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Systematical redesign method for topology optimized results using 3D-printing

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Abstract
3D-Printing enables designers to create parts with higher geometric complexity and gives them the opportunity to use new design methods such as topology optimization for industrial purpose. Topology optimization (TO) uses algorithms based on finite elements to provide the best material distribution for a given design space and defined boundary conditions. However, raw TO results are usually inconsistent and non-continuous structures that need to be redesigned. Since the smoothing tools and algorithms available on TO software programs are not covering all manufacturing aspects, this paper presents a strategy for interpreting and redesigning the optimized topology using five defined sub-structure elements. Several TO structures from the literature have been studied in order to choose those sub-structure elements that can fully describe any TO result. The approach called KS2 (Knoten-Stab-Schubfeld) ensures an efficient workflow. Three different reconstruction methods are considered in this work, from a manual to a fully automated one. The advantages and drawbacks of each method are discussed, and a systematic procedure is suggested, that can be applied on any optimized structure. Finally, the three variations were produced by means of 3d printing and compared with each other.

Keywords Topology optimization · 3D-Printing · Redesign · KS^2-approach

1 Introduction

Topology Optimization (TO) is a powerful tool that generates the best material distribution within a predetermined design space and under defined boundary conditions. The resulting optimized geometry is usually considered by designers to be a complex, bionic-looking structure that cannot be easily manufactured with conventional manufacturing processes where parts are produced by material removal like machining or by formative processes like casting or molding [1]. Additive manufacturing (AM) enables to get rid of significant conventional manufacturing constraints and offers a greater design freedom. Recent improvements in AM field aim to produce end-use parts and give designers the opportunity to take advantage of TO. Lightweight components can be designed specifically either for metal or polymer 3D-printing. Manufacturing constraints such as overhang angles, minimum curvature radius or minimum thickness are easy to take into account when performing TO. Nowadays, different TO approaches are available in the literature, such as element-based solution approaches, in which the domain is discretized into plenty of finite elements, or discrete approaches, which use discrete variables. As mentioned in [2], the most common optimization method is the solid isotropic material with penalization (SIMP). This density-based algorithm solves the TO problem in a discretized geometrical domain called

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"mesh", and generates the ideal force-flow paths in an iterative way. The SIMP-algorithm is widely implemented in TO software and is used in the industry for lightweight and high-performance applications.

The main drawback of the SIMP method is that the optimization delivers an organic shape in STL-format that often contains inconsistencies. Therefore, an interpretation and a reconstruction are required in order to get a manufacturable CAD-model and meet the client's requirements. Figure 1 illustrates different issues like a rough surface and unconnected fragments that make SIMP optimization results not directly manufacturable. As mentioned in [3], the generated mesh from TO software is often imported into a traditional CAD software for the post-optimization stages. Many researches have tried to automate the redesign process, but the tools currently available for smoothing the geometry are not reliable enough and a manual reconstruction by a designer has to be considered [4]. In the literature, the gap between the TO result and the final part remains unclear and highly depends on the designer's interpretation and experience as explained in [5], where a state of the art and a classification of the different post-optimization strategies has been established. This paper deals mainly with the interpretation, the redesign stages and introduces the KS^2-approach. This approach is based on the division of optimized model into five sets of sub-structure elements. The aim is to bring keys to interpret any TO results and thus help designers for the redesign process.

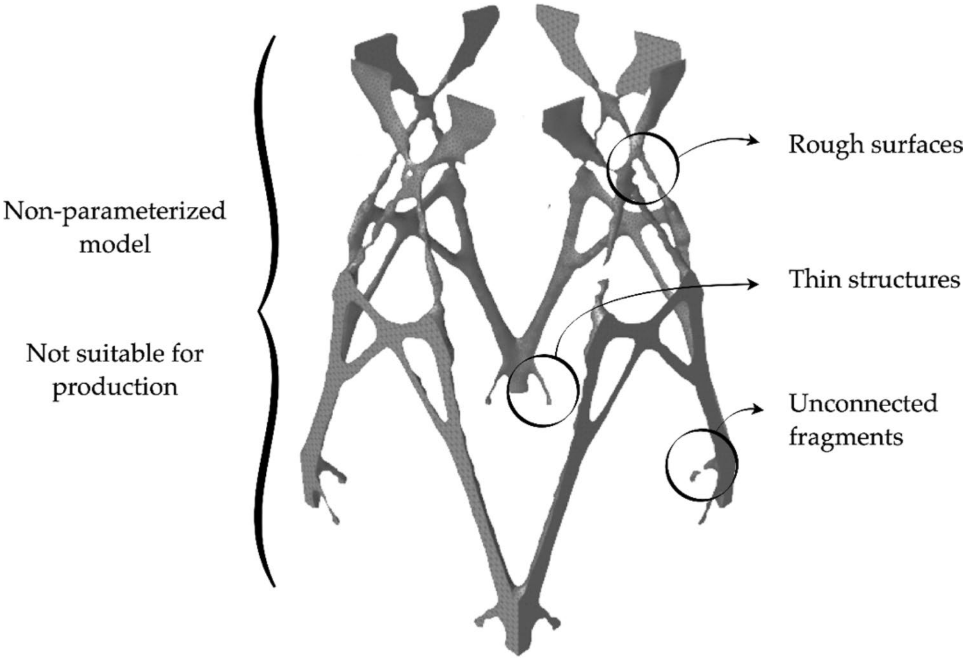
2 Topology optimization

2.1 Topology optimization methods

Structural optimization problems are divided into three groups: sizing optimization, shape optimization, and topology optimization [6, 7]. Among these three classes, topology optimization is the most general form. It's basically a material distribution problem that is solved within a given design space and under defined boundary conditions. The optimal topology is generated by algorithms in an iterative way and leads to a lightweight structure with high performance.

Different approaches can be found in the literature and differ by the solving method. On the one hand, gradient-based approaches, including SIMP-method, use discretized finite element densities as optimization variable [2] and provide a grey-level image made of element with a density value between 0 and 1 [8]. In order to get a design represented with elements with density of respectively 0 or 1, the SIMP method penalizes all the intermediate values, i.e., density values close to 0 are set to 0, and those close to 1 take the value 1. On the other hand, in discrete approaches such as the Evolutionary Structural Optimization (ESO), also called "hard-kill method", and the Bi-directional Evolutionary Structural Optimization (BESO), a discrete variable (Von Mises stress, energy density) is chosen as a "criterion function", and the elements with the lowest value are eliminated in each iteration. BESO is an extension of ESO, in

Fig. 1 Raw topology optimization result from a SIMP algorithm



which some elements can be added where material is needed [2, 9]. As a result, a grid with black and white elements is obtained where white indicate an empty space, and black means that there is material. In [10], Rozvany makes a detailed comparison of SIMP and ESO methods, and dedicates a chapter about their history and origin [11, 12]. Moreover, one should be aware that there are other topology optimization methods, such as Level-set optimization, that are not explained in this article.

