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Methodical software-supported, multi-target optimization and redesign of a gear wheel for additive manufacturing

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Abstract

Additive manufacturing gives new freedom to part design by enabling the manufacturing of complex structures. Mastering this degree of freedom poses challenges for product developers with experience from conventional manufacturing. In order to meet this challenge in a structured manner, a practical method is presented in which creative idea development is combined with software-based design optimization. First, optimization goals are defined. Then a baseline design is developed through a creative ideation process. Variants are derived from the baseline design, evaluated according to simulation results and selected. The method is illustrated by the development of a lightweight and function-integrated gear wheel.

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Keywords: part optimization; redesign; software; additive manufacturing; multi-material; laser beam melting; gear wheel; drive train; topology optimization

1. Introduction

Additive Manufacturing (AM) relies on a layer-by-layer build-up of part geometries instead of shaping or removing material [1]. Through this principle, parts can be designed with fewer constraints compared to conventional tooling or manufacturing. Additionally, the new design freedom allows for freeform surfaces, internal features and complex geometries. This geometric freedom is used for lightweight design, optimized fluid flow, enhanced cooling efficiency, damping and more [2]. These possibilities allow the optimization of parts for one or more purposes. Together with the design possibilities, new business models are emerging [3]. Lutter-Guenther et al. together with Thompson et al. state that, besides prototyping, the new possibilities in part design may create an economic benefit through the cost-effective production of small-series parts [2, 3]. Hence, part design does not only influence part performance but is also strongly connected to cost per part and the attached business case for the use of AM. Finding the most suitable part design in the nearly unlimited possibilities given by AM plays a critical role in the success of implementing AM.

For lightweight design of parts, geometric optimizations as lattice structures, topology optimization or biomimicry can be deployed [4, 5, 6]. Topology and lattice optimization are implemented in software tools where the underlying algorithm defines the parts structure. Furthermore, classic computer-aided engineering tools, which often are based on the finite element analysis (FEA), e.g. structural analysis, computational fluid dynamics (CFD) or heat transfer simulations, are employed to determine component properties. The part optimization is usually carried out in loops [7].

For part redesign, examples can be found in the literature, e.g. the bionic reinforcement of an additively manufactured A-pillar, the implementation of conformal cooling in hot extrusion dies or the redesign of a satellite structure for AM [8, 9, 10]. In most of the use cases, no comprehensive redesign strategy is employed and the focus is set on the Design for Additive Manufacturing (DfAM). However, product development methods like TRIZ or biomimicry construction guidelines like VDI 6224 can be applied for redesign but are originally suited for the development of new products [11, 12].

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Kamps et al. introduced a methodology of redesigning parts called BioTRIZ with the help of biomimicry focusing on screening and abstraction of nature's solutions for technical problems [13]. In general, the methodologies (VDI 6224 and BioTRIZ) apply software tools at a certain step of the product development cycle but no holistic approach for the use of software-based optimization is given. The application of a software algorithm for part optimization requires defined optimization goals and a clear ranking of those. Especially if the part undergoes a multi-criteria optimization. Otherwise, the support of software tools in the optimization process is not used purposefully. This leads to an inefficient part design and use of software tools. Design software and simulation tools often have high licensing costs. Especially for small- and medium-sized enterprises (SME), high software costs act as a barrier, which can limit their innovation potential [14]. Upcoming solutions like software-as-a-service (SaaS), which combine cloud computing (mostly browser-based) and pay-per use licensing, could be an answer to prevent high software cost. The biggest obstacle in the implementation is the request for data security and confidentiality towards third parties and the SaaS provider [15].

Design engineers with less experience in the field of AM design may be overwhelmed by the new freedom and the increased complexity. At the beginning of a redesign of a given part, finding the right starting point is challenging and there is a lack of systematic step-by-step methodologies to follow during part redesign. Zhu et al. propose a framework for AM part design including process selection for parts and determining design considerations from this choice [16]. However, the required steps in designing a part for AM are not specifically addressed. Kamps et al. propose a combination of TRIZ, biomimicry and DfAM with the focus on connecting TRIZ and biomimicry to design parts suitable for AM [13].

