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Streamlining design cycles with a flexible geometry reconstruction method

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ABSTRACT Topology optimization is a powerful tool for the development of light and strong structures. Due to the preliminary nature of the resulting design proposals, a geometry reconstruction process is required. This primarily serves the purpose to create a functional design. In doing so, parameterization of the geometry and the option to modify are demanded in product development as well as automation. A specific medial axis based reconstruction method not only facilitates the automation, but also the intervention with several possibilities for modification of an optimized design proposal. In this paper, we examine at an examplary use case, how this practice could reduce design iteration cycles, although intermediate new design requirements emerge. We discuss the advantages and limitations of this approach.

KEYWORDS: computational design methods, computer aided design (CAD), lightweight design

1. Design cycles – despite the use of topology optimization

Topology optimization facilitates the computation of innovative structures. However, due to the preliminary nature of the resulting design proposals, a geometry reconstruction process is required to transform the computation result into a viable engineering structure (Bendsøe & Sigmund, 2003; Subedi et al., 2020). Without a sophisticated reconstruction to computer-aided-design (CAD), the entire optimization process is at risk of losing efficiency.

Nonetheless, it is quite possible, that design parameters shift or additional requirements are submitted *after* the initial optimization. Consequently, the topology optimization would need to be repeated with updated data (Harzheim, 2014). The same applies to the reconstruction effort that – depending on the chosen method – may even be a laborious and time-expensive manual task (Subedi et al., 2020). This leads to iteration cycles (Harzheim, 2014). What if these seemingly unquestioned design cycles were abandoned? In this paper, it will be explored, whether new design requirements necessarily result in extensive design cycles, or if an alternative approach is able to bypass them.

2. Geometry reconstruction as crucial part of the process

Design cycles should actually be reduced by integrating topology optimization into the process (Harzheim, 2014). This is for the reason, that topology optimization is a targeted approach to develop a design proposal instead of time-expensive trial and error (Harzheim, 2014). Nevertheless, geometry reconstruction remains as time expensive task, because the topology optimization usually results in a rudimentary shaped design proposal. To bridge the gap between topology optimization and CAD-based downstream applications, automated computational design methods are researched (Subedi et al., 2020). Several reconstruction strategies adopt techniques from computer graphics, notably skeletonization, to abstract the topology optimization results into a 'geometric skeleton' (Cuillière et al., 2018; Denk et al., 2021; Kaloudis & Poulias; Nana et al., 2017; Stangl & Wartzack, 2015; Mayer & Wartzack, 2023). In the next steps, the concepts aim at the reconstruction based on the skeleton. There is a variety of different skeletonization methods. Curve skeletons as well as surface skeletons are used in this context. Respective

approaches use curve skeletons as a reference for a specified cross section that is extruded along the curves, so that a volume body is generated (Stangl & Wartzack, 2015; Cuillière et al., 2018; Nana et al., 2017; Amroune & Cuillière, 2022). Some differences occur depending on, whether the skeletons are polygonal lines, spline-curves, normalized in straight segments or curved segments.
Voxel-based approaches operate on a discretized data set. That simplifies the evaluation of neighbourhood relations or connectivity issues and allows for distance evaluation (Denk et al., 2021; Denk et al., 2020). These strategies also rely on a wire model by thinning the input respectively. Then, they reconstruct continuous geometric shapes based on a curve skeleton, too.
Altogether, such methods are especially suited for beam-like structures, but less so for surface-dominated ones (Cuillière et al., 2018; Kresslein et al., 2018). Therefore, recent advances have focused surface-based skeletonization addressing its inherent complexities. The higher-dimensional characteristic of a surface compared to a curve complicates the respective reconstruction (Denk et al., 2021; Mayer & Wartzack, 2023). One possible way is to use the contours of the surfaces as boundaries for the creation of mid-surfaces (Denk et al., 2021; Mayer & Wartzack, 2021). Subsequently, volume is created by thickening the mid-surfaces by a specified value. This is a tool for parameter-wise control. Another strategy operates with the surface skeleton itself and builds a polygonal mid-surface representation from it (Mayer & Wartzack, 2023). Using the medial axis this approach allows targeted interventions into the thickening with several thickening parameters. Their application for volume creation is prepared as a special design feature in such a way, that it is not necessary, but optionally possible, to intervene in the design and edit it (Mayer & Wartzack, 2023). In short, this is possible due to the computation of radii of maximally inscribed spheres by the medial axis skeletonization. This way, geometric information is gathered from the design proposal first hand. Despite a high automation level, this strategy is used extensively for parameter integration, feature-control and the opportunity to flexible design editing (Mayer & Wartzack, 2023). Ultimately, it is intended for creativity, possible design exploration and fitting of design requirements in the geometry reconstruction, that were not possible to be included in the optimization run itself. However, this reconstruction strategy not only enables nuanced design modification post topology optimization, but also offers significant potential to minimize design cycles when intermediate changes emerge after the optimization run.

