RECONSTRUCTION OF TOPOLOGY OPTIMIZED GEOMETRY WITH CASTING CONSTRAINTS IN A FEATURE-BASED APPROACH

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ABSTRACT

Topology Optimization (TO) is an established method for the development of high strength and lightweight structural components. However, its results have to be geometrically revised to obtain a computational model that meets product development requirements. Design has to be in accordance with manufacturing constraints. Geometry reconstruction therefore still is a typically manual and tedious task, but increasingly supported by computational and automated approaches. In this paper, the inclusion of a casting constraint in an automated Medial Axis based reconstruction method is presented. Since the Medial Axis provides cross-section values by the computation of maximally inscribed spheres, this information is used for geometry reconstruction and even further for the purposeful adaption of the cross-section to match Heuver's circle method. Thereby, the directed solidification of molten material is considered. With a predefined feeder position, the demonstrator of a suspension control arm is used to show the application of the method. Resulting CAD-models are also structurally evaluated for their stiffness characteristics.

Keywords: Topology Optimization, Medial Axis Transform, Computational design methods, Computer Aided Design (CAD), Lightweight design

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1 COMPUTATIONALLY CONSTRAINED RECONSTRUCTION OF TOPOLOGY OPTIMIZED RESULTS FOR MANUFACTURING PURPOSES

Computational design contributes to *design in a complex world* by new and innovative structures. The method of topology optimization (TO) is well suited for highly optimized structural components. However, in mechanical design after TO, there is large potential in computational design methods.

Initially, a discretized design space and a loading condition is given for TO. The widely spread approach with Solid Isotropic Material with Penalization (SIMP) computes a load path oriented material distribution (Bendsøe and Sigmund, 2004). Then, the immediate optimization result has to be interpreted and geometrically revised in Computer-Aided Design (CAD) for further product development (Subedi et al., 2020; Bendsøe and Sigmund, 2004). Manually done, this time consuming and tedious geometry reconstruction breaks with an otherwise continuous workflow of computational methods. Although there are approaches for automated reconstruction, they do not fully meet product development's demands. First, the CAD-model has to be parametric and feature-based to allow editability and downstream applications like simulations to be applied (Subedi et al., 2020). Second, for practical application the intended manufacturing process is a key aspect to consider in the design process. Reconstruction of topology optimized design proposals is made difficult by the fact that manufacturing requirements for a wide range of geometrical shapes have to be taken into account.

Due to design freedom and reasonable production effort, optimization methods were developed to consider selected casting constraints directly within the optimization run. Nonetheless, there are limitations to this practice. Adding constraints risks hindering the optimization and the quality of its result. Even a failure of the computation is possible. In general, manufacturing design rules are rarely considerable all at once, why manual interpretation and editing often is necessary to create the CAD-geometry. (Subedi et al., 2020)

Therefore, this work focuses on the geometry reconstruction that follows the optimization. The design proposal subsequently is processed with an automated reconstruction method by Mayer and Wartzack (2023). The proposed method of TO-reconstruction with the Medial Axis Transform (MAT) is combined with casting optimization. The research aim is to incorporate Heuver's circle method (Ransing et al., 2005). Hereby, the geometry reconstruction is edited with conditionally specified cross-section thicknesses. At the same time, parametrics and features are incorporated in the geometry to allow manual adjustments and to meet product development's demand on an editable CAD-model (Mayer et al., 2022). Unlike manual redesign, topology optimized results are faster to convert to CAD models and less dependent on human experience. Providing parametrics and features, various designs can be explored (Mayer and Wartzack, 2023). Finally this work's contribution to *design in a complex world* is the consideration of manufacturing constraints in a computational and feature-based geometry reconstruction method. It is structured as follows: in section 2, the state of the art is described. The medial-axis-based reconstruction method is presented in section 3, where also the incorporation of the casting constraint by Heuver's method is addressed. In section 4, the use case of a wishbone is presented with practical application of the proposed approach. Results, including structural simulation results, are discussed in section 5. A summary is given in section 6.