General abstraction of the required knowledge for part redesign from literature leads to three fields which are creativity, knowledge of DfAM for the selected AM technology and control of the optimization software tools and algorithms. For a successful part redesign competencies in all three fields have to be combined as can be seen in Fig. 1.
A lack of one or more of these competencies may lead to a part with a non-optimal performance, high costs, need for additional design loops and unnecessarily long development cycles. In this context, the need for an easy-to-use methodology to reduce the design complexity and for the efficient use of software-based optimizations in the redesign of parts for AM becomes clear. In the next chapter, a holistic step-by-step approach for the software supported part redesign and optimization is introduced with the focus on being applicable for engineers without detailed background in AM.

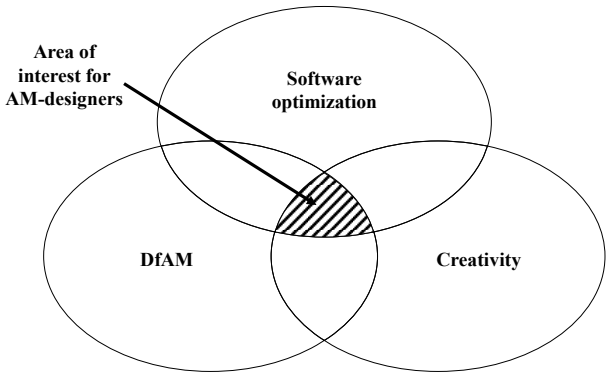

Fig. 1. Interface for design engineers: part redesign and optimization requires cross-functional competencies

2. Applied design methodology and sequence

Aim of the methodology is to give guidance to part redesign for AM and to arrange all necessary steps for a successful optimization. The proposed methodology (c.f. Fig 2) shows the concluding steps towards a redesigned part, methods that can be applied in each step and expected results of each step. Before the introduced methodology can be applied, a part and a suitable AM technology have to be selected. Possible methods are described in separate literature.

At first, optimization targets have to be identified to ensure optimization and tailoring of the part to underlying conditions. Suitable methods for identifying optimization targets are function or weakness analysis as described by Lindemann [17]. The abstraction of the parts functions is key in this step. This leads towards thinking in part functions and not in previously known solutions. Additional information can be gathered by studying successfully implemented redesign use cases. This step is critical as it starts the methodology and omissions or failures are dragged along the next process steps. In this step, workshops and consulting between product owner, manufacturing engineer and AM expert are advisable. As a result, the purpose and the optimization targets of the redesign are determined. Depending on the part, these may be e.g. reduction of weight, increase of part performance (cooling, reduced pressure drop, etc.) or reduced assembly effort. However, optimization goals can also be dissociated from the actual part e.g. if an innovative image or benefits in the supply chain are desired.

Secondly, the chosen optimization targets have to be rated as all targets can rarely be achieved to the same degree of fulfillment. Usually, a tradeoff between diametrically opposed and competing targets is necessary. Applicable methods include pairwise comparison as proposed in VDI 2225 or a value for benefit analysis [17, 18]. During this process, suitable criteria have to be applied. These can be derived from the part's boundary conditions and overall optimization strategy. With the help of the target rating, the sequence of the software-based optimization is determined.

Most important and underrated step is the creation of a baseline model since it is the foundation for further automated software-based optimization. If the baseline design has major design flaws, the optimization will not lead to a design best adapted to the operating conditions. To create a suitable baseline design, two steps need to be combined. On the one hand, established creativity tools like TRIZ, biomimicry and other tools known from conventional product development should be used [11, 12]. On the other hand, DfAM has to be considered since otherwise the part cost increases drastically or the manufacturing becomes impossible. In this step, a search in literature for solutions to the optimization targets and the