3. Flexible geometry reconstruction: methodology

The geometry reconstruction method is based on the medial axis skeletonization (Mayer & Wartzack, 2023), a concept originating as mathematical shape descriptor (Blum, 1967). The medial axis transform describes a shape by the set of centers of maximally inscribed spheres (Amenta et al., 2001). The sphere centers and the radii are known geometrical information. While the centers are based on the skeleton, the radii measure the distance from the skeleton to the closest points on the boundary of the input shape. Due to difficulties in exact computation of the medial axis transform for continuous shapes, oftentimes an approximate, discrete version is computed (Amenta et al., 2001). This aligns well with typical topology optimized design proposals as facet models and therefore interconnected vertices (Mayer & Wartzack, 2023).
For the operational computation of the spheres and the computation of the skeleton we use a Voronoi diagram. Given a set of vertices, such a diagram actually splits the set of 2D, or 3D space in cells closest to each vertex respectively in Euclidean distance. The vertices of the design proposal are used as input sample points. The relation between sample points, cells, vertices and the medial axis is shown in Figure 1. It should be noted, that any data outside the shape is neglected here. Reduced to 2D, the Voronoi diagram is easier to visualize, but the principal function is the same as in 3D. Assumed the Voronoi vertices are connected in the right way, a skeletal structure can be derived (Amenta et al., 2001).
In 2D, the connection of Voronoi points within the shape can be interpreted as a curve skeleton. In the more complicated 3D case, the skeleton also consists of surfaces (surface skeleton). The connectivity has to be evaluated according to Amenta et al. (2001). The Voronoi skeleton approximates the theoretical exact medial axis (Amenta et al., 2001). Thus, the MAT-computation results in a triangulated surface mesh. The quality is poor, with overlaying facets, redundant nodes and non-manifold geometry. Even slight unsteadiness in the input shape leads to large slivers in the skeleton (Tagliasacchi et al., 2016).