2 STATE OF THE ART

2.1 Reconstruction of topology optimized geometry with skeletonization methods

Computational approaches for geometry reconstruction of topology optimized structures follow different strategies (Subedi et al., 2020). For the reason of parametric and feature-based reconstruction, a skeleton-based strategy is focused in this work (Mayer and Wartzack, 2023). Approaches of this kind principally extract a skeleton from TO's design proposal and then generate geometry referenced to this skeleton. The term 'skeleton' is used in several definitions (Tagliasacchi et al., 2016). A skeleton can be composed of lines in the sense of curve skeletons or of surfaces in the sense of surface skeletons (Tagliasacchi et al., 2016). The skeletons may have polygonal or analytical data structure. Similarly diverse are the methods of skeleton computation. In papers of Cuillière et al. (2017), Nana et al. (2017) as well as Stangl and Wartzack (2015), Kresslein et al. (2018) and Amroune and Cuillière (2022) curve skeletons are computed by a contraction method. Along the skeletal reference-curve a defined cross-section is extruded. Thereby parametrically referenced 3D-CAD-geometry is created. The skeleton may consist of polygonal lines at first, which are converted to

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b-spline curves subsequently (Stangl and Wartzack, 2015; Kresslein et al., 2018). Nana et al. (2017) and Cuillière et al. (2017) perform a normalization in straight line segments. Amroune et al. (2022) use postprocessed, polygonal line segments and in particular focus on the junction area in between. Liu et al. (2018) use curve skeletonization for smoothing the contour of a planar structure before this structure is approximated with cubic b-splines. Again based on curve skeleton, Denk et al. (2020) propose a method by use of a homotopic thinning algorithm. Here, a distance transformation is applied, generated from volumetric pixels (voxels). This way, also cross-section information is computed. A similar procedure with a thinning algorithm is found in works by Yin et al. (2020) and Alves and Siefkes (2021). Resulting curve skeletons are simplified by neighbourhood relations of each single element and imported in the CAD environment as straight-line wire model (Alves and Siefkes, 2021). Altogether, curve skeleton methods are suited for beam-like structures. At junction points between skeleton lines or the referenced volume geometry, they face difficulties in the correct combination of single cross-sections (Cuillière et al., 2017; Kresslein et al., 2018; Subedi et al., 2020; Amroune and Cuillière, 2022). The identification of a cross-section in the area of junction is difficult. Especially non-beam-like structures are challenging. Abstraction of such by a one-dimensional line is error-prone. Deviations in topology are possible. As an alternative to curve skeletons the basis for further approaches are surface skeletons. Denk et al. (2021) compute a surface skeleton, whose boundary curve is converted to a boundary-line-based control grid for subdivision-surfaces. It is possible, to manually adjust the control grid and therefore alter the final subdivision surface reconstruction. Despite a global thickness value, the method does not incorporate local thickness editing. With the medial axis transform additional, geometrical data can be computed (Mayer and Wartzack, 2020). For this reason, the MAT is chosen for this work amongst several skeletonization strategies. Its geometrical information is used for parametric and feature-based reconstruction including the possibility of editing (Mayer and Wartzack, 2023). The given design freedom by the medial-axis-based parametrics is used to alter the design for casting requirements.

2.2 The medial axis transform

Originally, the medial axis (skeleton) originated as mathematical shape descriptor (Blum, 1967). It describes a geometrical shape by the set of centers of maximally inscribed spheres and their radii (Amenta et al., 2001). The maximally inscribed spheres' radii are the distance to the closest points on the input shape’s boundary. The centers and the radii together form the medial axis transform. Because exact computation for a continuous shape is difficult, oftentimes a simplified, approximate version with a finite set of medial spheres is computed (Amenta et al., 2001). This is the case for the method here (Mayer and Wartzack, 2023), since TO’s design proposal is represented by a discrete number of vertices. For MAT-computation a voronoi-diagram can be used. The design proposal's vertices are the input sample points. The relation between voronoi-cells, vertices and the medial axis is shown in Figure 1 by exemplary 2D-shapes.