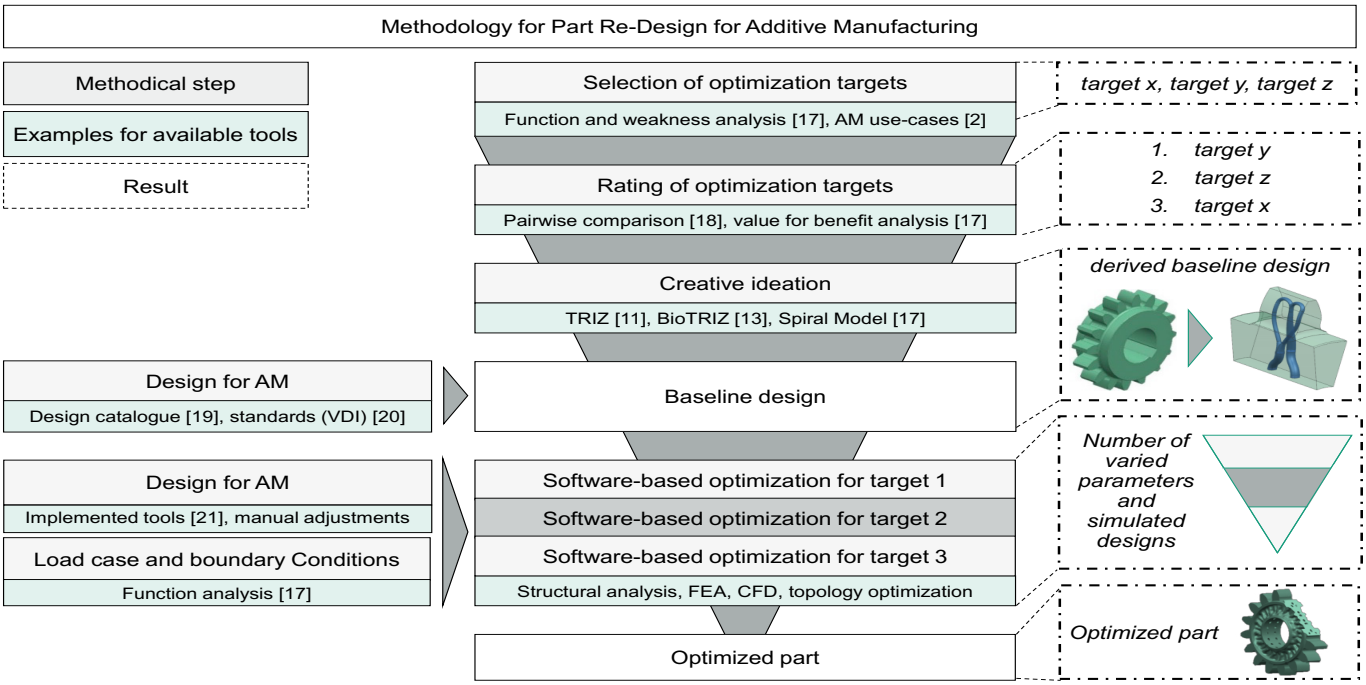

Fig. 2. Proposed part re-design methodology; Comprehensive methodical step-by-step approach reduces design complexity and gives directive for the combination of creativity, DfAM and software optimization with a selection of available tools

recombination of these can be useful. When transferring the ideas from the creativity process into the baseline design, DfAM limits have to be considered. These limits are specific to the chosen manufacturing technology and can be derived from literature. For laser powder bed fusion (L-PBF), process limits and design rules are described by many authors, e.g. by Adam and Zimmer or VDI 3405 Blatt 3 [19, 20]. In some cases, it may be useful to create more than one baseline design. This is especially helpful if two or three possible concepts for solving the optimization targets can be derived. With the help of the software-based optimization, a basis for a quantitative comparison is established supporting the design choice.

