines are adhered to so that the component can be manufactured in a reliable way, these geometric attributes must be compared with permissible limit values. Therefore, a database was developed which contains the limiting values for each of the identified guidelines. The investigated research works contain information on the permissible limit values. It was found that partly different limiting values are given for the same type of guideline. This can be attributed to the use of different materials, production machines and parameter sets. For this reason, the database should take these factors into account. The structure of the database results from the logical relationships of these factors. The database is divided into four hierarchical levels which are shown in figure 6.

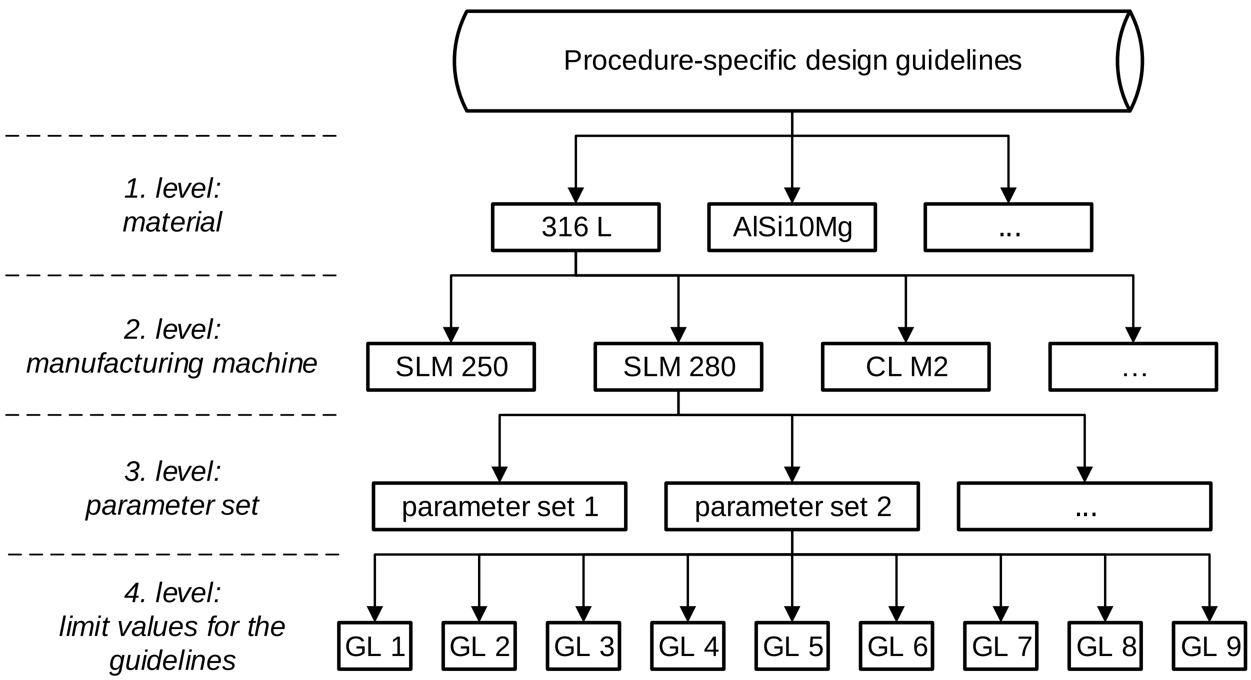


Figure 6: Hierarchical structure of the developed database.

The first level contains different materials. In the second level, the production machine can be selected. Specific parameter sets can be selected via the third level. Level four contains the permissible limit values for the corresponding guidelines under selected production boundary conditions.

One advantage of this database structure is that it can also implemented into standard software such as MS Excel. Furthermore, the database can be extended by additional factors on all hierarchy levels, so that additional materials, machines and parameter sets can be considered.

Identification of relevant geometric attributes

To identify the geometric attributes angles, areas, distances and radii mentioned above, a surface mesh is generated from the STL format. Merging coincident triangle corner nodes of the STL data leads directly to a triangular surface mesh of the part to be examined. The necessary geometric attributes can be determined from the generated surface mesh in three different ways:

By defining a building direction vector, overhang angles can be taken into account during the manufacturing process. The evaluation can be carried out via the surface normal vectors, which are directly assigned to each triangle. Alternatively, surface node normals can be computed as a weighted average of the neighboring triangle normals, resulting in a more smooth normal field [BKP+10], but with the drawback that nodes at features need a special treatment.