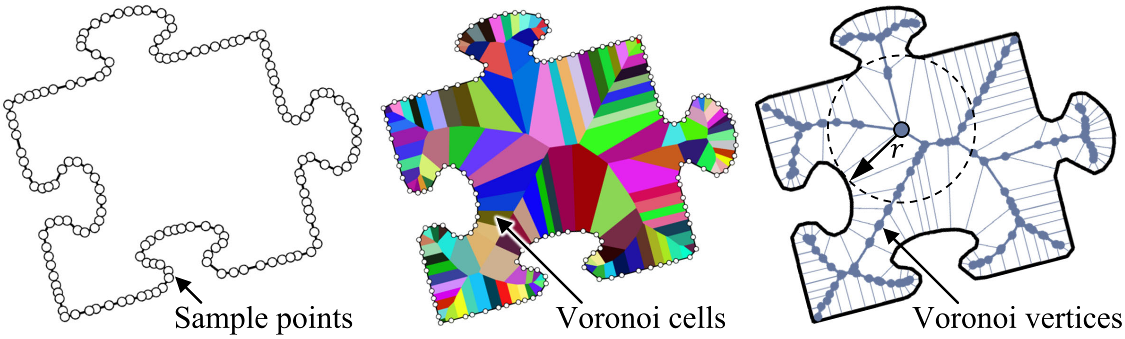

Figure 1. Skeleton computation through Voronoi diagram

Nevertheless, the definition of the medial axis transform provides the consistent evaluation scheme of maximally inscribed balls. We interpret the radii of the medial spheres as local geometric thickness of the design proposal. As stated earlier, we use this unique geometry information in a later stage for the incorporation of parameters and features. In general, for these reasons, the approach conceptualizes the medial axis for geometry reconstruction although some inherent drawbacks have to be addressed. The skeletonization results have to be revised into a so-called decomposition structure. Thus, we consider the resulting triangulated surface mesh for retopology into a quadrangular skeleton. The skeleton is roughly set up with quadrilaterals. While automated methods exist for this particular step (Huang et al., 2018; Wenzel et al., 2015), we rely on simple manual retopology due to the small number and therefore quick generation of quads. Self-intersections are resolved at this stage. If the valence of each polygon face is equal to four, the quadrangular polygons are convertible in parametrical description later on. The medial axis radii computed prior in the skeletonization are mapped to the quadrangular skeleton. Subsequently, they are used for thickening the skeleton structure if no intermediate editing is made. For the thickening, a specific feature moves each skeleton node in its respective normal direction and in the exactly opposite direction as well. Through decomposition into a quadrangular skeleton and applying medial axis radii for thickening, the method advances from a 2D mid-surface skeleton to a 3D volume geometry. In order to consider material at the boundary or rim area of the newly created shape, there is a second feature concerning the rim specifically. Like the first thickening, the respective medial axis radius is used as geometrical measure and similar to the first feature, the original skeleton vertex is the origin for creation of new vertices. Within the rim feature, there is an automatic segmentation of the rim area. Then, vertices of the rim area only are moved in the outward direction. By specifying the outward movement exactly per vertex, arbitrary shapes can be realised and controlled with the feature. The radii are the default geometric values and manipulated by the algorithm depending on the selected rim shape. A rounded and rectangular shape can be chosen by default. (Mayer & Wartzack, 2023)

It seems conceivable, to use the editing of radii not only for minor adaptions, but also for decisive and targeted intervention in the design process. In recent work, based on this idea the overall radii in an optimized structure were edited in a way that wall thickness increases towards a fictive inflow position (Mayer et al., 2023). The background is, that the model should correspond to Heuver's design law for casting (Miller et al., 2003). The geometry reconstruction method allows this specific opportunity (Mayer et al., 2023). Other reasons for intervening in the design are likely possible.

In each case, the shaped volume body through this process is a quadrangular mesh, which is transferred to CAD-environment. Thereby, the geometry is automatically converted to T-Spline faces first and then to mathematical parametric faces. While the topology optimized part of the structure (design-domain) is reconstructed this way, there are also parts of the structure that are explicitly excluded from the optimization run (non-design-domain). This may concern parts, where loads and constraints are applied, for example. The non-design-domain must be included in the final geometry as it is, and therefore is processed in parallel to the main geometry reconstruction. The geometrical ideal shape of non-design-area is directly used for identification by comparing the design proposal with the design space. The comparison uses face normals, 3D coordinates and the surface area of all faces in the design space. In contrast to the optimized area, the non-design-domain in the design proposal matches those values. So each facet of the design proposal is classified according to how well it is part of a larger face of the design space. In the reversal then there is an estimation for each BRep-face of the design space whether it is a non-design-face or not. Once identified, the non-design-area is imported in the CAD-environment additionally to the main geometry. Then a combination through boolean union is possible. Thereafter the

CAD-model is ready for further modifications in the CAD-environment, if necessary, and eventual downstream applications. (Mayer & Wartzack, 2023)