TO has experienced an incredible growth in research and industry applications over the last twenty years. The most important fields of practical application are the automotive industry, motorsports and aerospace industry. Indeed, the optimal material distribution contributes to a strong reduction of the components' weight, and this advantage is crucial in the seek of performance in racing or in fuel consumption to propel a rocket or a plane. Additive manufacturing plays an important role in the development of TO [13] since it allows the creation of more complex shapes. Each manufacturing process requires a specific design. For example, a part designed to be manufactured by a machining process, such as milling or turning, requires tool space and symmetries. A part intended to be forged or cast needs the mold to be removed. In fact, the result of the optimization is mainly used as inspiration for the final design, but both are often very different. Unlike material removal or material deformation processes, additive manufacturing offers new opportunities to designers. It allows to get rid of many manufacturing constraints and to give new design ideas.

In parallel with advances in additive manufacturing, many software programs have implemented topology optimization in addition to Finite Element Method (FEM). Nowadays, a bunch of software is available for commercial purposes. [14, 15] have listed a large selection of software and Matlab programs. In [15], Reddy highlights the main software capabilities, including the ability to take some traditional manufacturing constraints into account like symmetry or molding, as well as the vibration analysis. [14] extends the selection of [15] with two additional software programs and references about Matlab TO codes [16–22]. According to [15] the most implemented TO algorithm in commercial software programs is by far the density-based SIMP-method. However, even if the SIMP method is well implemented in TO software programs, this method provides TO results that require a designer's interpretation [15, 23, 24]. This post-optimization stage is essential to adjust the mesh and validate all the manufacturing constraints of the chosen process. These constraints are sometimes considered during the TO [25] but the result still has to be revised. The use of manufacturing constraints in the optimization programs can help to evaluate the difference in the amount of material needed and therefore the costs between the different processes, and help to get closer to the final result. The more the manufacturing constraints are taken into account upstream, the closer the TO result will be to the final design. However, the interpretation step remains necessary.

2.2 Decomposition of topology optimization result into sub-structure elements

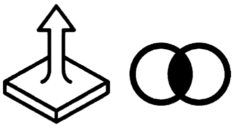
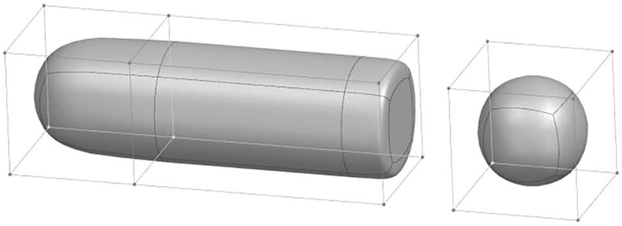
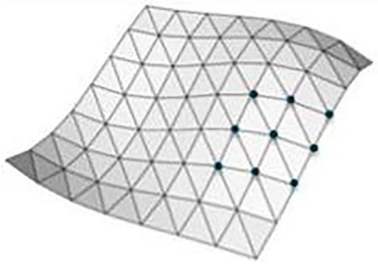
Since the solver determines the optimal design to either minimize the mass or maximize the stiffness of the part, this leads to complex and bionic-looking structures. The interpretation is then a challenging stage that highly depends on the designer's skills. Therefore, it has an important influence on the reconstruction step. This statement is the starting point of KS^2-approach. KS^2 stands for "Knoten—Stab—Schubfelder" which means "Node—Beam—Shear-field" in German. A study was conducted empirically to propose a systematic decomposition of any TO result. Seventy structures from TO were selected with various geometries (2D, 3D). From the observation of these TO results, some sub-structure elements have been identified that occur in all TO-structures due to the bionic aspects of the links. Beams, nodes and functional surfaces can be found in any topology optimized part. In order to ensure a full description of the geometry, shear-fields and interfaces have been added to the classification. According to the KS^2-approach, the five sub-structure elements are defined as follows:

Functional surfaces are surfaces of the component that are temporarily or permanently in contact with another external functional areas and thus enable the transfer of energy. Functional surfaces are usually defined as non-design space on the software since it must not be modified by the TO algorithm.

Interfaces are a particular type of functional area where the connection between two surfaces is done with connection elements (ex: bolts). Interfaces are always defined as non-design space in the pre-optimization stage.

Beams are structural elements, which usually have a larger dimension in any spatial direction than in the other spatial directions. Beams ensure the transfer of energy between two other sub-structure elements and can be represented in a simplified way by means of lines. They correspond to the force-flow path calculated by the TO algorithm and carry either tension, compression and sometimes bending loads.

Table 1 Excerpt of CAD-tools categorized for the workflow in Fig. 2 for manual reconstruction of the 3D models

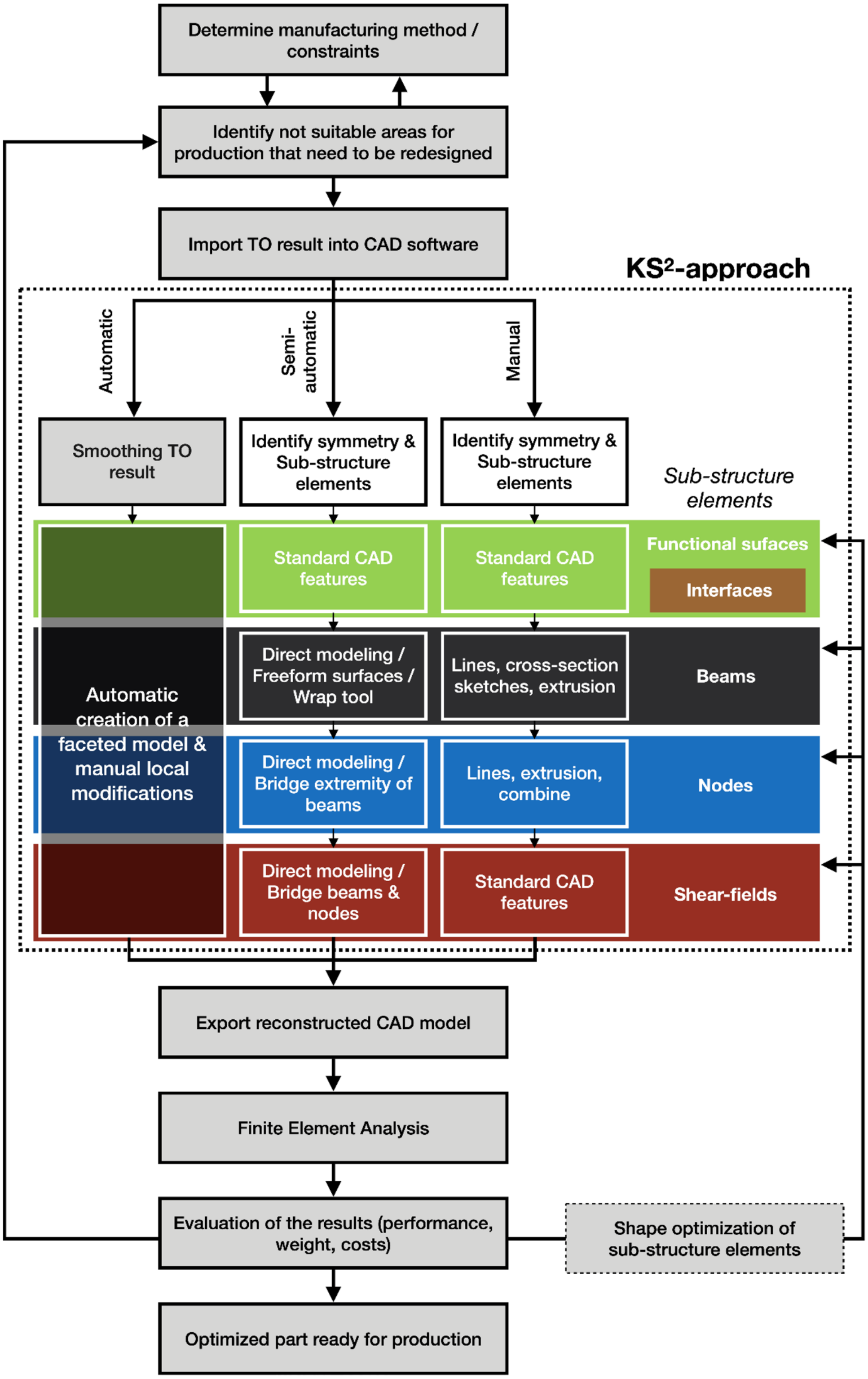
Standard CAD features	Line/Line-chain	Extrude, combine, boolean operation
	Rectangle	
	Circle	
	Arc	
	Ellipse	
	Spline	
Direct modelling/Nurbs-manipulation	Wrap mesh	
	Bridge cages	
	Split cages	
	Sharpen NURBS	
Automatic faceting/manual manipulation	Faceted surface / points	

