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AUTOMATED WORKFLOW WITH SIMULATION-DRIVEN TOPOLOGY OPTIMIZATION FOR THE ECONOMIC DESIGN OF HYBRID-MANUFACTURED TOOL COMPONENTS (SIM-AM 2025)

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Abstract. This paper addresses the challenges and solutions in manufacturing trimming tools for the production of automotive panel components, essential for precision manufacturing. With the growing diversity of vehicle models, up to 1,500 distinct tool geometries per Original Equipment Manufacturer are required annually worldwide, presenting challenges in cost efficiency and scalability. Traditionally, these tools are produced by milling from a block of material or casting, leading to high material waste and machining costs, particularly for complex geometries. The paper investigates emerging hybrid manufacturing approaches that integrate a non-additive substrate with an optimized additive manufactured structure, offering cost-saving potentials up to 50 %. Additive Manufacturing enables complex designs and material efficiency, but the optimal design depends on the additive process used in each case. Structural optimization must be customized to the selected additive process, taking into account material properties, design restrictions and process costs. The decision-making process must remain adaptable, as the optimal manufacturing method may vary depending on the tool geometry. Given the vast number of geometries to be assessed annually, manual evaluation is impractical. The paper proposes an automated workflow to systematically evaluate and classify the best manufacturing strategy for each trimming tool, ensuring economic efficiency and effective solutions.

1 INTRODUCTION

Trimming tools are critical instruments used in the manufacturing process of automotive panel components. With the increasing diversity of vehicle models and the need for precision manufacturing, the global production demands necessitate approximately 1,500 unique tool geometries per Original Equipment Manufacturer (OEM) annually [1]. This high variability poses significant challenges to the manufacturing processes of cutting tools, both in terms of cost efficiency and scalability. Traditionally, these tools are produced either by entirely milling them from a six-sided block of material or by casting a blank and subsequently machining it to achieve the final geometry [2, 3]. While these methods are well-established, they involve substantial material waste and high machining costs, particularly for complex geometries [3]. A contributing factor to the relatively high expense is the increased hardness of tool steels, which typically exceeds 50 HRC [3].

Emerging hybrid manufacturing approaches offer promising alternatives to these conventional methods [4]. By combining a non-additive substrate plate with an optimized additive manufactured (AM) structure on top, cost-saving potentials can be realized. AM allows for near-net shape designs and material efficiency, but the optimal design with regards to cost and functionality varies depending on the specific additive process used. To ensure economic efficiency, the structural optimization must be tailored to the chosen additive process, taking into account factors such as material properties, design restrictions, and process cost. Furthermore, the decision-making process must remain flexible – depending on the characteristics of the trimming tool geometry, a fully subtractive manufacturing method or a hybrid approach may represent the most effective solution.

Given the substantial number of geometries to be assessed annually, a manual topology optimization and redesign with final evaluation of the most suitable manufacturing method is impractical [5]. To address this, an automated workflow is essential to systematically evaluate and classify the best manufacturing strategy for each trimming tool geometry. This paper introduces and elaborates on an automated workflow, detailing its development, implementation, and the potential benefits it offers in terms of cost reduction, scalability, and process efficiency for the production of trimming tools in the automotive industry.

2 STATE OF THE ART AND RESEARCH GAP

2.1 Fundamentals of cutting tools

Trimming, according to DIN 8580, is classified as a cutting process [6]. Alongside other processes such as knife cutting, nibbling, splitting, tearing and breaking, trimming is categorized under the subgroup dividing. Typically, trimming is a downstream process following forming or drawing operations, utilized to remove excess material and approximate the desired sheet geometry to the final product [6].

Conventional tool concepts consist of an overall system that is usually assembled onto a prefabricated cast bed, with a total weight of several tons. This system is composed of numerous tool components, commonly referred to as cutting blades. Figure 1 illustrates the segmentation of a tooling system used in the trimming process for the production of an automotive outer body panel.