4. Results: 3D shaped skateboard truck

4.1. Why this use-case is particularly important for this work

The study in this work relates to a skateboard truck. This is the assembly connecting the deck of the board with the wheels. Besides rubber and bearing parts, there are two main components: the baseplate, which is screw-mounted to the deck and the hanger, which is centrally pin-bolted to the baseplate and carrying the wheels on the outside. As it is the case with many sports products, lightweight design is a strong advantage that is demanded in professional and hobby sports. The less mass, the easier is the handling of the skateboard. Mass reduction is also likely to decrease moments of inertia. At the same time, the skateboard truck is a heavily stressed component, as it must transfer the athlete's load to the ground, including high-agile movements multiplying emerging forces.

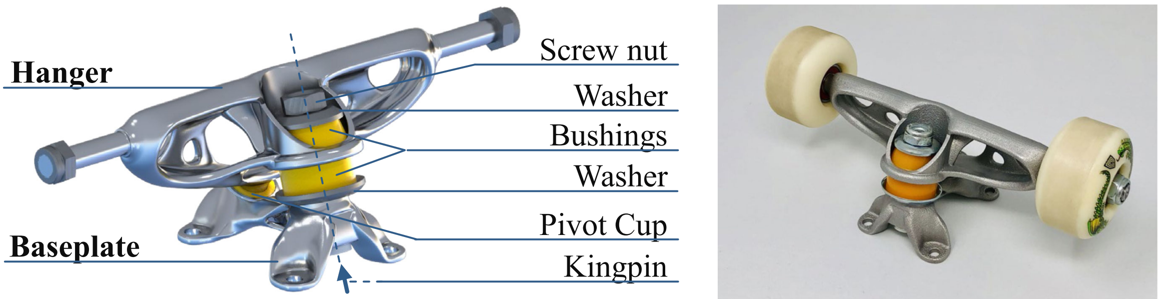

Figure 2. Assembly of the featured component with the final exhibit manufactured using selective laser sintering

A first goal with this study is to identify a lighter shape for both, the truck and the baseplate. Rather than relying on a trial-and-error-approach, the topology optimization is applied. The presented demonstrator was carefully chosen due to several specific reasons. Addressed beforehand one of them is the fact, that indeed in the practical design process, subsequent requirements occurred after the optimization, which led to design modifications.
Another reason that makes this demonstrator particularly intriguing is that the load cases are barely predictable. As a skateboard is not used for straightforward rolling, but for flipping and turning at any possible angle, the truck and baseplate components must withstand loads from various directions.
Given this context, it is especially important to note that topology optimization is an optimization and specialization regarding the circumstances declared in the computation only. This means results are not optimized for any other load than declared beforehand in the numeric simulation. Properly accounting for the load situation would require the implementation of all load cases that the manufactured component is expected to endure. (Mattheck, 1997)
For this work, we pursue a different, more explorative approach. This is where the second, overarching goal comes in. According to this goal, we plan to bypass repeated design cycles and employ the flexible geometry reconstruction method in such a way that a feasible structure results. Instead of time expensive diversifying load cases and implementing them into topology optimization, it accordingly is part of this study, to consolidate the load cases and enhance the structure's robustness against various load scenarios in the reconstruction step. Ideally, this strategy should not only maintain, but also improve the structural stress-appropriate design. The method of choice is the presented geometry reconstruction approach. By leveraging its flexible editing options, we aim to bypass repeated topology optimization design cycles and use the initial design proposal. We investigate, if such a pragmatic approach could serve as practical and efficient solution.