Nodes are defined as areas where at least three beams intersect. Nodes are subdivided into different categories according to their spatial geometry (planar or non-planar nodes), the number of beams converging at the node, and the angles between the converging beams.

Shear-fields have been added to the KS^2-approach in order to define some regions that cannot be represented by any of the four previously introduced elements. Indeed, the representation of a TO result with the four elements defined so far has limitations. Shear-fields are finite surfaces that are bounded by their contour and which can be connected to functional surfaces or beams by transition points.

To validate the sub-structure elements definitions, students and engineers with different backgrounds were asked to interpret TO structures using the five element definitions of the KS^2-approach. This experiment showed that all participants decomposed the parts in a similar way, which reinforced the relevance of the definitions. Thus, an objective and universal interpretation of TO results can be achieved through the KS^2-approach. Furthermore, its systematic nature helps designers prepare more effectively for the redesign stage. During the interpretation, all small fragments that appear in SIMP optimization results are eliminated, as they don't meet any of the five definitions. The definition of these sub-structure elements is essential for the understanding of the KS^2-approach that is described in Sect. 3.

Fig. 2 Post-optimization procedure for KS^2-approach



3 Interpretation and redesign methods: KS^2-approach

Different post-optimization strategies are available in the literature and have been sorted by [5] into an interpretation step and a redesign step. Interpretation and redesign strategies are separately broken down into three categories: automatic,

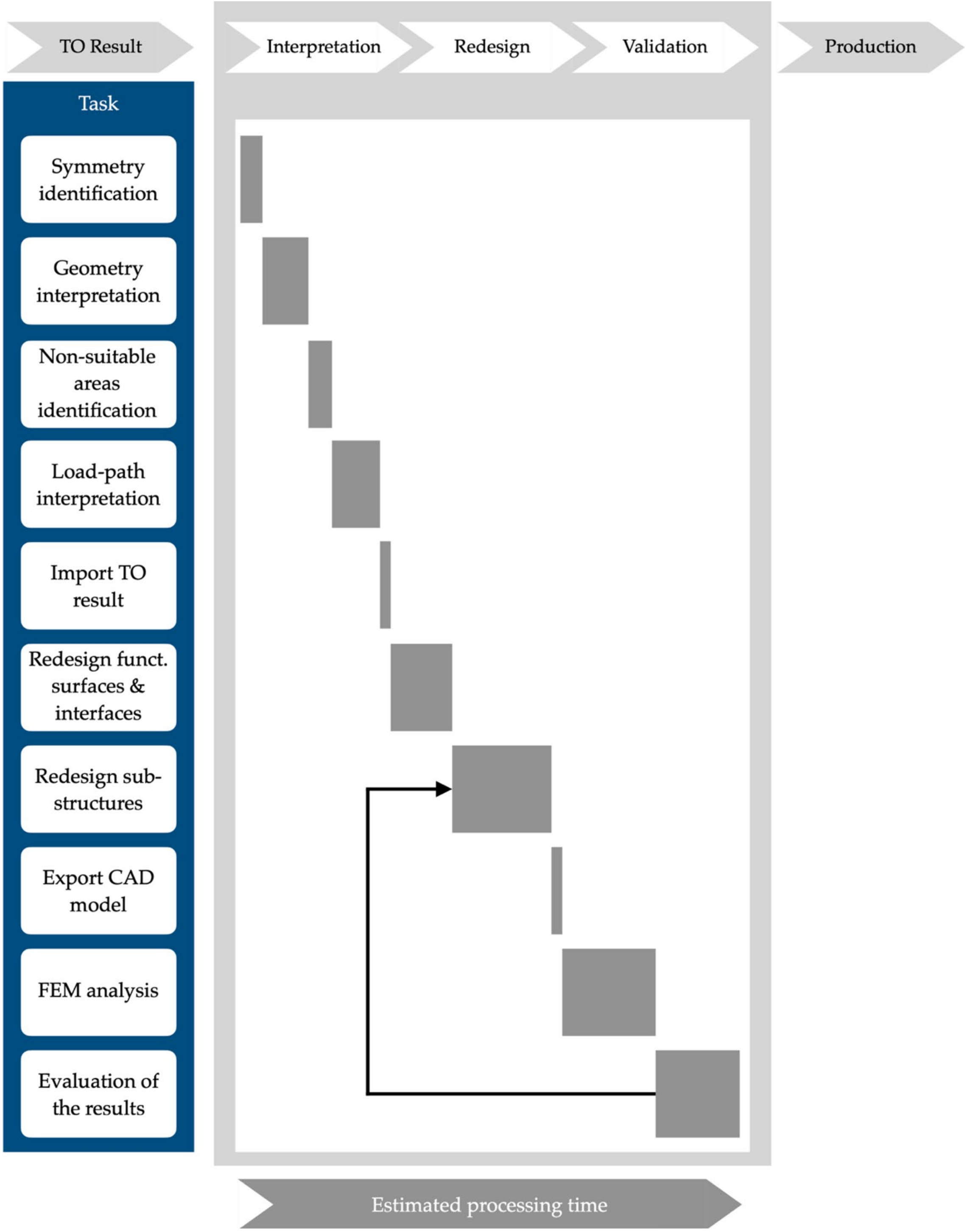


Fig. 3 Post-optimization process according to VDI2221-2-2019 [28]

semi-automatic or manual, according to the degree of automation.