After deriving a baseline design, the software-based optimization step begins. First, the boundary conditions and load cases have to be determined. One suitable method is the function analysis [17]. If a function analysis was already carried out in step one, the results can be used as an input for the load cases and boundary conditions of the simulations. When implementing the boundary conditions, most times simplifications and assumptions have to be made. This influence should be estimated at the beginning and expressed as uncertainty at the end of the methodology. Additionally, a tradeoff between simulation accuracy and simulation time has to be considered. Especially when performing Finite Element Analysis (FEA), the mesh resolution effects simulation time extensively. To find a compromise between accuracy and time, preliminary tests are advisable. Additionally, DfAM has to be considered in the software-based optimization. On one hand, this can be ensured by implemented AM constraints in the applied software, e.g. build-up direction in topology optimization [21]. On the other hand, manual adjustments and boundaries have to be deployed, e.g. suitable choice of limits for parameter variations like minimal diameter of cooling channels. Methods which can be applied in this step are related to the optimization targets and may include FEA or Computational Fluid Dynamics (CFD) connected with a parameter optimization of the baseline design. The main variable for the second optimization target should be determined by preliminary tests or analytical methods and held constant. This leads to the fact that one variation possibility still exists in the 2nd optimization loop and so on. However, the variation of the remaining variable should only be carried out in a positive direction for the first optimization target. With the help of simulation tools, the most suitable variant of parameters which describe distinct features of the baseline design can be found.

If more than one design concept was derived as a baseline design, the results of the first optimization can be used to eliminate inadequate concepts. As a next step, the concepts are evaluated in regard to the second target. With the simulation results, further inadequate concepts or variants can be disregarded. These steps lead to a decreasing amount of design concepts and variants until only one design remains. This design is the optimized redesigned part that fulfills the requirements from the optimization targets.

3. Validation in a multi-criteria optimization of a gear wheel

In this section, the introduced methodology is validated by redesigning a gear wheel with multiple optimization targets. Such a part redesign is applicable without high computational power. To illustrate this, all described calculations were performed on a consumer mobile workstation (i7(4C/8T), 16GB). To reduce friction and to dissipate heat, gears run in oil leading to splashing losses. This leads to a decrease in gear box efficiency. To further increase the efficiency, the functions of cooling and lubrication of the oil can be split. This leads to the development of new cooling concepts for gears; for example, Siglmueller et al. introduced a conformal cooling of the tooth with inside channels and a water cooling system [22]. Tests of this set up showed a cooling effect of up to 50 K. However, the

Pairwise comparison	Criteria 1	Criteria 2	Criteria 3	Sum
Tooth root strength		2	2	**4**
Cooling capacity	0		2	**2**
Lightweight design	0	0		**0**

0 – „less important than“
1 – „equal important than“
2 – „more important than“
(read from row to column)

Fig. 3. Evaluation of optimization targets - pairwise comparison to determine rating of optimization targets

required energy for running the water cooling was high due to pressure losses, which did not lead to an overall improvement of the system efficiency. To minimize the required energy for the cooling system we propose gas as a coolant. The existing cooling circuit of the air conditioning system is to be utilized for this purpose. AM is required to manufacture a gear with these complex internal cooling channels.

To increase efficiency, three targets were derived using a function analysis

- Tooth root strength
- Cooling capacity
- Lightweight design

There is a conflict of objectives among the resulting targets. The complexity can firstly be reduced by prioritization using a pairwise comparison, which is illustrated in Fig. 3.

The derived order of priority is strength – cooling – lightweight design. The targets are used as exclusion criteria at the end of the target-related optimization stages. The order of the optimization stages and the resulting exclusions is dependent on the prioritization. In the example, the first exclusion is based on strength, the second on cooling and finally on mass reduction.

The next step of the methodology is the creative generation of concepts, for example using the TRIZ procedure model [11]. Due to the possibility of generating innovative approaches, this step is vital and has the potential to economically exploit the freedom of AM design. TRIZ was applied to derive the following optimization concepts (see Fig. 4):

a. The strength is to be increased by reducing the number of channels (3) in the critical areas at the level of the tooth root. The channel adapts the Venturi principle (cf. mark in Fig. 4 a)) to increase the flow velocity in the critical heat dissipation area and thus increase the cooling capacity.
b. Strength and cooling capacity are to be enhanced by splitting the ducts with an associated reduction of the diameters.
c. By integrating lattice structures into the ducts, the strength should be increased by stiffening the geometry. The cooling capacity shall be enhanced by increasing the heat transfer area and turbulences.