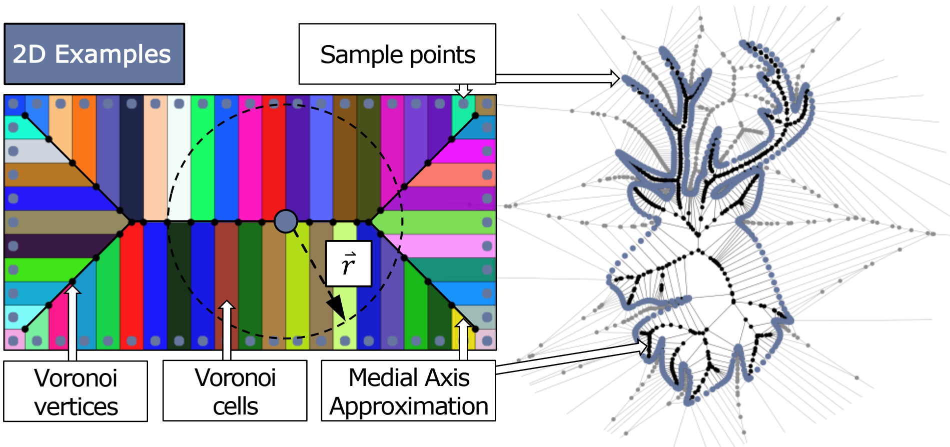

Figure 1. Medial axis approximation computed by voronoi diagram for two sets of 2D-input-sample points: a rectangular and a more elaborate shape.

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2.3 Casting optimization through the medial axis transform and Heuver's circles

Because the MAT principally uses maximally inscribed spheres of a shape, it has already been used for optimizing casting designs (Miller et al., 2003; Ransing et al., 2005). In geometrical methods for casting solidification, Ransing et al. (2005) use the medial axis transform for optimization of directed solidification. MAT spheres are used for evaluation in terms of solidification time. Solidification in the casting process has a crucial impact on the casted component's quality. Generally, crystallisation begins at the mould walls and gradually proceeds inwards into the casting by subsequent thickening of the solid layer. The sections freezing last are the most likely locations of defects such as shrinkage cavities or porosity (Ransing et al., 2005). Critical sections can be determined numerical with the Finite Element Method. While this is computationally expensive and appropriate especially for more complicated shapes, purely geometry-based approaches are low-cost and applicable in early design stage (Ransing et al., 2005). It is assumed that the geometric shape directly conditions the thermal characteristics during solidification. Therefore, the ratio of heat containing volume V to heat transferring area A is described as modulus. Chvorinov's rule relates the casting's modulus to solidification time t_s (Wlodawer, 1966).

$$t_s = k \cdot \left(\frac{V}{A}\right)^2 = k \cdot M^2 \tag{1}$$

V: Volume
A: Area
t_s: Solidification time
k: Metal-, mold-, material- and temperature-dependent coefficient
M: Modulus

Heuver's circle method continues this scheme and suggests that the modulus should progressively increase towards the feeder in order to achieve a directional solidification without cracks and shrinkage cavities (Ransing et al., 2005). Descriptively for the 3D case, Heuver's method can be imagined with maximal spheres inscribed into the casting's inner volume. The sphere's radii then should continuously grow towards the feeder in order to achieve a beneficial solidification behaviour (Ransing, et al., 2005; Wlodawer, 1966). According to this geometrical method, a larger diameter of an inscribed sphere corresponds to greater time for complete solidification.

3 GEOMETRY RECONSTRUCTION METHOD FOR CASTING

3.1 Computational geometry reconstruction with parametrics and features by the medial axis transform

Our approach combines directional solidification in the casting process by a combination of Heuver's method and geometrical skeletonization from Mayer and Wartzack (2023). The connection between both theories can be illustrated by the analogy of the so called grassfire flow propagation, that was introduced for MAT computation (Blum, 1967). It can be imagined with fire fronts spreading from a geometrical shape's boundary with identical velocity. Then the MAT skeleton locates, where opposing fire fronts meet (Tagliasacchi et al., 2016). This applies to the inner as well as the outer space of an input shape. In the following, the focus is limited to the inner volume. The given analogy of grassfire propagation mimics solidification in a casting process (Miller et al., 2003). Assuming the thermal conditions of a casting mold to be homogeneous and solidification to be uniform corresponding to Heuver's method, solidification progress can be imagined anti-normal directed from the casted parts geometry (Miller et al., 2003).