The KS^2-approach has been developed to fill the gap between raw unstructured TO results and final manufacturable components through a defined procedure [26]. The designer's analysis of the components is thus guided and, consequently, less subjective. The entire process is shown in the graph in Fig. 2. The given procedure concerns the post-optimization stages [27]. Furthermore, a excerpt of the methods of CAD-tools (e.g. in Siemens NX, Altair Inspire) shown in Table 1 can be used to perform the reconstruction. The same process is given in Fig. 3 as a standard design process graph

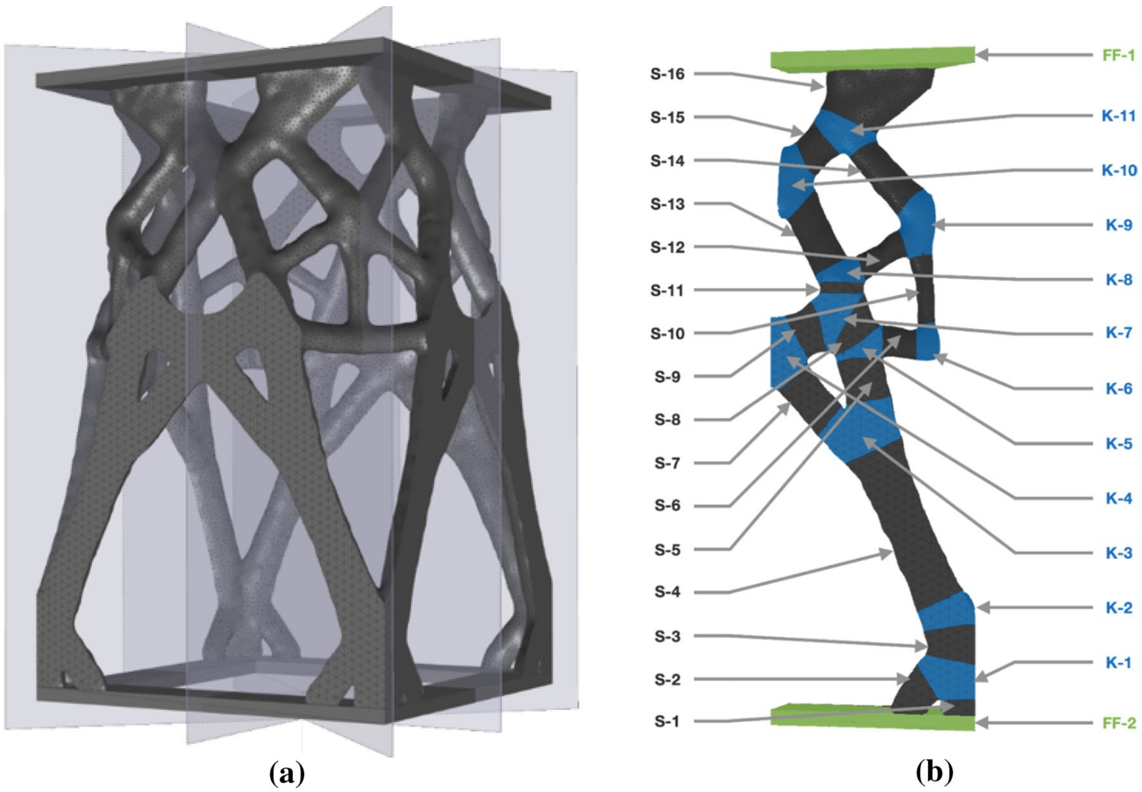


Fig. 4 **a** Symmetry identification; **b** Interpretation of the portion from TO result to be mirrored

according to the VDI2221-2-2019 design manual [28]. The choice of manufacturing method has a significant impact on the reconstruction stage. Indeed, geometrical constraints are very different depending on whether the part is manufactured in a traditional way or by additive manufacturing. After this first decision is made, the designer can identify all regions that don't fulfill the manufacturing requirements. For instance, AM processes can print accurately parts that are thin up to a certain point. In addition, overhangs can be avoided by using angles smaller than 45°.

Basically, the procedure described here is based on the commercially available software tools from Altair Inspire and has not been implemented numerically. This could be automated numerically in further work. Prior to the start of the redesign process, [1] advises to use built-in smoothing functions in TO software to aid for the interpretation. Then, the designer proceeds with the KS^2-method and choses the degree of automation he wants to apply for the manual reconstruction tools already implemented in common CAD-tools based on Table 1. The more the reconstruction is automated, the less manufacturing constraints are well taken into account. Some TO software programs include a reconstruction of the TO result into a faceted model. This operation is considered in the KS^2-approach as an automatic redesign and corresponds to the left path on the graph Fig. 2. The reconstructed model is composed of hundreds of small facets that can be modified locally. The other options contain more designer interactions. The first two steps of each reconstruction methods are identical. Before both semi-automatic and manual reconstruction, the TO result must be interpreted by identifying the symmetry planes and the sub-structure elements according to their definition given in Sect. 2.2. A possible way to represent the interpreted optimization result is to use different 2D or 3D views and mark the elements with the corresponding colors, as shown in Fig. 4. Each element is numbered with the corresponding letter. "K" for nodes (Knoten), "S" for beams (Stäbe), "FF" for functional surfaces (Funktionsfläche), "SST" for interfaces (Schnittstellen) and "SF" for shear-fields (Schubfelder). Note, that the structure in Fig. 4 does not contain shear-fields.

Once the sub-structure elements are identified, they can be redesigned following the order from the graph in Fig. 2. The functional surfaces are directly related to other components. They require very accurate dimensions and specific geometries and are therefore reconstructed with standard CAD features.

Two reconstruction methods are suggested for the beams. The semi-automatic way consists in using direct modeling. Direct modeling is as an alternative approach to standard feature-based parametric solid modeling. Shapes are created by free-form modeling of NURBS surfaces and can be easily and intuitively modified afterwards. The implementation of direct modeling in software packages is combined with operations like symmetry or wrapping, which can be used to redesign the beams semi-automatically by selecting the starting and ending sections directly on the TO result. For a manual reconstruction of a 3D TO structure using standard solid modeling, the beams can be represented in a first step by lines created with the coordinates of their ends, then in a second step, the sections of the beams can be made in sketches that will be extruded along the previously created lines. Once the beams are created, an adjustment can be made to satisfy the 45° overhang angle constraint for AM. Direct modeling tools offer the opportunity to easily modify the created blocks by moving their faces, edges or vertices. For manual redesign, those changes can be made by modifying the coordinates of the lines. Regarding the nodes, they can be reconstructed semi-automatically by using the bridging tool between the extremities of the beams. With standard CAD features, the lines created for the beams can be linked together and the extrusions of the sections can be extended along those paths. Then, the different branches can be combined to make a single block. Shear-fields have various geometries depending on the TO structures. Direct modeling is way more convenient for redesigning these elements since free-form surfaces are easy to manipulate to fit the optimized mesh. However, redesigning with traditional CAD tools involves creating a sequence of sketches and operations.