4.2. Use case results

The need for flexibility is apparent already from start on. The design spaces of hanger and baseplate are limited in some dimensions, regarding the necessary clearance of deck, wheels and pin bolting. We adopt the characteristic overall dimensions from a reference-truck widely used in the market. Further, we adopt the principal restrictions by add-on-parts or necessary clearances. This grants comparability as well as compatibility with add-on parts and bore-hole-patterns. However, within the mentioned limits and in lateral direction to the main axis of the board, the design spaces still offer great spatial freedom. At the same time the decision where to restrict material placement is crucial for the optimization. Thus, a first-time-right choice with regard to an *optimal* solution is difficult. We set the design space limits in our own assessment to the best of our knowledge and save the extra time of design space evaluation for a potential few percent benefit.

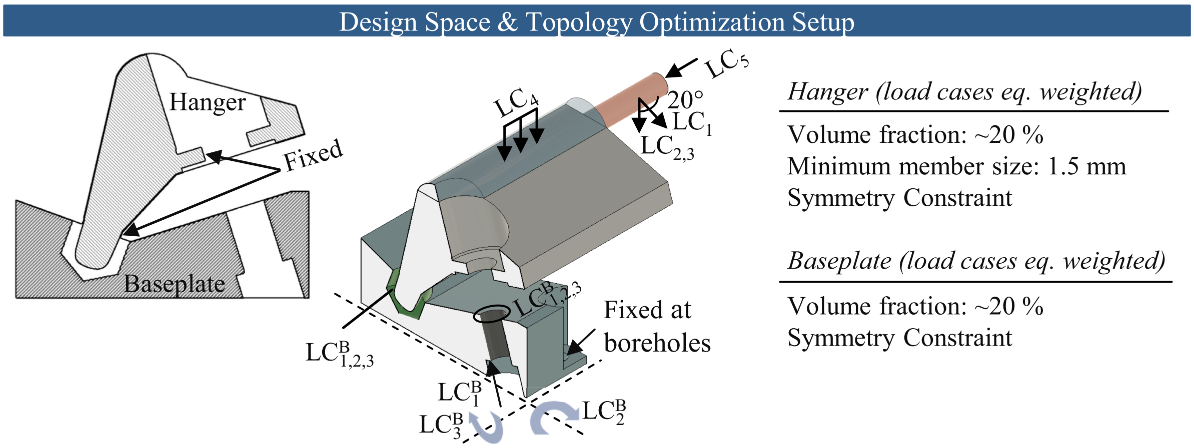

Figure 3. Principal setup for truck and baseplate

The next aspect where flexibility proves advantageous relates to the load cases. Although they can hardly be considered in all possible variations, we defined a collection of most anticipated forces. Two numerical FE-simulations were conducted, one for the hanger and one for the baseplate. The loading situation with five load cases for the hanger and four load cases at the baseplate with multiple forces each is shown in Figure 3. This includes one axled riding (LC_1), steering, (LC_2), vertical force (LC_3), grinding (LC_4) and lateral force (LC_5) concerning the hanger. On the baseplate we simulated a vertical force (${LC_1}^B$), steering (${LC_2}^B$) and a kingpin moment (${LC_3}^B$). Here, each load case is composed of several forces. Pressure at contact points is present in all load cases for instance. The constraints are abstracted and applied at the indicated positions of pivot area and the kingpin borehole. On the baseplate, there is a fixed constraint at the four boreholes, which serve the attachment of the component to the deck. For the purpose of stiffness optimization, the absolute values of the forces are less relevant than their relative magnitudes among each other. We designate functional surfaces (bearing seat, pivot point) as non-design-domain and therefore exclude them from the material removal. Also, there is a substantial amount of material intended around the extension of the main wheel axles. Since this material can fade by the athletes' practice of "grinding", it should not contribute to the structural rigidity in the numerical simulation. We therefore do not incorporate it in the topology optimization, but include it afterwards. Here we use the software Ansys Workbench for the topology optimization. The optimization results did not exhibit clear convergence (Figure 4). In the hanger structure, some struts remained rudimentary, and the baseplate featured a single central strut that appeared weak given its thickness. Although these observations suggest the need to revise the topology optimization setup, the two design proposals were nevertheless accepted for geometry reconstruction. This decision marks the exploration of an unconventional process step.
As illustrated in Figure 4 we intentionally utilize all available edit options, which will be detailed below. Referring to the schematic process of design cycles in Figure 4, we already apply some editing options directly in the initial process step of geometry reconstruction without yet completing a full cycle (Harzheim, 2014). The material in the grinding area around the main wheel axles is integrated post-optimization. For this, we combine the mesh of the design proposal with a separate mesh model and proceed with skeletonization. Following the skeletonization and the retopology, editing on the reconstruction method specific features becomes applicable as described in Section 3. Several adjustments are easily made directly at the skeleton. Where only rudimentary and thin struts exist,