In order to efficiently compute the MAT, voronoi diagrams are used (Fig. 1). A voronoi diagram of a set of 3D-sample-points separates space in convex polyhedral cells, such that within each cell the distance to the associated sample point is closest. Here, the Euclidean distance metric is used. Voronoi vertices are the corner points of the voronoi cells in $\mathbb{R}^3$. They are mandatorily equally distanced from at least two nearest sample points located on the boundary. In 2D, the connected voronoi points themselves form a curve skeleton (Fig. 1), whereas in the general 3D case, the skeleton is areal (surface skeleton). Voronoi vertices in 3D are not necessarily part of the medial axis. A subset of so-called "poles" has to be identified that represents the medial axis. The poles corresponds to the two

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voronoi vertices of a voronoi cell most far in the inner volume of the input surface (Amenta et al., 2001). The poles' connectivity follows the sample points' connectivity. So in the more complicated, general 3D case, this voronoi skeleton of inner poles is an approximation to the medial axis (Amenta et al., 2001). Onwards this is denoted as medial axis. Resulting from the MAT-computation is a triangulated surface again. The medial axis skeleton's mesh quality is poor, with overlaying edges, redundant nodes and non-manifold geometry. Design proposal's significant geometry elements are displayed qualitatively, not explicitly. For example, junction-edges are not represented by a single edge in the skeleton, but by several, jagged edge-segments. This effects in several surface segments stacked into each other, complicating the geometric data structure. In addition, the medial axis represents even the slightest unsteadiness in geometry, leading to large slivers in the skeletal form (Tagliasacchi et al., 2016). Nevertheless, its definition follows the consistent scheme of maximally inscribed balls. The radii of the medial spheres provide additional information about the local geometric thickness of the design proposal. The approach uses this geometry information in a later stage for the incorporation of parametrics and features. (Mayer and Wartzack, 2023)

After the medial axis skeletonization, the results have to be processed into a decomposition structure as starting point for reconstruction. The resulting triangulated medial axis skeleton is manually revised into a quadrangular skeleton in the computer graphics software Blender3D. Quadrangular polygons are convertible in parametrical description like NURBS, if the valence of each polygon face is equal to four. At the same time, self-intersections are resolved within this step. Medial axis radii computed in the skeletonization are mapped to the quadrangular skeleton. This information is interpreted geometrical as cross-section-diameter. Thus, it is used for thickening the skeleton structure. For this, each skeleton node is extruded in its respective normal direction and in the exactly opposite direction as well. As a result, the 2D surface skeleton becomes a 3D volume geometry. In order to consider material at the boundary and rim area of the surface skeleton, there is a second offset concerning the rim specifically. Similar to the first offset, the respective medial axis radius is used as geometrical specification. The resulting volume structure is again a quadrangular mesh. There may be one or several bodies. The quadrangular bodies are subsequently transferred to CAD-environment. Thereby, the geometry is automatically converted to T-Spline faces first and then to parametric faces. (Mayer and Wartzack, 2023)

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 has to 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 TO's design proposal with its design space. The comparison uses face normals, 3D coordinates and the surface area of all faces in the design space. In contrast to optimized area, the non-design-domain in the design proposal matches those values. Once identified, the non-design-area is imported in the CAD-environment additionally to the main geometry. (Mayer and Wartzack, 2023)

3.2 Casting adaptation in a medial axis based approach to geometry reconstruction

Including topology optimization, the overall principle steps in the workflow are shown in Figure 2.