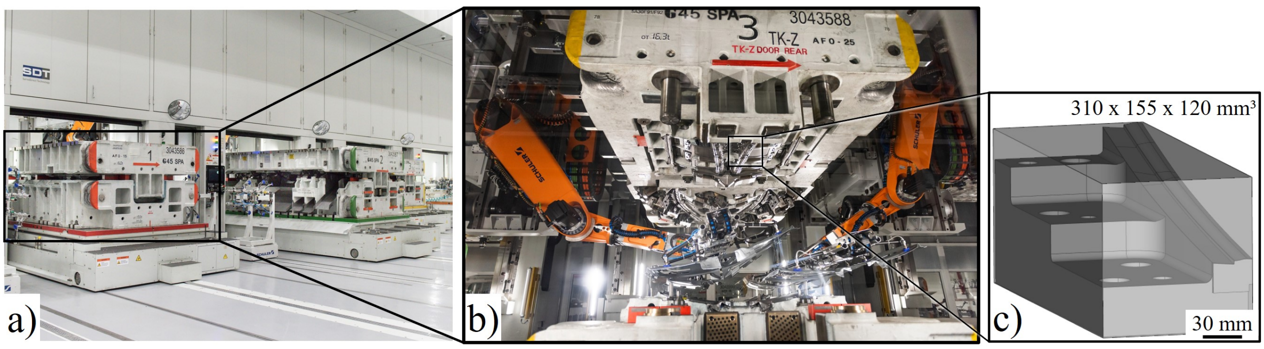

Figure 1: Classification of the cutting tool system for the production of an automotive outer body panel: a) system consisting of multiple individual stages, b) individual system comprising a cast bed, c) final tool component within bounding box for raw material need [7]

Each body panel shows distinct component geometries, requiring at most one-digit part numbers per design. To assess the loads during the trimming process more precisely, the tool component within the cutting process can be analyzed in greater detail regarding its force interactions, as illustrated in Figure 2. The forces most relevant to the load-oriented design of the upper cutting blade are the vertical force F_V and the horizontal force F_H. These reaction forces must be exerted by the cutting blade depending on the sheet metal material being processed, thus imposing stress on the structure [8].

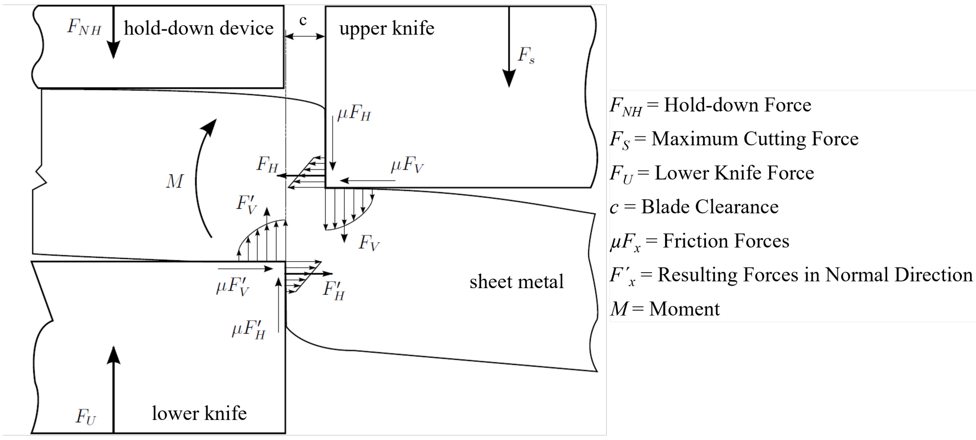

Figure 2: Forces and moments during the shearing process according to [8]

The calculation of the maximum cutting force F_S is performed using Equation 1, taking into account the tensile strength of the sheet material R_m, the elasticity coefficient e, the sheet thickness s and the cutting length l_s [9].

$$F_V = F_S = R_m \cdot e \cdot s \cdot l_s \tag{1}$$

The resulting force and moment distribution during the cutting process, in addition to the maximum cutting force F_S, also includes resulting lateral forces F_Q affecting the tool geometry. These forces for high-strength sheets can be described by the following Equation 2 [10].