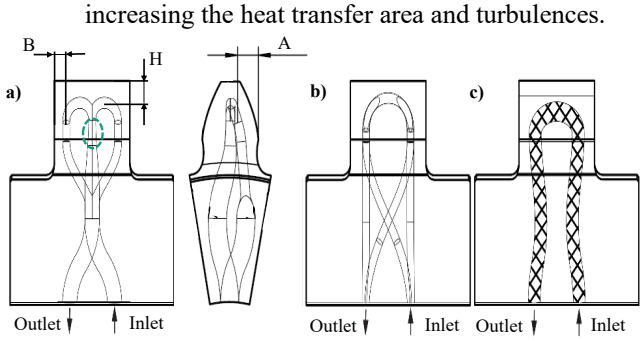

Fig. 4. Overview of derived concepts

The actual concept development based on the inspirations of the TRIZ solution algorithm is closely linked to the design aspects of DfAM. When generating the baseline models, the process-specific guidelines and recommendations were consistently applied [20]. The following influences were taken into account: dimensions of the cavities (e.g. channel diameter), the possibility of powder removal, overhang-free alignment, wall thickness and strut diameter in the lattice concept.

The optimization process in each stage is based on software and is driven by either manual influence or a procedural algorithm. While progressing, it is of fundamental importance to ensure that the achieved target states are largely maintained, even if the geometry may change as a result of subsequent optimizations. The first optimization derived from TRIZ is the variation of the channel position parameters to increase strength while retaining the individually selected cross-sectional areas. At this point, the cross-section areas of the channels are not varied. Only the channel position in the tooth itself varies. To achieve this, a linear contact simulation of the gears in the most critical engagement position with constant torque was performed in Siemens NX. Gear fragments were used to reduce the calculation time, considering the conformity of the results. An adaptive mesh was set up, followed by a mesh refinement study to further reduce computational time without compromising numerical accuracy. The model was validated by analytical calculations of the load-carrying capacity according to ISO 6336 [23]. The stress results are automatically evaluated in the tooth root area and transferred to an optimization loop. This loop represents a software-driven, cross-parameter optimization.

In each iteration (cf. Fig. 5), one of the parameters is changed and the others are kept constant. The parameter limit values and thus the range in which the parameter can be varied by the algorithm are selected by the designer with the aid of TRIZ and in particular taking into account the DfAM aspects. Furthermore, the optimization goal of minimal stress in the tooth root and an abort criterion are selected.

In concept 1 parameter A describes the position of the lateral position of the returning channel, parameter B the horizontal distance of the channels to the tooth boundary and parameter H characterizes the distance towards the head of the tooth. Through the iteration of the parameters in their specific boundaries, the stress in the tooth root σ_{F0} is determined, and the parameter combination with the lowest stress value is chosen. This process was able to optimize the position of the channels depending on the selected parameters and was run

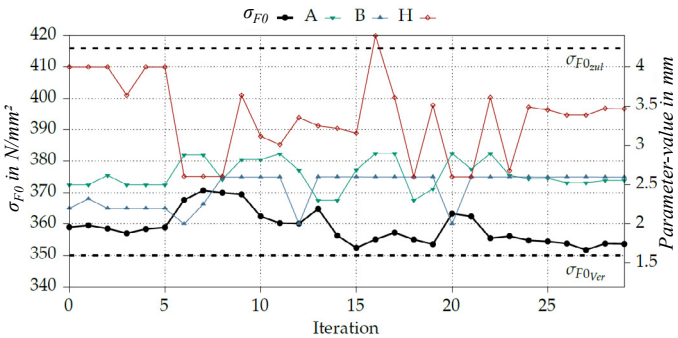

Fig. 5. Iterations of the structural simulation of concept 1 for the optimization of the channel position leading to minimal tooth root stress

through all three concepts. The final parameters of the channel geometry were implemented in the individual concepts, and the resulting maximum tooth root stresses were determined in order to disregard one concept (Concept 1: 353 N/mm²; Concept 2: 338 N/mm²; Concept 3: 371 N/mm²). The third concept was neglected because the tooth root stress exceeded the experimentally determined fatigue strength of gears with cooling channels [24].