Once the optimized topology is redesigned, the parametric model is exported to perform a FEM analysis. Critical areas where stress levels are high can optionally be adjusted by shape optimization. When all manufacturing constraints and customer's requirements are met, then the part is ready for production. The goal of this approach is to bring a systematic redesign method for TO that can be applied by any designer on any optimization result. The interpretation is guided by the identification of sub-structure elements and this results in a homogenization of the process that no longer depends on the subjectivity of the designer. The decomposition of the TO result into sub-structure elements and its simplified representation with colors makes the redesign task more efficient and well structured. In the following section, the KS^2-approach is applied to an example of a coffee table.

4 Results

4.1 Application of KS^2-approach

In this section, the three presented redesign methods from the KS^2-approach are applied on a topology optimized coffee table. Some prototypes of the reconstructed models are manufactured additively using Fused Filament Fabrication (read 4.2) process.

Figure 5 shows the optimized structure of the coffee table after using the smoothing function and illustrates how the amount of material can be adjusted after optimization. By sliding the cursor from left to right, the unconnected features become connected and new elements appear. On the model on the right side of the image, all beams are connected, and this result is selected for the post-optimization stage. It represents around 35% of our design space which is a 280 mm x 280 mm square frame extruded over 450 mm high.

The manufacturing process chosen for the coffee table is AM. Thus, for aesthetic reasons and to meet manufacturing constraints, the overhangs and sharp edges must be removed during the redesign phase. The identification of symmetries

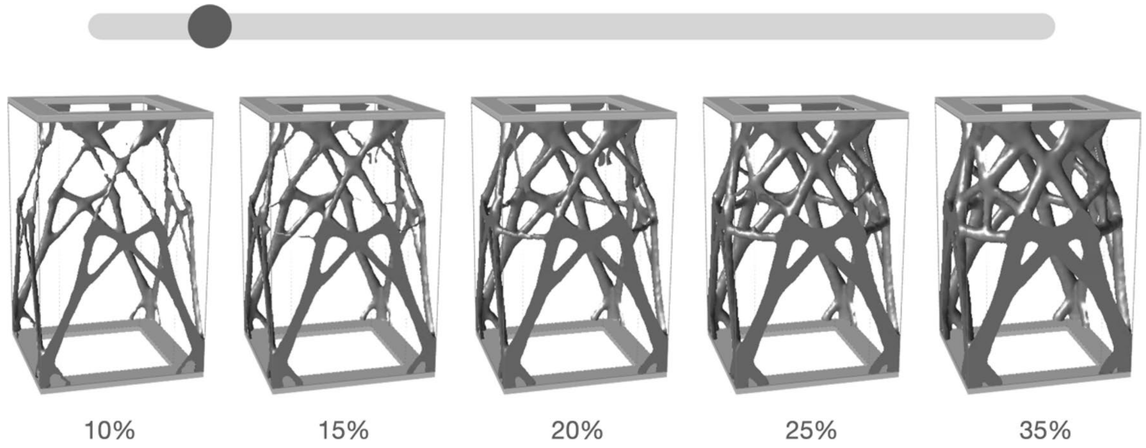


Fig. 5 Adjustment of the amount of material after topology optimization

in the structure is the first step of the interpretation. This allows the decomposition into sub-structure elements to be done on the portion to be mirrored and saves the designer time. Symmetries are shown in Fig. 4(a), as well as the interpreted portion (b).

4.1.1 Automatic redesign

The automatic reconstruction applied on the previously smoothed TO mesh is a free-form surface-based fitting tool from Altair Inspire that provides a faceted model. As for generating a traditional mesh, the number of facets for the reconstructed model can be adjusted, as well as the curvature rate. That means sharp edges from the TO result can be rounded on the automatically reconstructed model by increasing the curvature. The automatic redesign for the coffee table is given in Fig. 6(a).

2500 faces and a curvature rate of 50% provide a model smoother than the TO mesh. However, manufacturing constraints are not taken into account during this process. Some edges remain sharp and the overhang constraint is not met. The model can be modified later during the shape optimization step, though, by adjusting each facet, moving the face, an edge or a vertex. However, it is not wise to consider such a modification to meet all manufacturing constraints since it would take too much time, especially when the number of facets is high. It makes sense to carry out such modifications in regions which, after smoothing, have resulted in very small or not connected structures that can't be manufactured. These can then be manually redesigned (e.g. deleted or combined with other structures) so that manufacturing requirements are considered. Nevertheless, it becomes a very interesting feature to locally modify imperfections. Figure 6(b) illustrates how a shape optimization can be performed on facets. By slightly dragging the facet, a bump can be observed on the surface Fig. 6(c).

4.1.2 Semi-automatic redesign

The semi-automatic redesign method with direct modeling enables to quickly reconstruct the sub-structure elements. Beams can be redesigned in a first step as in Fig. 7(a) by using the built-in wrap tool available on several CAD software programs such as Siemens NX or Altair Inspire.

The TO result is used as a background to wrap the TO mesh and create free-form surface blocks. Then, as with the facets from automatic redesign, the beams can be moved, refined and modified to meet manufacturing constraints.

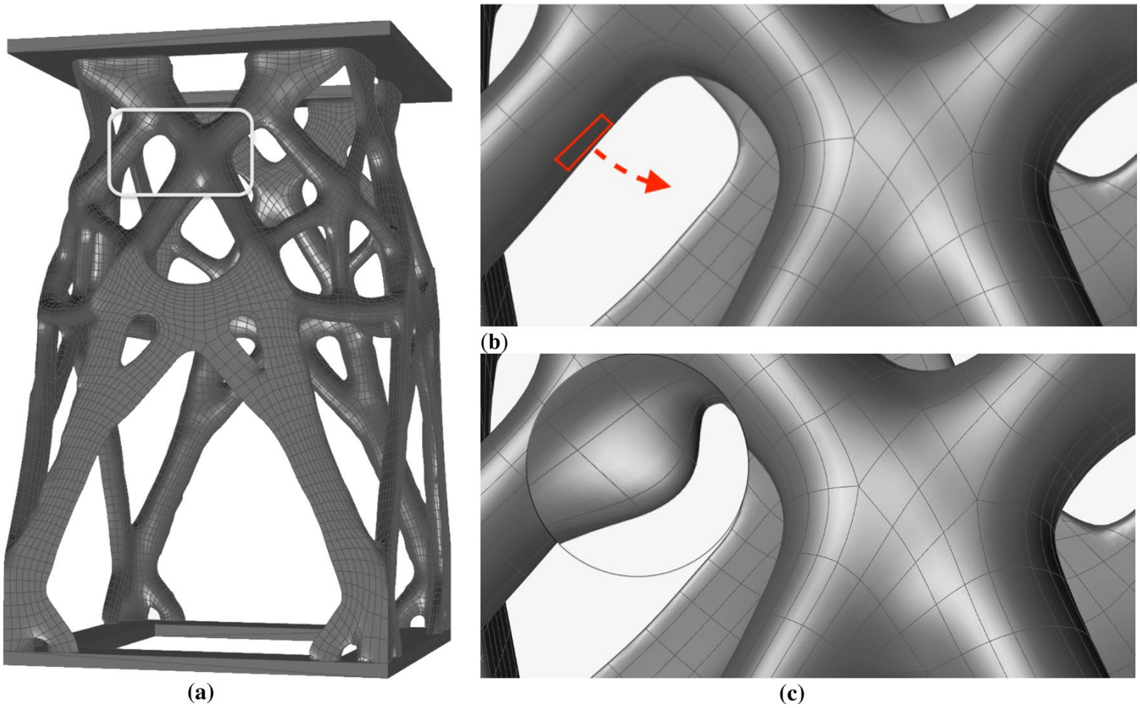
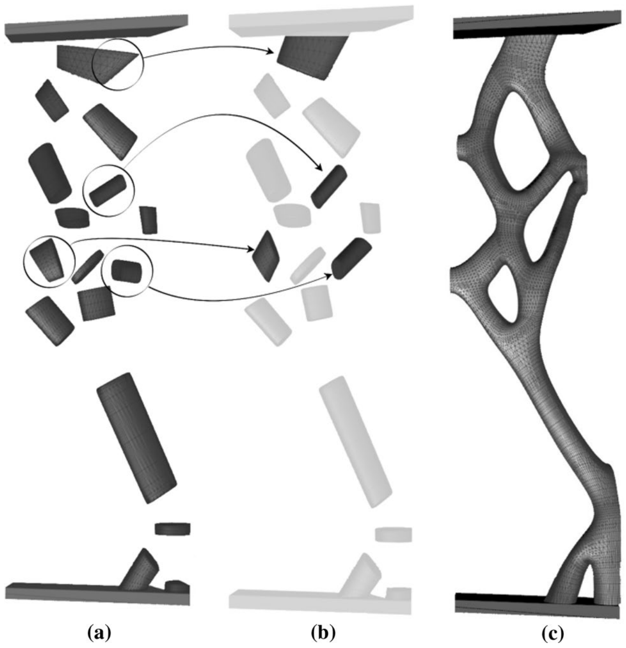