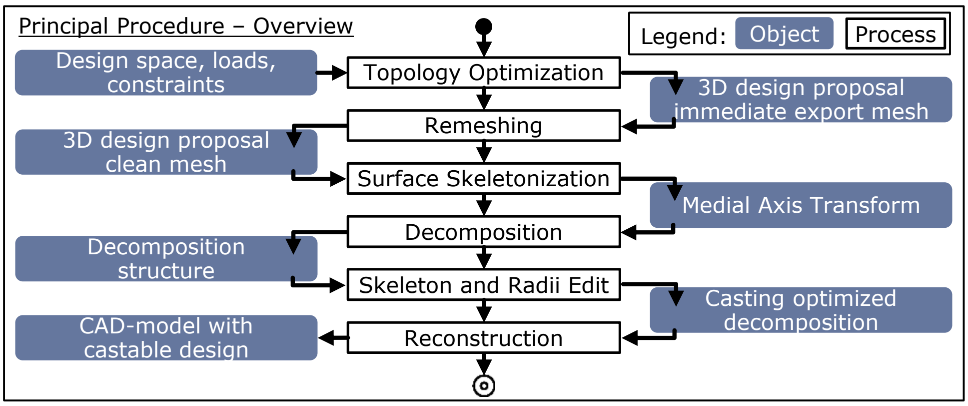

Figure 2. Principal steps in the proposed approach for casting optimized geometry reconstruction of topology optimized design proposals.

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After TO, geometry reconstruction itself starts with remeshing the design proposal's surface mesh. The processed mesh is skeletonized with voronoi-based medial axis computation. The resulting surface skeleton again is processed to the decomposition structure. This term describes a quadrangular mesh and associated medial axis radii, on which subsequently feature-based geometry is created. The medial axis radii are variables in specific thickening-features. They can be freely edited before volume creation. This opens up design freedom for manual or computational adjustments of the geometry. This can be done with regard to design aspects like design for manufacturing. For the reasoning technique of Heuver's circles, the radii are adapted to coincide Heuver's rule of increasing radii towards the feeder. Every radius is edited to fulfill a gradient-based growth in the direction chosen in the graphical user-interface. Besides this geometrical editing, within this approach it is also possible to geometrically or topologically edit the skeleton. The editing of the 2D skeleton directly alters the final 3D reconstructed geometry.

4 CASE STUDY

4.1 Demonstrator: optimization of a wishbone

An exemplary wishbone is used for practical demonstration of the proposed method. The structural suspension component connects a wheel to a vehicle's chassis. Because it is part of unsprung mass, a mass reduction at this component results in an increased performance, better driving characteristics and efficiency. First, an optimization study is performed in the commercial software Ansys Workbench version 2019 R2.The relevant loadcases are the extreme running conditions of braking while cornering. The optimization is performed with isotropic material settings. The objective is the minimization of compliance by an objective volume constraint of 25 % initial volume. A symmetry constraint in the xz-plane is set. The optimization setup is shown in Figure 3 as well as two possible design proposals exported as triangulated surface meshes. In the design proposal on the right (Fig. 3) a further casting restriction has been set, so that demolding in z-direction is possible.

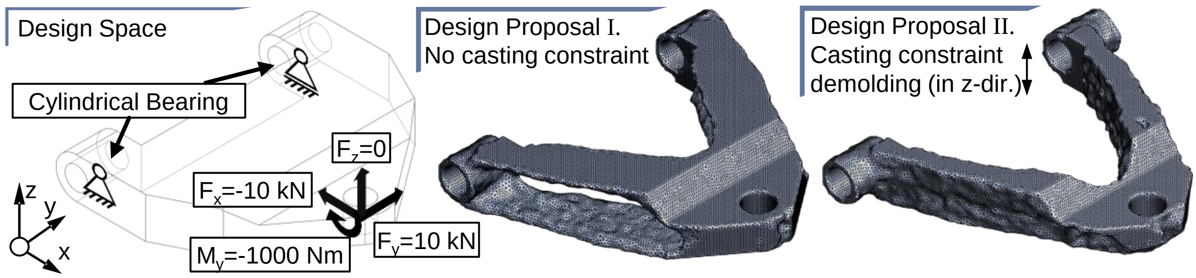

Figure 3. Optimization setup and resulting design proposals as facetted surface geometry.