$$F_H = F_Q \leq 0.33 \cdot F_S \tag{2}$$

2.2 Fundamentals of Hybrid Additive Manufacturing processes

Hybrid Additive Manufacturing (HAM) combines additive processes with non-additive processes [11]. Non-additive processes may, for instance, originate from the field of subtractive manufacturing, where a base plate is produced through milling and subsequently used as the foundation for HAM. The goal of HAM in the context of tool components is to produce structures using the most economically efficient method for each application. The cost-effectiveness of additive processes is directly influenced by the build rate, which is why two highly productive additive methods are considered in this case. Directed Energy Deposition using Arc Welding (DED-Arc) utilizes cost-effective wire as a base material, which is melted by an electric arc and deposited layer-by-layer to create a three-dimensional object [12, 13]. Powder Bed Fusion processes (PBF-LB/M) use lasers as an energy source to fabricate components within a metallic powder bed [13]. These methods are also suitable for HAM of an additive structure on an inserted base plate. A variant aimed at increasing productivity is Macro Laser Powder Bed Fusion (M-PBF-LB/M). M-PBF-LB/M integrates coarse metal powder exceeding 150 µm with a laser source capable of up to 8 kW, facilitating the efficient fabrication of additive components [14].

2.3 Description of research gap

Topology Optimization (TO) is an effective method for designing additive manufactured structures tailored to their specific loads while minimizing material usage and production time [15]. The corresponding simulation and optimization of the structure to be manufactured are carried out with the support of specialized software. This process not only requires access to appropriate software solutions but also specific expertise. According to the current state of the art, such simulations and optimizations involve a certain amount of time. Thus, a dedicated optimization becomes economically viable as the production volume of a component increases in the context of series production. Figure 3 illustrates the proportion of design costs in the total costs of a topology-optimized component across varying production quantities of a given design.

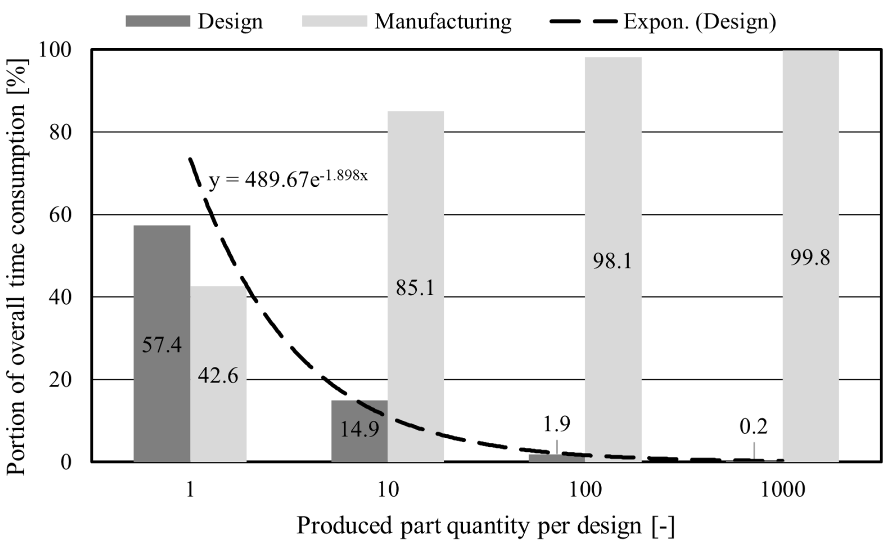

Figure 3: Proportion of part design and optimization time relative to the overall manufacturing time for an AM tooling component, considering higher production quantities and a manually reworked tooling component

Referring to the required quantities of a tool component in the shearing process, it becomes evident that the time consumption for simulation and optimization of a single component range between 50 – 60 % of the total manufacturing time directly corresponding to the manufacturing cost. The objective of this publication is to minimize manufacturing costs by specifically considering design efforts, thereby enabling the effective optimization of tool components with low production quantities.

3 METHOD

When discussing Design Automation (DA), there are multiple approaches to implementing it through software solutions. These approaches include Parametric Design (PD), Algorithmic Design (AD), and Generative Design (GD) [16]. All methods differ significantly in their input and output variables, as illustrated in Figure 4. The approach of GD is intended for creating various comparative geometries, utilizing different generators to produce multiple comparable design outputs. To achieve the goal of comparing multiple design variants across different HAM processes, the GD approach is employed. One platform option in the GD domain is Synera, developed by Synera GmbH. A conceptual workflow, based on the flowchart in Figure 5, is implemented and further detailed within this paper. Synera operates using a node-based visual programming approach to create generative