Fig. 6 **a** CAD model from automatic reconstruction; **b** Close-up on facet displacement; **c** Close-up on modified surface example

Fig. 7 **a** Reconstruction of beam with semi-automatic method; **b** Modification of beams using freeform surfaces manipulation; **c** Reconstruction of nodes with semi-automatic method



Modifications are show in Fig. 7(b). The second step consist in reconstructing the node by bridging beams together to build a single block (Fig. 7(c)). The obtained structure is mirrored to get the entire part. The reconstructed coffee table is shown in Fig. 8.

4.1.3 Manual redesign

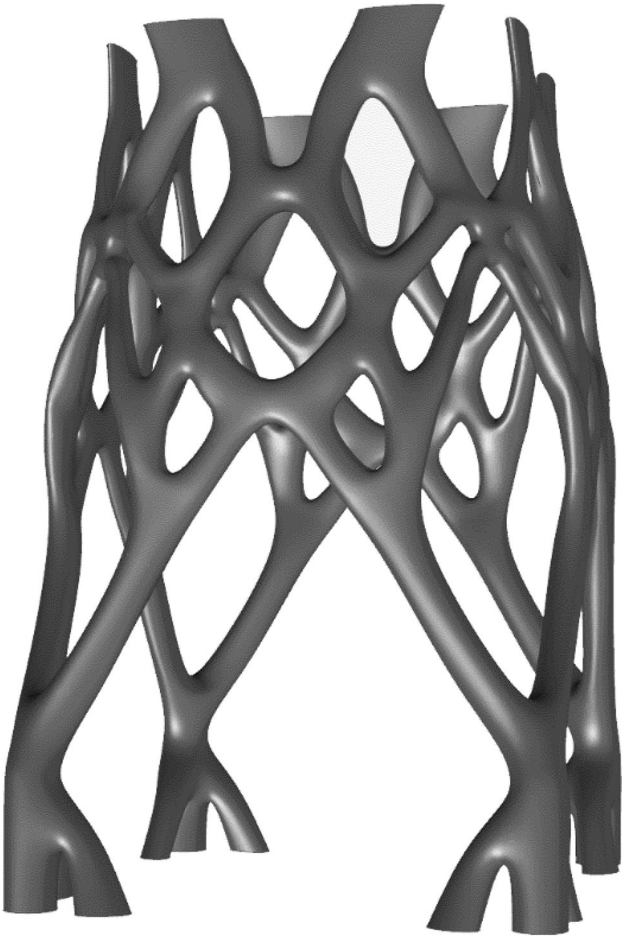
The manual redesign presented in this section is not automated at all and can be done on many CAD software programs since only standard CAD features are necessary. In this example, the CAD model is done on Siemens NX. The substructure elements are created in several steps. For instance, beams are created by extruding their cross-sections along the center-lines. Each center-line is made by inserting its ends' coordinates into the CAD program and iteratively adjusted to fit the corresponding beam location. Then, the cross-section to be extruded is drawn within a sketch in a plane normal to each center-line. Figure 9(a) shows the "line skeleton" overlayed on the portion of the TO result to be mirrored. Figure 9(b) shows the extruded beams The orientation of the beams can easily be modified by changing the coordinates of the lines.

For the nodes, the center-lines can be linked and the beams' cross-sections can be extruded along these junctions. In order to get the part connected properly, the "combine" feature is applied on all elements. Once the structure is completed and mirrored, the redesigned model given in Fig. 10 is obtained. The structure has a constant cross-section and its diameter is set as a parameter. Many parameters can be set to define the beams cross-sections. A parameter can also vary along a beam.

4.1.4 Comparison between automatic, semi-automatic and manual redesign

Three reconstruction methods derived from the KS^2-approach have been presented in the previous section and the CAD models are shown in Fig. 11(a–c) again for comparison. Each method has its advantages and disadvantages which are reviewed in this section. The automatic redesign method instantly generates a model very close to the optimization result. The fact that the result is too close to the optimized result sometimes brings the imperfections of the TO mesh. Those imperfections can be locally removed quite easily with facet manipulation. However, due to the large number of facets, modifications become very complex and time consuming when the entire structure has to be modified. It is therefore difficult to deal with the manufacturing constraints. The semi-automatic method by direct modeling has many advantages. First of all, the creation of the sub-structure elements is straightforward with an acceptable time efficiency. Secondly, the modification of the structure is intuitive and enables to take manufacturing constraints into account. Changing the geometry may also cause a performance loss. A compromise between performance and manufacturability must be found by carrying out a FEM analysis. The main drawback of the semi-automatic method is that the model is

Fig. 8 Reconstructed model with semi-automatic redesign



difficult to parametrize compared to manual redesign. In addition to the ability to assign parameters to the structure, the manual method with standard CAD tools also enables easy modification of sub-structure elements to meet manufacturing constraints. However, given the numerous steps required to create the sub-structure elements, this approach is highly time-consuming. The time required for the manual approach is estimated to be at least twice as long as for the semi-automatic method. Moreover, it's very difficult to fit the geometry of the TO result. Nevertheless, both semi-automatic and manual reconstructions can handle symmetry, which might reduce time efforts. While the automatic and semi-automatic methods are applicable to any type of structure, the manual one is more suitable for beam-like structures.