In the resulting surface mesh, typically non-manifold edges and self-intersections occur. For this reason, the mesh is repaired subsequently by a voxel-based remeshing in the graphics software Blender3D. The surface is approximated with voxels of manually set size and then turned into a polygonal mesh. Here, the voxel size was chosen to be as large as the initial edge length in the mesh. With this surface mesh as input shape, medial axis skeletonization is performed (Mayer and Wartzack, 2023). Each point on the input shape can be referenced to the maximal inscribed sphere it is limiting. The radius of the sphere corresponds to the so called local feature size of this point (Fig. 4, A.) (Amenta et al., 2001). This is interpreted as wall thickness here. In Fig. 4 the wall thickness distribution is illustrated by colour. In addition, the inner surface skeleton is referenced to the maximal inscribed spheres and their radii which is described by the MAT (Fig. 4, B.) (Mayer and Wartzack, 2023). As a next step, the triangulated skeleton is revised, because it is a non-manifold, self-intersecting structure and not able to be converted to a parametric surface (Mayer and Wartzack, 2023). The revision is remodeling the principal geometric shape of the triangulated medial axis in coarse quadrilateral faces (Fig. 4, C) (Mayer and Wartzack, 2023). Hereby the size of the quadrilateral polygons is a tool for resolution of varying cross-section-thickness. A small amount of quadrilaterals inherently invokes a more uniform cross-section thickness distribution in the later reconstruction (Mayer and Wartzack, 2023). The information about cross-section values, respectively the medial axis radii, is mapped from the triangulated skeleton's vertices to the new quadrilateral skeleton's vertices via nearest neighbour search (Mayer and Wartzack, 2023).

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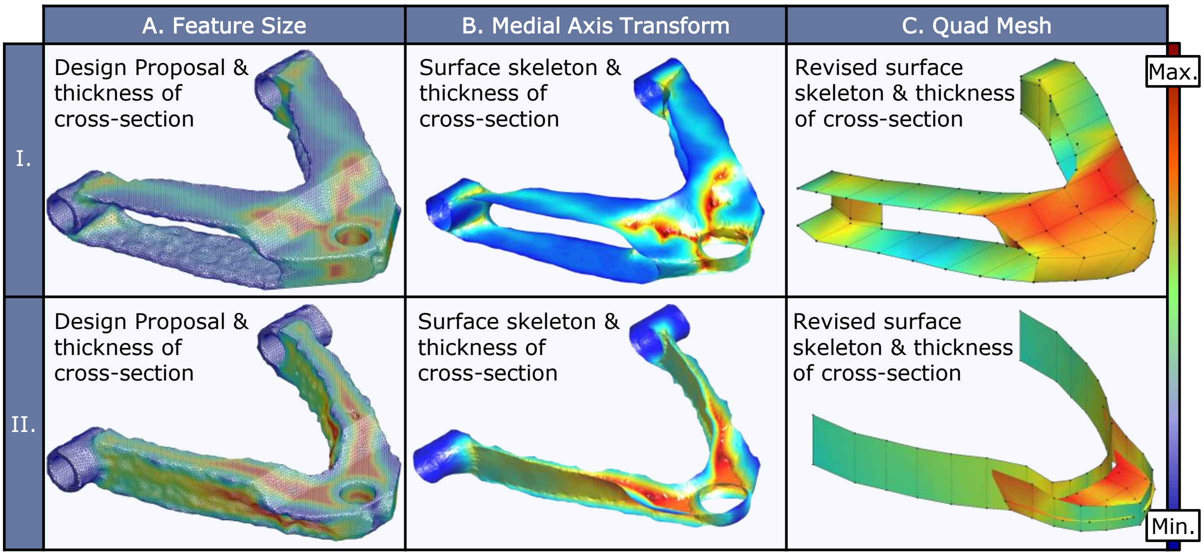

Figure 4. Results of medial axis skeletonization: feature size (A.), MAT (B.), quadrilateral mesh (C.) and respective radii are illustrated by colour.

In the mapping process, a Laplacian Smoothing evens out the radii values mapped to the quadrilateral mesh (Fig. 4, C.) (Mayer and Wartzack, 2023). Although the smoothing can be skipped, it in general contributes to evening out topology optimization's typical jagged boundary contour. As a result, the values for cross-section distribution in this example are at a more similar level in the quad mesh than in the MAT skeleton (Fig. 4).