In the next step, the remaining two concepts (a, b) are optimized with regard to the cooling capacity. The optimization is based on the target of achieving the highest possible cooling capacity at an acceptable pressure loss. The only variable parameters are the cross-sectional areas, which were held constant in the first optimization step and may only be reduced in order to keep the strength levels obtained by the first optimization. A multiphysical simulation was performed in a gear wheel fragment with one single channel of each concept, consisting of a CFD flow analysis in conjunction with heat transfer phenomena. The heat load was assumed on the basis of the intended transmission power. For cooling, convection was modeled in addition to the capabilities of the fluid flow. The channel roughness associated with AM was also taken into account. The pressure point of the working circuit is close to the evaporation temperature in order to further increase the cooling capacity through an evaporation process in the critical area of tooth contact. For the approximation of turbulences in the ducts, the SST-model was used. The flow analysis was validated on the basis of analytical calculations on reduced pipe fragments. To increase numerical efficiency, a study on mesh refinement regarding flow velocity and amongst turbulence models was performed. The remaining concepts were compared according to the evaluation criteria heat transfer and pressure loss depending on the stepwise reduction of the cross-sectional areas (cf. Fig 6).

Based on this comparison, the final concept exclusion took place. In concept 1, the reduction of the cross-section at the Venturi nozzle led to a high increase in cooling capacity mainly due to the acceleration of the cooling gas. A cross-section reduction of concept 2 did not lead to an increased cooling capacity and was overall lower compared to concept 1. In conclusion, concept 2 was excluded due to the low cooling capacity and high pressure loss.

The remaining concept was then optimized according to the tertiary target of mass reduction. The process-driven approach of topology optimization via secondary software is chosen for

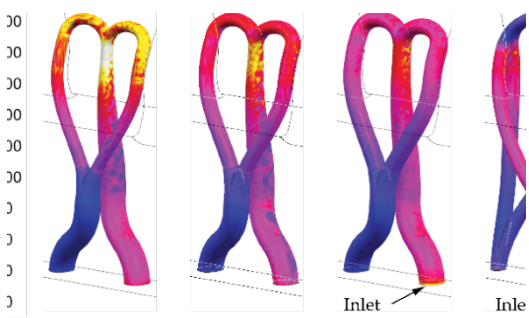

Fig. 6. Heat transfer of concept 1 and 2; Increased Venturi effect through reduction of the channel cross-section leads

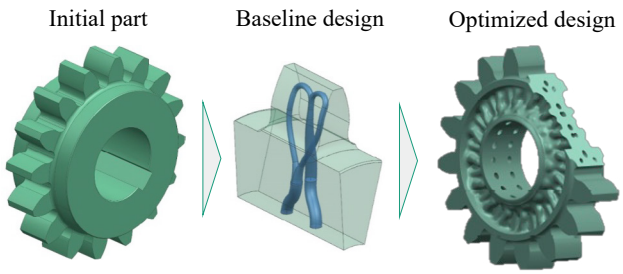

Fig. 7. Optimization process from initial part, baseline design towards optimized design with included cooling channels and 48 % mass savings

this purpose in which mechanically relevant areas are differentiated and the non-relevant areas are removed based on a structural simulation. The specific requirements of the additive production (DfAM) are considered by implemented boundary conditions like the determination of the build-up direction. The force introduction is modeled by a surface load with a rotational fixed constraint. With this optimization step, all material not required to transfer the load is eliminated, and the mass could be reduced by 48 %. The final result of this redesign by structural optimization can be found in Figure 7. The example shows a multi-criteria optimization of strength, cooling capacity and lightweight design.

4. Discussion

By applying the proposed methodology, the gear wheel was optimized to meet diametrical targets (tooth root strength vs. cooling capacity and lightweight design) and the redesign was successful. The foundation of the optimization steps was laid in identifying and rating the optimization goals. For this purpose, a functional analysis and a subsequent pairwise comparison were conducted. By including these well-known methods into the redesign methodology, designers work with familiar tools, hence avoiding rejections or concerns. Within this optimization, the baseline designs were created via TRIZ, which proves a strong tool in creating innovative ideas by combining solutions from different fields in this optimization context. As a next step, parametric models describing the cooling channel position within the gear tooth were set up. Through an optimization loop, these parameters were varied in preset boundaries and the tooth root stress was automatically evaluated. More than 30 iterations per concept were calculated and the minimum stress values were compared to eliminate one concept. By means of the optimization loop, many variants were screened in a quick procedure and eliminating one concept lead to a decreasing complexity and time-savings before going into the CFD simulations. When performing the CFD simulations, another concept could be excluded due to insufficient cooling capacity. A topology optimization was carried out on the remaining concept in order to decrease the part weight. In this step, setting the cooling channels as a non-design space proved to be challenging mainly because the software tool had to be switched.