4.2 3D-printing

The reconstruction methods from the previous section have provided three different CAD models. The design guidelines for additive manufacturing have been applied during the semi-automatic approach. In this section, the three different designs are printed in a small version using Fused Filament Fabrication AM process to compare with the CAD models.

FFF (Fused Filament Fabrication), also known as FDM (Fused Deposition Modeling), is a widely used technique in 3D-printing. It offers an efficient and cost-effective method for manufacturing complex structures. The basic principle of FFF involves the extrusion of a thermoplastic filament through a heated nozzle. The filament is fed into the nozzle, where it is melted and then deposited layer by layer onto a build platform. As each layer is added, the material quickly solidifies, creating a solid object. One of the significant advantages of FFF is its ability to produce intricate and complex structures. FFF also offers a wide range of material options, including different types of thermoplastics such as PLA, ABS, PETG, and more.

The printer used for this experiment is the Raise 3D Pro2 Plus from the iMAD department of the Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau (RPTU). It has a build volume of 305 × 305 × 605 mm and supports a wide

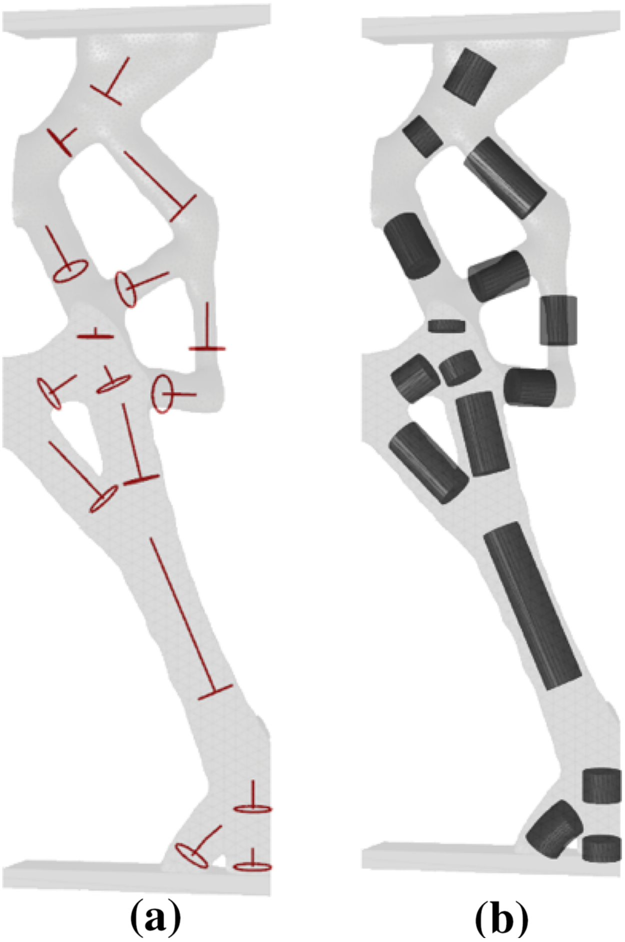


Fig. 9 **a** Lines & cross-section sketches for manual reconstruction; **b** Extruded beams along lines

range of materials. The dimensions of the coffee table are 280 × 280 × 450 mm. In order to connect the elements of the printed part as soon as possible to ensure more stability, the structure was printed upside down. Otherwise, the four legs of the table would have merged at a height of more than half the structure.

The three models were printed at a 20% scale. The results of the three printed parts are presented in Fig. 12(a–f) next to their CAD models. The semi-automatic and manual methods are the most convincing in terms of print quality. For the semi-automatic approach performed in this example, this conclusion was to be expected since AM constraints were considered during the redesign stage. The directions of the beams were modified in order to avoid overhang angles greater than 45°, and therefore print the part without any support. This consideration of manufacturing constraints explains the difference between the redesign model and the TO result. When manufacturing the prototype of the manual method, the choice was made to get as close as possible to the optimized result and to use supports for the overhang.

5 Discussions and conclusion

The KS^2-approach presented in this article solves the general problem of analysis and interpretation of topology-optimized parts by decomposing the TO result into defined sub-structure elements. This ensures uniformity in the interpretation of TO structures by different designers and makes this task more convenient. The guided interpretation provided by the KS^2-approach does not require any experience or engineering background and enables a systematic and transparent redesign. A great amount of time is saved on the reconstruction after getting a clear, methodical and systematic interpretation of the TO result. The graph given in Fig. 2 shows the different steps of the post-optimization process, including three possible reconstruction methods. By applying these methods to a practical example, the potential of each method was highlighted. On the one hand, the automatic reconstruction is definitely the fastest one and local modifications are easy to perform. However, the modification of the whole structure to meet the manufacturing constraints is limited.