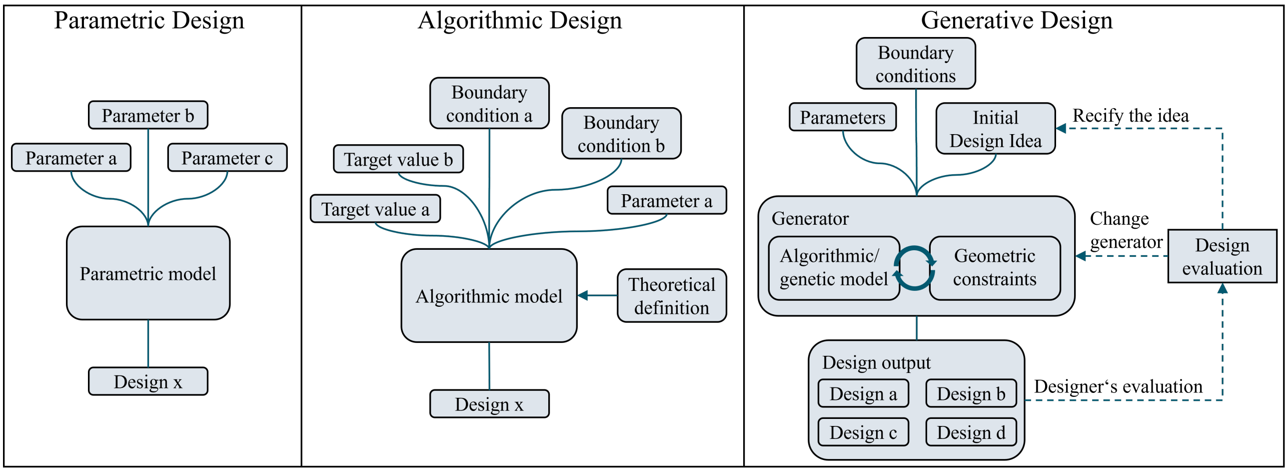

Figure 4: Different DA methods illustrated with their specific input and output data [16]

workflows reusable for a high amount of same-type geometries. This approach adopts an incremental strategy toward achieving the overall objective. Accordingly, the task of identifying the most economically optimal solution was decomposed into the principal components outlined above. Following the definition of the core workflow functions, the individual steps were elaborated in greater detail, and the associated dependencies were systematically incorporated.