In general, the comprehensive approach of the part redesign with its structured steps and a clear procedure helped in optimizing the part. Especially the start of the redesign phase was applicable and can be followed by design engineers without AM background. The step of creating the baseline design requires a certain amount of AM knowledge,

particularly AM design rules. Following the basic rules derived from literature e.g. channel diameters and overhang angle can already lead to printable parts. Nevertheless, this step holds the biggest challenge for design engineers with no AM background. Software optimization is straight-forward through optimization of the rated targets, and the narrowing down of the number of concepts is achieved easily. However, CAD and CAE skills are required to set up a suitable baseline design with the possible freeform surface and in conducting the iterative optimization. A growing number of optimization tools has inbuilt DfAM rules as boundary conditions which can decrease the complexity and help designers. Additionally, experimental validation of the results should be carried out, especially since material models for AM are still under development. Only with such validations near-reality predictions are made possible.

Furthermore, a continuous software chain is desirable since switching software tools is not a value-adding step and may lead to the loss of information in the model. This shows the demand for integrated continuous software solutions from design to print preparation in AM.

5. Summary and Outlook

The introduced step-by-step methodology for part redesign for AM provides an applicable tool for design engineers without AM knowledge. Additionally, the proposed methods for conducting the redesign steps leave freedom to the designers but still offer enough support. The complexity in optimizing parts for multi-targets is reduced through an early prioritization and by using the CAD optimization tools steps-by-step. Furthermore, no complex cloud- or browser-based software is required, which facilitates the implementation and use of the methodology in SMEs. The use of CAE tools for optimization has great potential in screening many variants of a concept. However, skilled engineers are required for the design and setting up the simulations may take a large amount of time. When relying on software tools for optimization, there are limitations such as the availability of certain features given by state-of-the-art research. Usually the implementation of new features in software tools takes time. For example, multi-material processing in L-PBF is possible but no suitable software solution for CAE is available [25].

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References

[1] VDI, Verein Deutscher Ingeniuere e.V.; VDI 3405; Additive manufacturing processes, rapid manufacturing; Basics, definition, processes; Beuth Verlag; 2017.

[2] Thompson M., Moroni G, Vaneker T, Fadel G, Campbell R. I; Gibson I, Bernard A, Schulz J, Ahuja B, Martina F, 2016. Design for Additive Manufacturing: Trends, oppurtunities, considerations, and constraints, CIRP Annals – Manufacturing Technology 65, p. 737-760.

[3] Lutter-Guenther M, Seidel C, Kamps T, Reinhart G. Implementation of Additive Manufacturing Business Models, Applied Mechanics and Materials, Vol. 794, pp. 547-554, Nov. 2015.

[4] Teufelhart S. Belastungsoptimiertes Design von Gitterstrukturen für die additive Fertigung nach dem bionischen Prinzip der kraftflussgerechten Gestaltung, Dissertation, Technical University of Munich, 2016.

[5] Kamps T,Gralow G, Schlick G, Reinhart G. Systematic Biomimetic Part Design for Additive Manufacturing; 3rd CIRP Conference on BioManufacturing; Procedia CIRP 65 (2017). p. 259-266 2017.

[6] Gibson I, Rosen DW, Stucker B. Design for additive manufacturing. In: Additive Manufacturing Technologies. Springer; 2010. p. 299–332.

[7] Henning F. & Moeller, E. Ed.. 2011, Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung, Hanser, München.