4.2 Computational geometry reconstruction of a wishbone with casting constraints

The medial axis radii mapped to the quad skeleton are considered for cross-section thickness per default. Based on their value, the 3D-geometry is created later. However, the medial axis radii can be edited before geometry generation. Furthermore, the skeleton itself is editable. (Mayer and Wartzack, 2023)

The unconstrained optimization result shows a profile that is tedious for mold splitting (Fig. 5, I.).

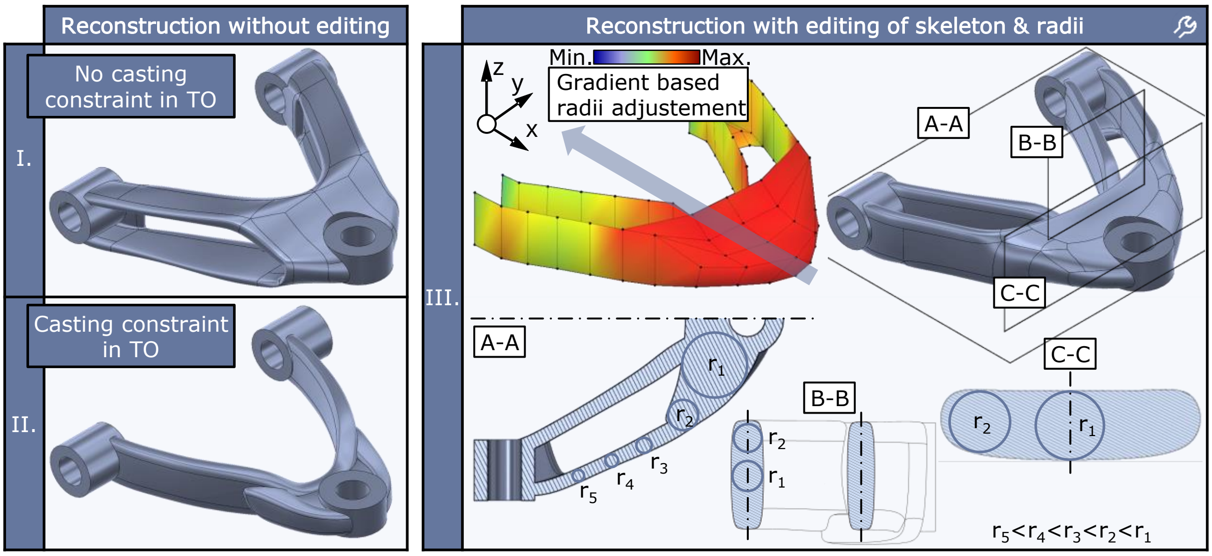

Figure 5. Geometry reconstruction results with the presented approach:
I. Result without prior demolding constraint,
II. Result with prior demolding constraint within topology optimization
III. Result without prior demolding constraint in topology optimization and, instead, usage of feature-based editing of this reconstruction approach.

Because of that, all parts that would otherwise require a tedious mold splitting or casting cores are repositioned and turned by 90 degrees (Fig. 5, III.). This is done directly on the lower dimensional