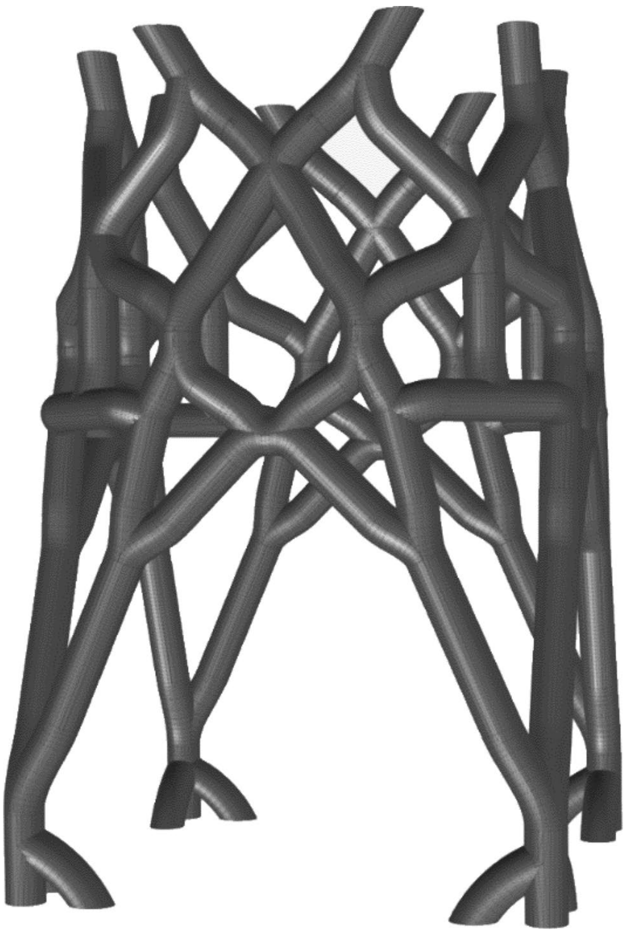


Fig. 10 Reconstructed model with manual redesign

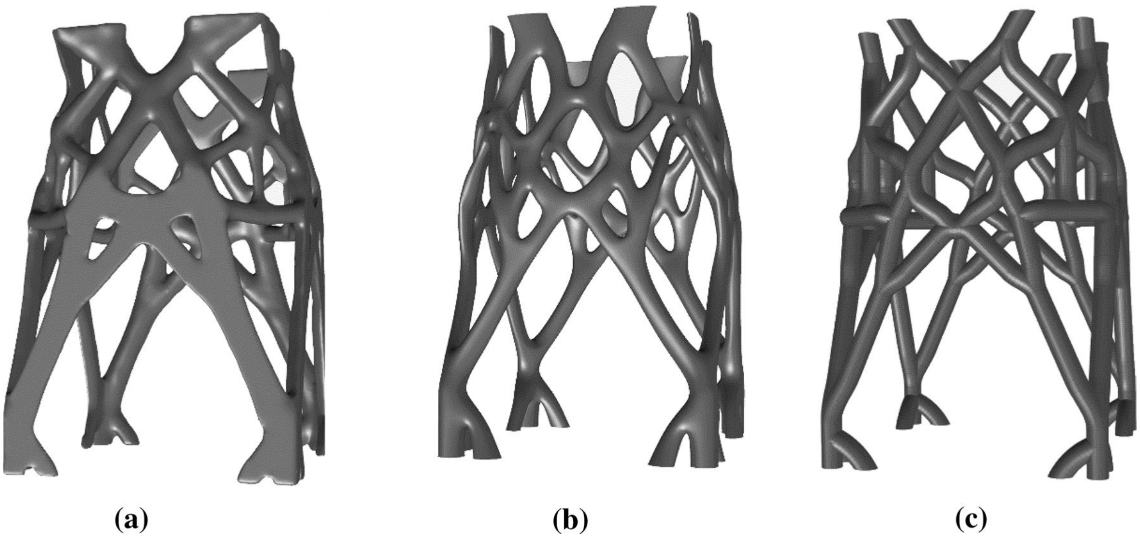
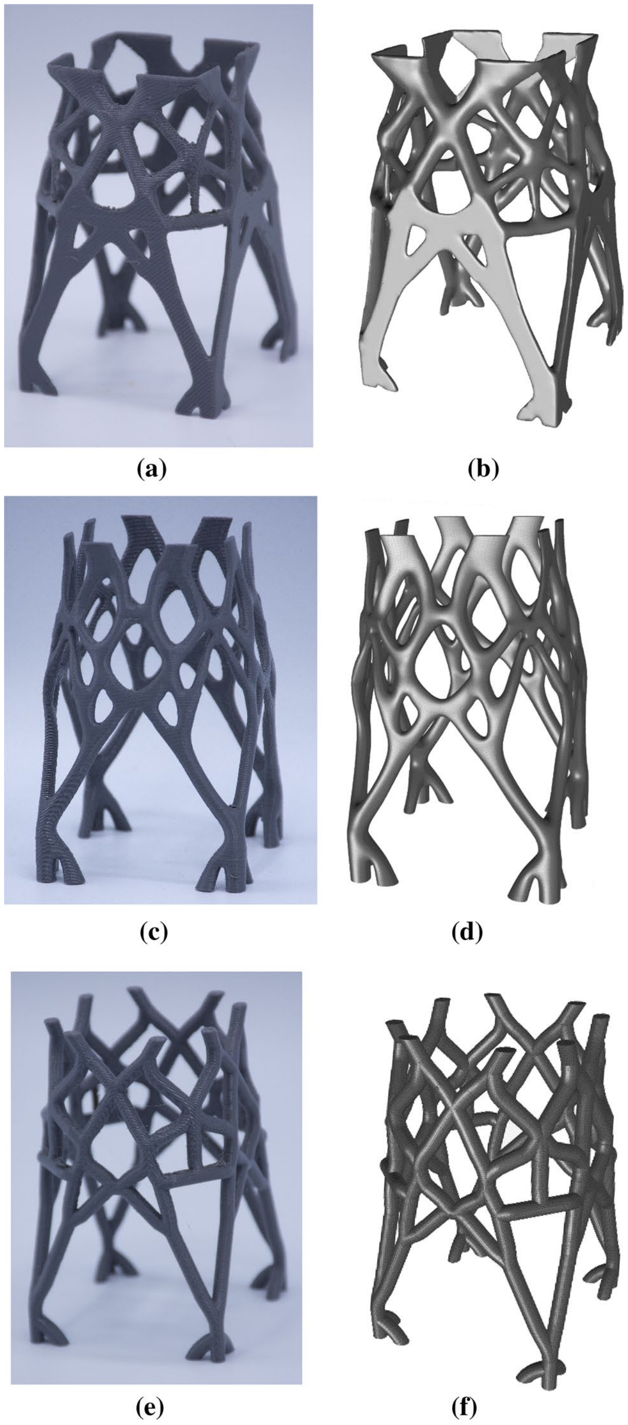


Fig. 11 **a** Automatic redesign; **b** Semi-automatic redesign; **c** Manual redesign

Fig. 12 Comparison 3D printed vs CAD model: **a** 3D printed automatic redesign; **b** CAD model automatic redesign; **c** 3D printed semi-automatic redesign; **d** CAD model semi-automatic redesign; **e** 3D printed manual redesign; **f** CAD model manual redesign



(a) (b)

(c) (d)

(e) (f)

Substructure elements can also be considered via automatic reconstruction, as in subsequent manipulation or even in the definition of local manufacturing parameters. This will be specified in more detail in further work. On the other hand, manual reconstruction with standard CAD features, although it has the advantage of being able to parameterize the model, is a long, difficult and time-consuming process. The semi-automatic method offers a good compromise between the fast and hardly modifiable automatic and the long and parametric manual one. The creation of the CAD model through direct modeling offers good efficiency, both in terms of time and modification. Furthermore, unlike the manual method, the semi-automatic approach is not limited to beam-like structures and can be applied on any TO result. Additionally, manufacturing constraints can be easily considered in the design process. Especially for additive manufacturing which lends itself well to TO resulting shapes, the choice must be made between a design that is close to the optimized structure but which requires supports during the printing process, or a part less similar to the TO result but which can be manufactured without any support. This reflection can be done during the reconstruction or before a possible shape optimization. Advances in additive manufacturing allow for further use of the potential of topology optimization. Some examples of applications were presented in the literature for the automotive or aerospace industry, as for example in [4]. Certainly, AM will increasingly be used, but TO is not limited to this manufacturing process. In the motorsport industry, composite structures are very common and can also be subject to TO [24]. The KS^2-approach is also suitable for this type of parts.

The KS^2-approach still has potential avenues for improvement. Firstly, automating the recognition of substructure elements would be beneficial, eliminating the need for manual intervention in the process. The mesh density used during the SIMP optimization stage can influence the resulting geometry, and consequently the interpretation. Therefore, an automated interpretation would provide several design opportunities ready for redesign in a short amount of time. Furthermore, it would be valuable to develop a specific algorithm for the redesign process using CAD features or direct modeling. Some TO algorithms, such as level-set, already produce consistent structures that can be further refined through smoothing techniques prior to manufacturing. However, researchers are actively working on developing advanced smoothing algorithms specifically tailored to topology optimized structures.

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Declarations

Competing interests The authors declare no competing interests.

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