[8] Heinrichs A, Siegel D, Frank P, Bomke P, Naguschewski R., Frank M. Bionische Entwicklung einer additiv gefertigten A-Säulen Verstärkung, Karosseriebautage Hamburg 2017, Proceeding, Springer Fachmedien Wiesbaden 2017.

[9] Hoelker R, Haase M, Khalifa N.B, Tekkaya A.E. Hot Extrusion Dies with Conformal Cooling Channels Produced by Additive Manufacturing, Materials Today: Proceedings, Volume 2, Issue 10, 2015, Pages 4838-4846.

[10] Boschetto A., Bottini L, Eugeni M, Cardin V, Nisi G.G, Veniali F, Gaudenzi P. Selective Laser Melting of a 1U CubeSat structure. Design for Additive Manufacturing and assembly, Acta Astronautica, 2019.

[11] Orloff, M. A.. ABC-TRIZ. Cham: Springer International Publishing, 2017. ISBN: 978-3-319-29435-3. DOI: 10.1007/978-3-319-29436-0.

[12] VDI, Verein Deutscher Ingeniuere e.V.; VDI 6224 Blatt 3: Bionik - Bionische Strukturoptimierung im Rahmen eines ganzheitlichen Produktentstehungsprozesses. Duesseldorf: VDI-Verlag (September 2017).

[13] Kamps T,Gralow G, Schlick G, Reinhart G. Systematic Biomimetic Part Design for Additive Manufacturing; 3rd CIRP Conference on BioManufacturing; Procedia CIRP 65 (2017); p- 259-266 2017.

[14] Kohn S, Huesig S. Potential benefits, current supply, utilization and barriers to adoption: An exploratory study on German SMEs and innovation software, Technovation, Volume 26, Issue 8, 2006, Pages 988-998.

[15] Haselmann, T, Roepke C, Vossen G.(2011). Empirische Bestandsaufnahme des Software-as-a-Service-Einsatzes in kleinen und mittleren Unternehmen, Arbeitsberichte des Instituts für Wirtschaftsinformatik, Westfälische Wilhelms-Universität Münster, No. 131, Inst. für Wirtschaftsinformatik, Münster.

[16] Zhu Z, Pradel P, Bibb R, Moultrie J. A framework for designing end use products for direct manufacturing using additive manufacturing technologies; Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 5: Design for X, Design to X, Vancouver, Canada, 21.-25.08.2017.

[17] Lindemann U. Methodische Entwicklung technischer Produkte; Springer-Verlag Berlin Heidelberg; ISBN: 978-3-42-01422-2; 2009.

[18] VDI, Verein Deutscher Ingeniuere e.V.; VDI 2225 Blatt 3: Technisch-wirtschaftliche Bewertung; Duesseldorf: VDI-Verlag 1998.

[19] Adam G, Zimmer D. Design for Additive Manufacturing—Element transitions and aggregated structures, CIRP Journal of Manufacturing Science and Technology,Volume 7, Issue 1,2014,Pages 20-28.

[20] VDI, Verein Deutscher Ingeniuere e.V.; VDI 3405 Blatt 3; Additive Fertigungsverfahren; Konstruktionsempfehlungen für die Bauteilfertigung mit Lasersintern;; Beuth Verlag; 2015.

[21] Gaynor AT, Guest JK. Topology optimization considering overhang constraints: Eliminating sacrificial support material in additive manufacturing through design; Struct Multidiscip Optim 54:1157–1172. 2016, https://doi.org/10.1007/s00158-016-1551-x.

[22] Siglmueller F, Kupfer S, Kamps T, Schmitt M, Lohner T, Reinhart G, Stahl K. Efficiency of additive manufactured gears with conformal cooling. In: 21st International Coloquium Tribology. 2018.

[23] ISO/DIN 6336-2, Calculation of load capacity of spur and helical gears; part 2; calculation of surface durability. 2006.

[24] Kamps T. Leichtbau von Stirnzahnrädern aus Einsatzstahl mittels Laserstrahl-schmelzen; Dissertation, Technical University of Munich, 2018.

[25] Anstaett C, Seidel C, Reinhart G. Multi-Material Processing in Laser Beam Melting. Direct Digital Manufacturing Conference; 2016.