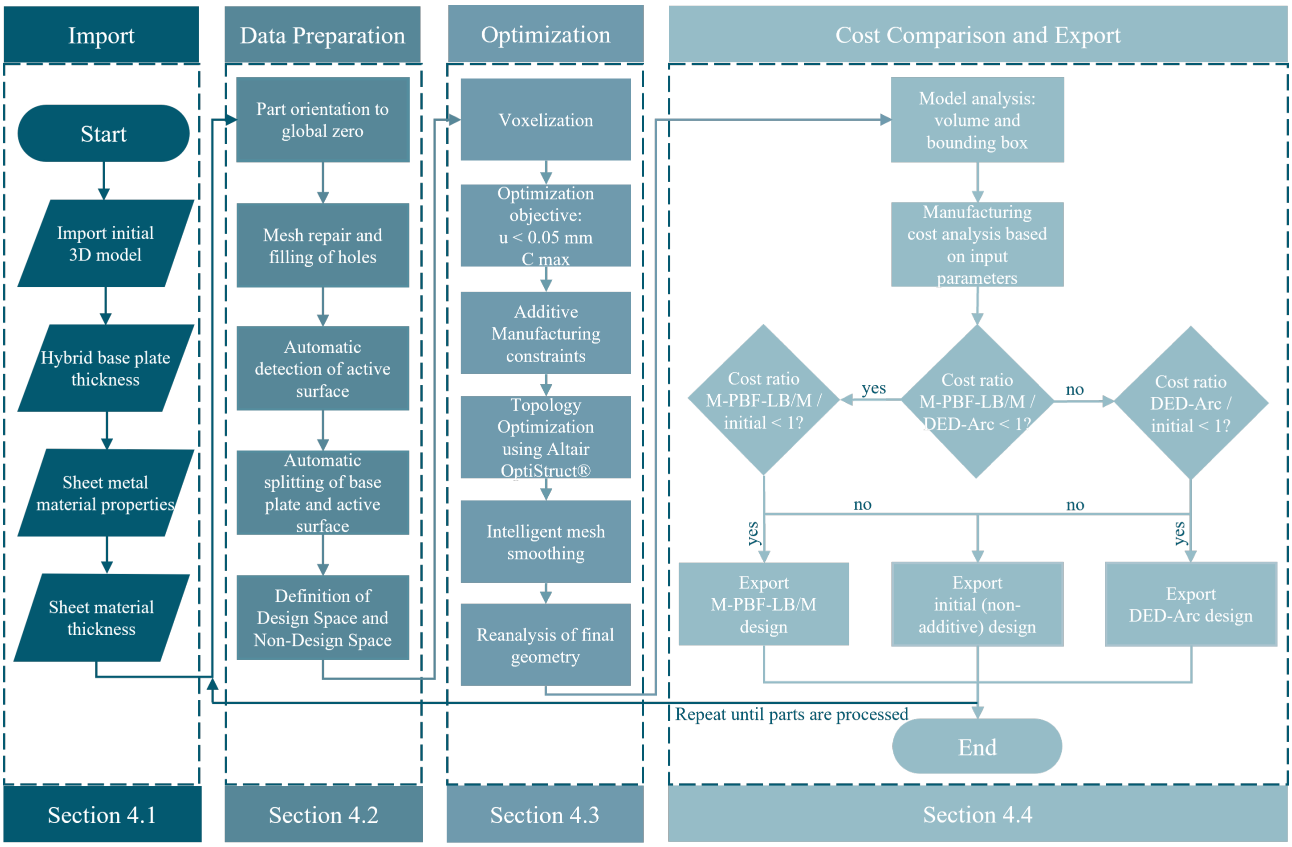

Figure 5: Flow diagram of the GD and comparison approach

4 IMPLEMENTATION

4.1 Import

The workflow can directly access the local folder structure where the collected geometries are stored. This enables all tool components on one side of the system to be automatically saved from the interface program into that predefined folder layout, making batch processing possible and allowing a current-state assessment. In addition to storing the geometry data as design boundary condition, additional tool system specific parameters must be provided via a text file. These include the intended thickness of the hybrid non-additive base plate s_p and the material properties of the sheet metal to be processed as specified in Equation 1.

4.2 Data Preparation

Ensuring the processing of different geometries follows a consistent approach, a defined initial state for each component must be established. This involves determining the geometric center of each geometry and setting it to $X = 0$ and $Y = 0$ in the global coordinate system. For rotational alignment, an automatic detection of the longitudinal axes of the base plate's boreholes was utilized. Additionally, the bottom plane of the imported geometry represents the $Z = 0$ position. This predefined orientation serves the intended thickness of the base plate s_p of the model, allowing for the HAM on a non-additive base plate at a certain Z-height and is illustrated in Figure 6. After positioning, the component can be automatically divided into its functional surfaces, Design Space (DS) and Non-Design Space (NDS).

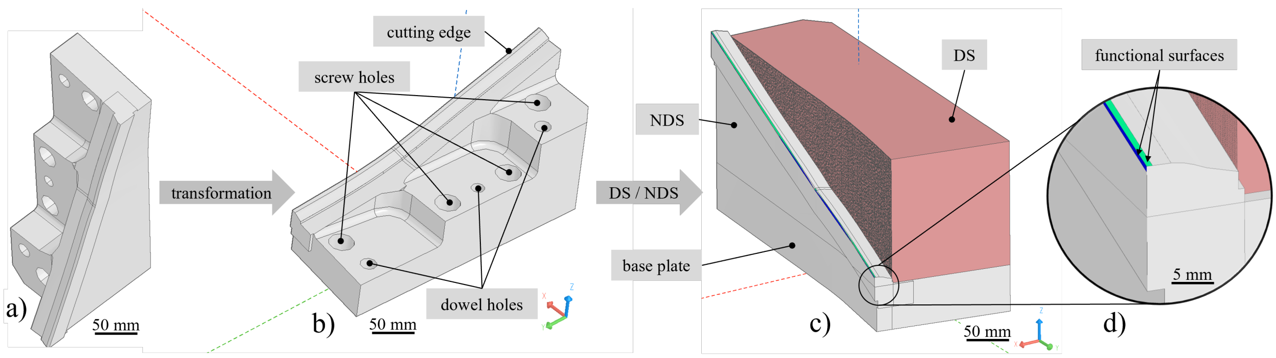

Figure 6: Data preparation workflow including a) initial import orientation, b) aligned geometry to defined position, c) division of geometry into DS and NDS and d) functional surface detection