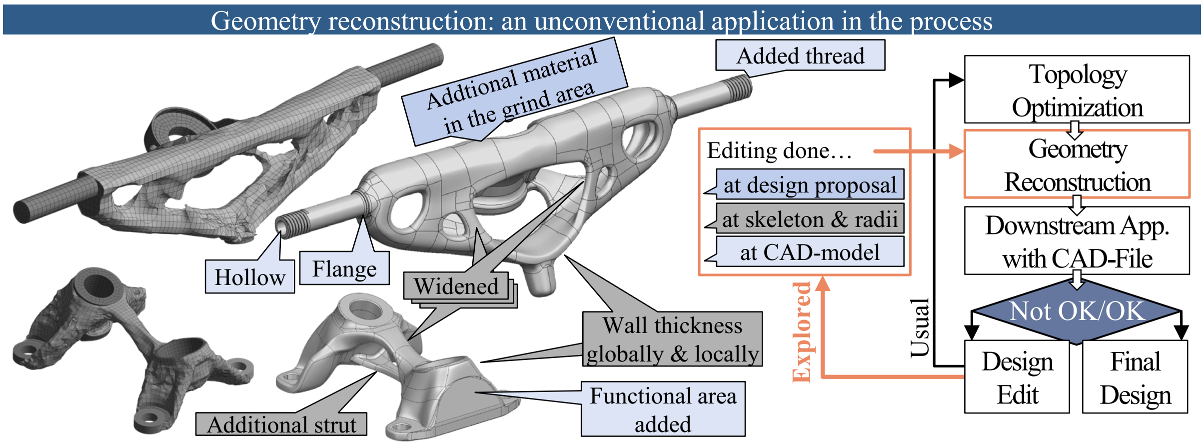

Figure 4. Overview of flexible editing operations used in the geometry reconstruction method for modification of the optimization result

connections are established (Figure 4). At these locations as well as several other locations concerning hanger and baseplate, we broaden the skeleton. At the baseplate, even an additional strut is integrated by simply extending the skeleton. The radii at these newly generated skeleton parts automatically adopt the values from the nearest radii of the existing skeleton, but can be overridden if necessary. As the reconstruction features are directly controllable in the radii (wall thickness specification), it is possible to make a targeted final result with regard to the final weight. The next step involves volume creation. Following the CAD-conversion, we combine the reconstructed geometry with the non-design-domain by boolean addition of pivot, bearing seats and the boreholes. Even at this stage, further modifications are possible. We incorporate flanges for the wheel seats and contact faces for the kingpin. Additionally, based on the feedback of athletes, who highlight the need of a flat surface on the frontal side of the baseplate, we include this functional plane in the model. The previous adjustments and these CAD-intern modifications are highlighted in Figure 4.

4.3. Validation

Before geometry reconstruction, the design proposal of hanger and baseplate were abstract, non-parameterized triangulated surfaces. With the featured method, it is possible to reconstruct feasible and adapted designs that accommodate large-scale parametric changes. The successful geometry reconstruction while saving time and design cycles with the extracted CAD-files as final data is a notable achievement in itself. Nonetheless, we examine the structural properties with the finite element simulation. A further goal with this demonstrator was to enhance the optimized reconstructed design's robustness towards unforeseen loads. Since the application of various arbitrary loads makes the validation difficult, we choose exemplary load cases that were not explicitly defined during the initial optimization.