The determination of cross-sectional areas and their change in the building direction requires a greater effort than the previously described method. Intersecting the surface mesh by cutting planes perpendicular to the build direction generates polygonal lines with vertices where the mesh edges hit the plane. These polygonal lines may be used to compute the cross section area by shoelace formula (Gauss's area formula). This must be done at discrete positions in the building direction, where the average edge length of the STL mesh data is an appropriate dimension for a discretization parameter.

The measurement of distances and radii can be realized by a third method, which is based on the extraction of medial axis points and the computation of diameters of maximal circles or balls as described in [MBC11]. In 2D, several circles or balls are layed into the component so that they touch the walls at least at two points without intersecting the walls or touching each other. The medial axis is a result of linking the centers of the circles. Wall thickness and curvature radii are determined by the radii of the maximum circles. This works well for structural part members ('inside') as well as for cavities, e.g. gap widths ('outside') (see figure 7). Furthermore, it may be applied in 3D (balls) as well as in 2D (circles), i.e. for cross sectional polygons as mentioned before. Optionally exploiting the angles between the normal vectors at the boundary points of the maximum circles or balls to distinguish radii and thickness measures give rise to a powerful tool for the identification of various geometric attributes relevant for a number of guidelines.

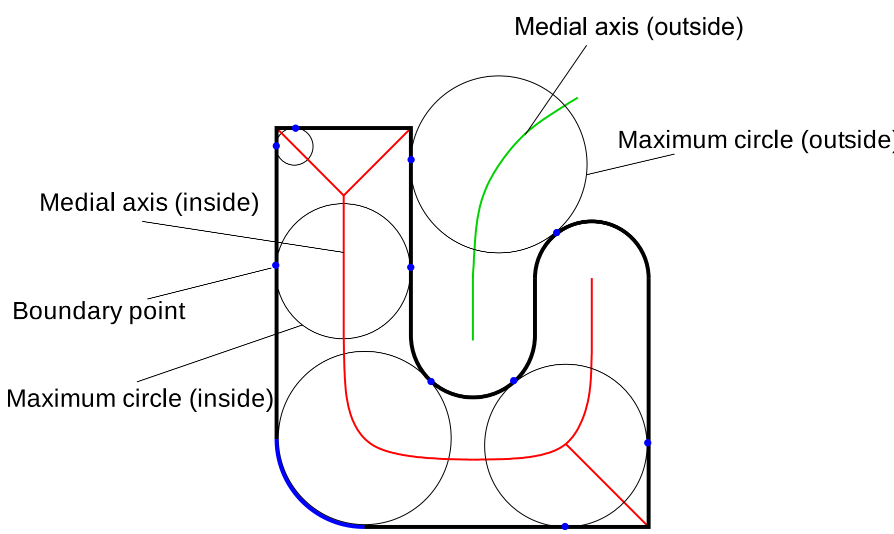


Figure 7: Schematic representation of the method of medial axis points and maximum circles for the determination of radii and distances.

The three presented methods allow the determination of the relevant geometric attributes, thus making a reliable analysis of the manufacturability of components even before production starts possible, if the limit values of the database are used for comparison.

Summary and Outlook

Additive manufacturing offers the potential to produce complex structures. However, additive manufacturing is subject to production restrictions that must be taken into account when designing components. For this reason, numerous design guidelines have been developed in recent years to allow the best possible production. The verification of complex structures with regard to compliance using design guidelines involves a great amount of effort. For this reason, a software-based design checker has to be developed. The STL data format was identified as a good starting point for recording the geometric shape of a component, since it contains all the relevant geometric attributes.

To identify the most important guidelines for the automated design checker, three extensive literature sources were reviewed and all guidelines relating to the laser beam melting process were identified. The number of guidelines was reduced by prioritization and subsequent abstraction. As a result, nine guidelines were identified that must be checked before production in order to guarantee reliable production.

A database structure was created for the design checker, where the database contains limit values to be compared with values of the designed geometry. The structure takes into account influencing factors such as the material, production machine and parameter set intended for production. The advantage of the database structure is that it can also be implemented in MS Excel, for example, and be extended individually at all levels. This allows additional materials, machines or parameter sets to be added to the database.

For the software-based inspection of the component design, there are three ways to identify the relevant geometric attributes angles, surfaces, distances and radii. They can be used to check all the guidelines that must be taken into account for robust additive manufacturing.

In the next step, the presented results of this method will be implemented into a software program. This has to be validated by using components of varying complexity. Furthermore, it is intended to implement the guidelines of priority level 2. This provides for compliance with guidelines for the best possible additive production to be checked. Additional implementations of guidelines for e.g. a cost-effective design result in the potential of a multi-target-optimized design check. This allows several diverging design goals to be weighed against each other and an optimal component design for additive production to be identified.

Acknowledgement

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