4.3 Optimization

Once the geometry is prepared for topology optimization, the loads and constraints must be considered. Since the forces described in section 2.1 are assumed only for a specific point in the cutting process sequence, a surface load was applied as a simplified model of the real load for structural optimization of the entire tool component. This involves defining an "undercut" with a width w and depth d of $1 \cdot 1\,mm^2$ across the entire length of the cutting edge l_s. This subdivision was already accounted for in the geometric processing and described as functional surfaces. Using the following formula, and considering the Equations 1 and 2, the pressure in both the cutting p_S and lateral directions p_Q

can be determined as following Equations 3 and 4:

$$p_S = \frac{F_S}{l_s \cdot w} \tag{3}$$

$$p_Q = \frac{F_Q}{l_s \cdot w} \ . \tag{4}$$

Through automated detection of the segmented cutting edge, pressure can be applied to the topology optimization model in a manner that is dependent on geometry and considers the analyzed cutting length. Furthermore, the optimization model is assigned the appropriate material, and the fixed constraint at the bottom of the base plate is defined. Figure 7 illustrates the final automated definition of boundary conditions for the example. With the geometry and boundary conditions of the model

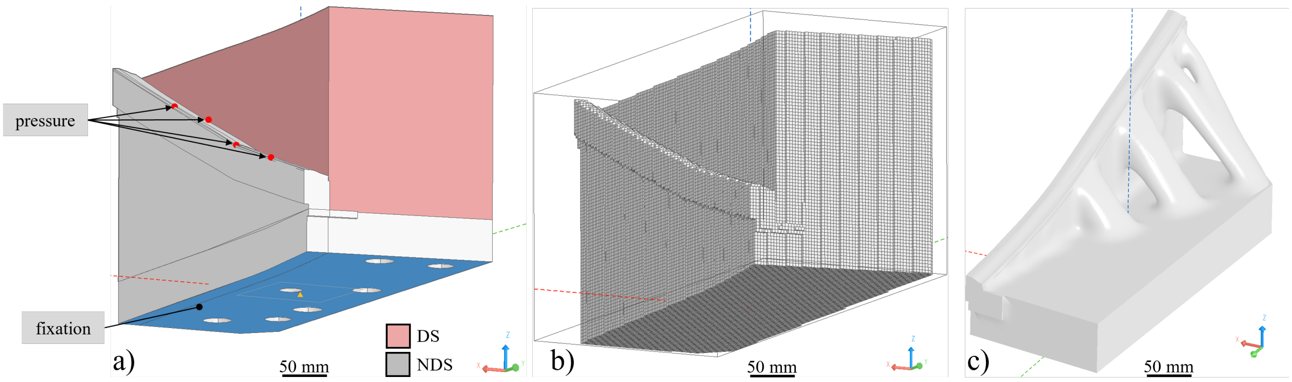

Figure 7: Representation of a) automated boundary conditions on optimizing model including pressure (red) and constraints (blue), b) voxelization of model for the discretization of the component volume and c) result of the M-PBF-LB/M optimization

prepared, the final topology optimization can be initiated. Altair OptiStruct, developed by Altair Engineering Inc., is used as the solver which is available as a separate node within Synera. This solver offers a variety of settings for manufacturing and optimization requirements. Additionally, manufacturing constraints specific to different AM processes can be integrated and considered in the structural design. The following manufacturing constraints in Table 1 are provided to the solver to achieve appropriate results for production using M-PBF-LB/M and DED-Arc. The overhang angle β is defined as the maximum deviation of a surface perpendicular to the build plate toward the build platform. This angle is larger in the M-PBF-LB/M process due to the support provided by the powder bed, compared to the wire-based DED-Arc process. The parameter member size d_x describes the minimum and maximum thickness of the structures that can be processed in the respective method.

Table 1: Manufacturing constraints of different AM processes as an input for topology optimization [17] [18]

	M-PBF-LB/M	DED-Arc
Maximum overhang angle β	60°	40°
Minimum member size d_{min}	$3\,mm$	$5\,mm$
Maximum member size d_{max}	$30\,mm$	$10\,mm$

Finally, the optimization objective is set to weight reduction, with a maximum allowable displacement u of the loaded structure defined as $u \leq 0.5\,mm$. This deformation represents the maximum permissible deviation under load from the target geometry for the manufacturing process and applies to all types of trimming tool components. Upon completion of the respective optimizations for the HAM processes M-PBF-LB/M and DED-Arc, the results can be compared with the non-additive baseline in terms of weight, material consumption and processing time. This comparison enables a direct selection of the variant with the minimal manufacturing costs for each case.