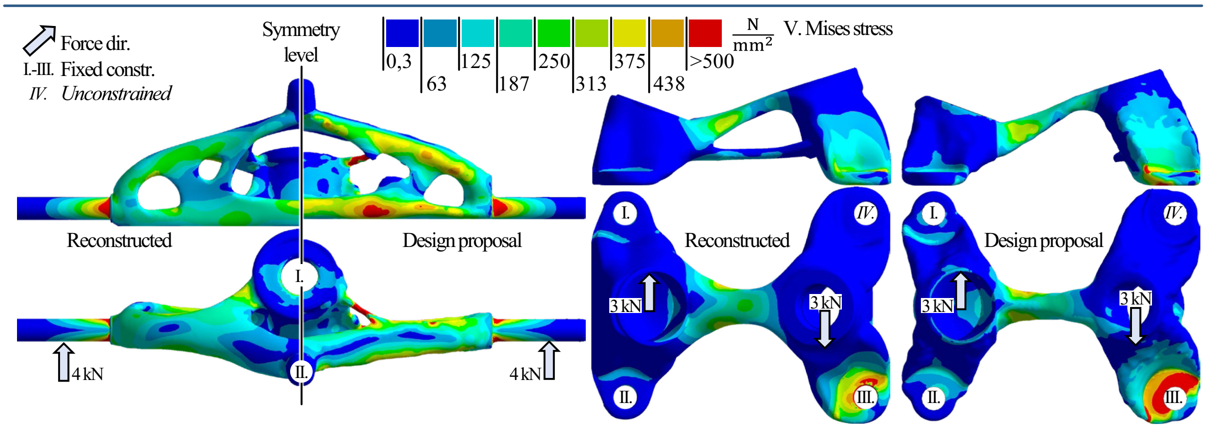

Figure 5. Finite element simulation of hanger and truck with a load case, that was not explicitly considered in the design proposal

The symmetrical load case for the hanger consists of a frontal force at the wheel seat surfaces. For the baseplate, the load case is a combination of lateral forces, with only three of the four boreholes constrained to simulate the practical scenario of a loosened screw. Before simulation, the additional material considered for grinding was removed again. We choose the same titanium alloy material model as in the optimization setup. There is additional material due to the modifications with an increase of 20% for hanger and truck as well. However, the additional material is structurally well placed. While both design proposals show some critical points of increased stress concentration, the reconstructed results are more evenly loaded. This is further supported by the evaluation of strain energy, which is reduced by 40% from the design proposal of the hanger to the reconstructed result. Similarly, the reduction is 30% in case of the baseplate. So, even accounting the increase of material, the reconstruction of both components still perform better than the design proposals. Although this comparison involves one load case among many conceivable, we consider the widened struts, included constraints, while simultaneously not having to repeat the topology optimization process, as improvement.

5. Discussion: topology optimization – does it have to be all or nothing?

Clearly, in engineering development the 'first-time-right' principle is crucial. A process with topology optimization might not have any design cycles. It can prove to be a consistently straightforward workflow supported by software for each, optimization, geometry reconstruction and CAD as well. However, for a maximal benefit topology optimization has to be applied in an early stage in product development and thus, design changes are still possible to emerge. It is a rather theoretical construct, if topology-optimization-application is only thought of a one-time application with no noteworthy adjustment made in the reconstruction from design proposal to final design. Instead, modifications are likely possible. This does not always have to be the case, but the skateboard truck presented here is a good example of various adjustments that had to be considered in the aftermath. With this study, we investigate two goals. First and subordinate, the skateboard truck should be developed as a lightweight version. The final mass of the hanger (170 g) and baseplate (63 g) indicates a distinct lightweight construction, achieving savings of approximately 20 to 25% compared to benchmark products.