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(2D) skeleton before volume geometry is created. The skeleton retains the mapped information of medial axis radii despite of this geometric change. Then, the medial axis radii are adapted according to Heuver's circle method. With the feeder placed at a central position, the medial axis radii are edited to increase in diameter towards the feeder position. Figure 5 shows the quadrilateral skeleton of the unconstrained optimized control arm after editing. It becomes apparent by the colour scheme, that parts close to the intended feeder position are enlarged. After changes to skeleton and radii have been done, the structure is thickened automatically (Mayer and Wartzack, 2023). Subsequently, the result is automatically transferred to CAD-environment. The non-design-domain is imported in the CAD-system in parallel. The design-domain is automatically converted from quadrangular format to T-Spline faces (Mayer and Wartzack, 2023). Both geometry parts are united with each other by boolean operations. So that no casting cores are needed, the former part is filled with solid material (Fig. 5, III., see cross-section from C-C). In addition to consideration of casting constraints within the reconstruction process (Fig. 5, III.), the geometry without further casting consideration is shown (Fig. 5, I.). As well the geometry is shown, that results from reconstruction of the design proposal computed with a demolding constraint set in the TO (Fig. 5, II.).
As can be seen in Figure 5, exemplary inscribed circles in three respectively chosen cross-sections of the edited structure show increasing radii in the direction of the feeder position (Fig. 5, III.). For the two casting relevant models (Fig. 5, II. and III.), a structural analysis is performed in order to estimate the reconstruction quality and mechanical characteristics. Both, in the TO and in the finite element analysis of the reconstructed models, isotropic material is used. The analyses are static implicit with linear elastic material in both cases. The same loadcase as shown in the TO setup is applied respectively (Fig. 3). The comparison in Table 1 is based on strain energy sum in relation to the respective volume by multiplication of both values (Rozvany, 2009). A lower value indicates a more efficient use of material and is therefore favourable. Depending on the reconstructed model's performance, the value is coloured in green or orange in Table 1. Results show the reconstruction-edited geometry III. to have a higher volume than the geometry I., where demolding constraint has been set in the TO itself. This is due to the fact, that in the front part of the model, near feeder position, solid material has been added. Although related to the higher volume fraction, the stiffness and material usage of the reconstruction-edited geometry are better, which is shown by the comparison key figure (Table 1).

Table 1: Comparison of stiffness between the geometry with casting constraint set in topology optimization (II.) and the geometry with casting considered in the presented reconstruction approach (III.).

	Geometry II.	**Geometry III.**
Objective volume fraction $v_f^{objective}$	25 %	25 %
Volume $v^{CAD\text{-}model}$	62,150 mm³	105,880 mm³
Volume fraction $v_f^{CAD\text{-}model}$	23 %	39 %
Number of Elements	21,794	36,956
Maximum displacement	3.44 mm	1.63 mm
Strain Energy Sum $c^{CAD\text{-}model}$	29.909 J	14.045 J
Comparison key figure: $c^{CAD\text{-}model} \cdot v^{CAD\text{-}model}$	1859 kJ·mm³	1487 kJ·mm³

5 DISCUSSION

The presented work has the objective of combining design for casting and the medial-axis-based geometry reconstruction approach. Design for casting is considered by Heuver's method and by feature-based editing in the reconstruction approach. The decomposition of a topology optimized design proposal in a 2D-quad-skeleton with associated medial axis transform allows an efficient way of feature-based geometry editing for topology optimized structures. In reconstruction, geometry

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therefore can be designed to suit splitting of the casting mold. Further, the skeleton's radii are editable to coincide with Heuver's circle method for directional solidification. Both aspects are successfully applied to the demonstrator of a suspension control arm. Although no demolding constraint is set in the TO, the optimized design proposal is changed from a geometry that is complex during casting to a geometry that is favourable for a simplified mold splitting without necessity of casting cores (Fig. 5). Of course, such intervention changes the conditions of the previous topology optimization setup, but in turn allows a more casting specific design. Direct comparison of mechanical properties between the resulting geometry, where casting is considered in the reconstruction process (III.) and the geometry, where casting is considered within the TO (II.), shows better stiffness at the former in relation to the volume. It should be noted that Heuver's method is insensitive to material properties and boundary conditions like specific cooling in the mold. The presented work does not claim to provide perfectly castable results. The total amount of casting design guidelines, different casting techniques, as well as the interpretation of experienced engineers are not captured with this approach. However, the geometrical reasoning technique of Heuver's circles is compatible for application in the proposed geometry reconstruction method. It is complemented by the possibilities and given design freedom through skeleton- and radii-based editing. The approach therefore provides effective geometry adaption for a more castable design.

6 SUMMARY AND OUTLOOK

In terms of *design in a complex world*, this computational geometry reconstruction method is a contribution to the practical task of geometric interpretation and reconstruction of topology optimized designs, where various design goals have to be considered. The approach provides parametric and feature-based CAD-models and is able to meet specific design constraints for casting. Thus, the method contributes design in product development and integration of topology optimization in the process. It is automated at the steps of skeleton extraction and 3D geometry synthesis of the design domain. Further automation as well as incorporation of further design guidelines will be subject for future research.

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