4.4 Comparison and Export

The final main step of the automated workflow involves the comparison and export. In this step, predefined cost models are supplemented with real data within the workflow. Figure 8 illustrates the components of these cost models for both subtractive and AM. The outcome of each version across different HAM methods is comparatively presented in Figure 9 for various example components, with respect to the costs of subtractive manufacturing.

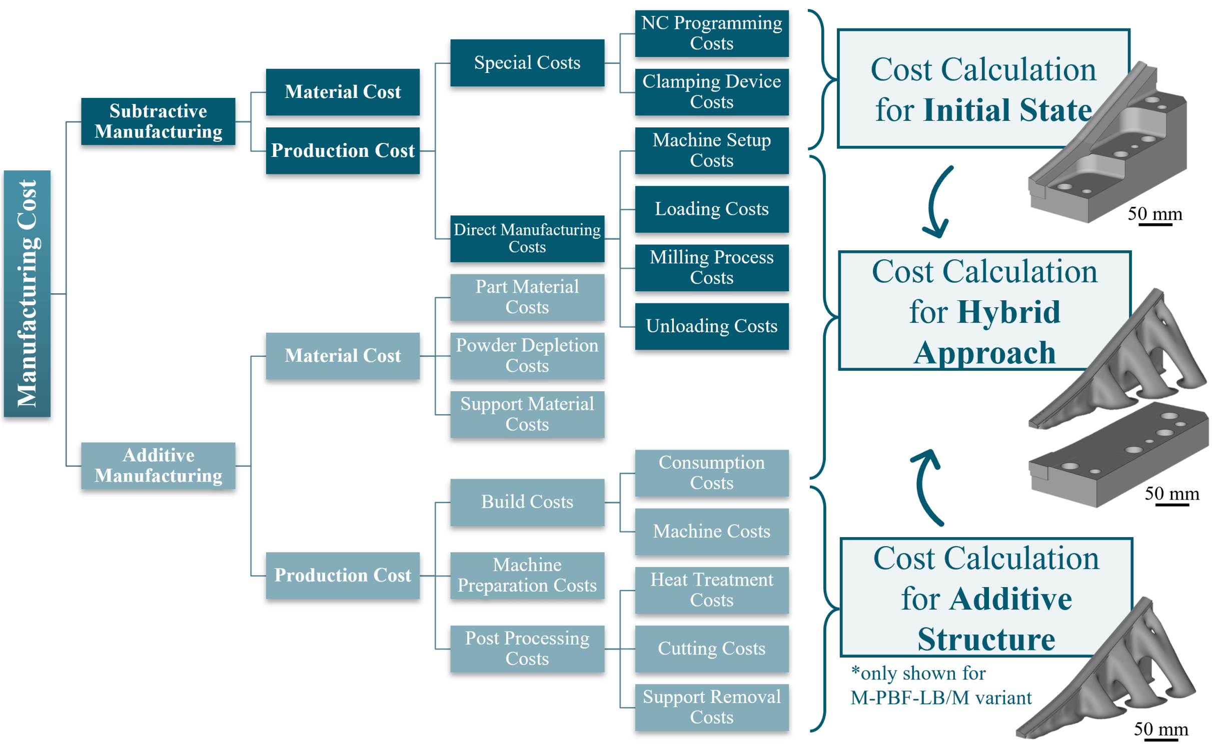

Figure 8: Itemized cost models for subtractive and AM used for evaluation of manufacturing cost based on [19, 20, 21, 22, 23]