The second and overarching goal was to examine, whether new design requirements necessarily result in extensive design cycles, or if the presented method is able to bypass them. Employing this method, we aim for development of a feasible structure tolerating various loading scenarios. Through the manual modifications described in Section 4.2, we avoided repeating the topology optimization process even after new requirements had emerged. Structural adjustments with targeted interventions can be incorporated to the geometry this way. From a structural point of view, design changes to optimization results have to be attentively reviewed in order not to deteriorate the optimized structural characteristics. We deliberately make it even more pointed by using an unconverged optimization result. In case of the design proposal and reconstructed geometry of the hanger there are unsatisfactory high stress values at the wheel axes near the transition to the main body. The wheel axes are non-design-domain and the main body is the actually optimized geometry. While the non-design-domain as to be expected shows similar results in design proposal and reconstruction, especially in the main body structure there are less stress concentrations in the reconstruction, indicating a uniform loading and well material placement. This also applies to the baseplate. A uniformly loaded geometry without unnecessary material indicates a good lightweight design (Mattheck, 1997). Instead of a negative impact, the structural quality even improved. The comparison of the reconstructed result to the design proposal does not mean that the reconstruction could in any way outperform the topology optimization itself, which is uncompromisingly bound to the initial constraints. If this turns out to be a less optimal solution than possible, the reconstruction is able to enhance the design proposal. The reconstruction might have some more design freedom depending on the priorities and requirements. Here, for instance a 20% increase in mass from design proposal to reconstructed design is clearly possible still staying below the weight of existing lightweight trucks. The extra material is put in good use for technical adaptations. For sure, the structural quantifiable evaluation is based on one load case. These quantified simulation results therefore remain in an exemplary character and should not be considered holistic. Likewise, there is no proof of a robust structure that withstands even unpredicted forces. This would require a more precise definition of the valid forces. However, we do not expect the reconstructed shapes to have a clearly deteriorated behaviour, as hanger and baseplate show similar material placement in design proposal and reconstruction. There is even additional material in the reconstructed designs. It is rather reasonable to assume that adding material to the suggested material placement and presumed paths of force flow produces advantageous structures.

In doing so, the geometry reconstruction method does not take the place of a good optimization setup. As initially stated, first-time-right is the crucial task. However, oftentimes the topology-optimization-setup is ambiguous. Here, the design space and a meaningful estimate of target volume fraction were difficult resulting in the unconverged design proposal. Then again, it is an advantage if designers are able to rectify the structures with the reconstruction method itself. Choosing this remains an option and designers still can opt to run through an optimization again. Here, we explored the reconstruction approach and presumably saved time not running through large design cycles, although the actual time was not measured. In line with the intention of this paper to make targeted use of the modification options, the focus here is not on the automation component of the method. The modifications described in Section 4.2 are manual. Yet, the skeletonization, the detection of non-design-parts in the design proposal, the mapping of skeleton radii to the revised quad skeleton, as well as the CAD-conversion of the non-design-parts and the actual reconstructed volume, are automatic. Therefore, time efficiency is considered even within the reconstruction process itself.

In summary, the exploration of this unconventional approach leads to an original lightweight structure while potentially reducing design cycles. Thus, the topology optimization does not necessarily have to be seen as an all-or-nothing-process, but can be usefully supplemented to enhance its utility.

6. Conclusion of an unconventional approach

The flexibility of a specific medial axis based geometry reconstruction method is demonstrated using the example of a skateboard truck. From a topology optimized design proposal as starting condition, we are able to edit the design of hanger and baseplate within the otherwise automated reconstruction process. We consider requirements and derive a final shape. Although the optimization is adhered to less stringently this way, it is possible to develop a sophisticated design. Especially considering that the topology optimization result is not fully converged and postponed requirements emerge, the back and forth between optimization and design is avoided. The reconstruction method usefully supplements the process and therefore aligns well with this year's ICED-conference motto, 'Design is a Team Sport'.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and DeepL in order to ensure correct English and improve readability. This applies selectively to individual sentences. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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