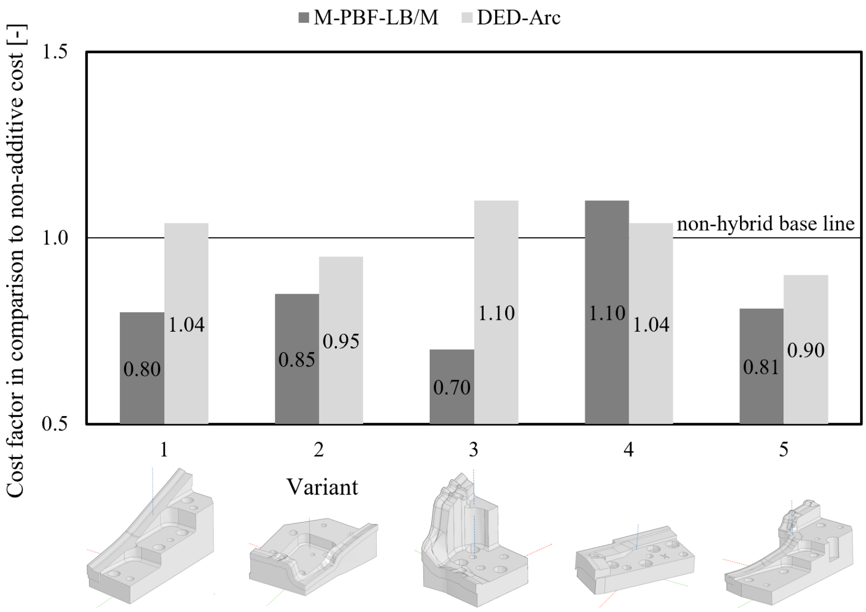

Figure 9: Comparison of different optimization results and corresponding manufacturing costs in relation to non-hybrid costs

The comparison is implemented as a function in the workflow and calculates the cost factor relative to the non-hybrid solution (1.0). Based on this calculation, the most effective and optimized solution can be exported from Synera and directly imported into slicing programs. Through batch processing, multiple solutions can be generated automatically, enabling the optimization of numerous components without manual intervention. In this example, variants 1, 2, 3 and 5 exhibit the most cost-efficient solutions for HAM employing M-PBF-LB/M. In detail, variant 3 demonstrates the best solution for the hybrid approach, whereas variant 4 is not feasible for HAM and will continue to be produced via subtractive methods.

5 EVALUATION

This paper demonstrates the successful implementation of an automated approach for creating hybrid-manufactured trimming tools. To highlight the benefits of this development, a comparison of the time required for optimizing the previously mentioned 1,500 tool components per year is presented within Figure 10. The assumption is based on a manual effort involving active employee participation of 60 minutes per optimization cycle in the initial situation. This includes the entire optimization process chain, such as preparing models, setting boundary conditions, reviewing and evaluating optimization results, redesigning the result, reanalysis of the redesigned part and preparing for final hybrid manufacturing. In comparison, the fully automated workflow requires an average manual effort of only 2 minutes per tool component, covering merely the import and export of geometrical boundary conditions for each tool component.

Though this comparison was simplified, the main conclusion can be drawn that workflow-based design allows for significant cost savings. The comparison reveals that this approach enables up to 97 % time savings. By integrating Figure 9 and Figure 10, a time-efficient method is combined with a cost-oriented manufacturing approach, significantly enhancing the overall production efficiency for toolmaking of trimming tool components.

Figure 10: Simplified comparison of both optimization methods for 1,500 individual components per year related to an employee's annual working hours

6 CONCLUSION AND FUTURE WORK

The developed workflow allows for the direct application of this approach by designers of tool components, enabling significant optimization of the manufacturing process for trimming tool components. With further additive process developments and implementations of hybrid approaches, the optimization workflow can be expanded to include process-related preparations, such as slicing, completing a holistic approach. Consequently, a comprehensive workflow can be achieved using only the input of the cutting edge geometry, without the need for subtractive manufacturing design connections. This reduces the preparation time of the components to a minimum. Additionally, with minor adjustments, this approach can be applied to other areas. Thus, from a tool system designed for manufacturing outer body panels, not only the cutting process but also all other forming processes and their respective tool components can be automatically optimized and evaluated.

Further developments should be added to the workflow, incorporating innovative design optimization techniques. Traditional TO focuses on minimizing mass or maximizing stiffness. In this case, however, manufacturing time is the primary concern, which does not necessarily correlate with minimal mass. Optimizations based on scan track or weld path to meet minimum requirements could unlock additional potential in decreasing build time. To achieve this, additional functions, such as a slicing module, need to be integrated into the workflow. This slicing module can determine time and material requirements, which can then be optimized to a minimum to meet the maximum displacement requirement. Also, the developed structures should be tested under real-world conditions to compare and validate their full mechanical functionality against that of non-additively manufactured tool components.

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