Sustainability-Oriented Topology Optimization Towards a More Holistic Design for Additive Manufacturing

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Abstract. The Design for Additive Manufacturing of final products needs to target many design objectives, e.g., function, low lead-time, costs, ecological footprint and possibly more. In balancing the latter, results of design changes are frequently counterintuitive, and this happens especially when it comes to sustainability-related qualities. The latter are commonly modeled by a Life-Cycle Assessment (LCA) of the fabrication and use-phase. However, it is likely that related data is not yet available before most design decisions have been fixed. Even though Additive Manufacturing can enable more design freedom than conventional technologies, the process-specific parameters need strong consideration. The earlier this happens in the design process, improvements might have the biggest impact. Topology optimization can be an efficient method for conceptual design and design automation. However, the respective models often need to be simplified, e.g., regarding nonlinear material properties or intricate manufacturing constraints. For this reason, it is typically not possible in topology optimization to deal with all previously mentioned criteria.

A Sustainability-oriented Topology Optimization method is proposed within a generative engineering framework. Multimodal analyses of intermediate topology results should enable the computation of intricate measures. For example, regarding Laser Powder Bed Fusion-based Additive Manufacturing expedient build directions and an estimation of support structures are calculated. A predictive LCA model is included that calculates the ecological footprint measures on basis of the intermediate topology results. For that purpose, a simplified product system with representative processes is modeled. The presented approach enables a more holistic Design for Additive Manufacturing that can deal with a multitude of multidisciplinary criteria in a coherent way.

Keywords: Generative Engineering · Topology Optimization · Sustainability · Sustainable Design · Lightweight Design · Metal Additive Manufacturing · Design Automation · Life-Cycle Assessment · Design for Additive Manufacturing

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1 Introduction

Lightweight design is essential for parts that are mobile, such as for car or aircraft parts. The environmental impact that results from their use phase can outweigh the contribution of the fabrication. However, in additive manufacturing of lightweight designs also less material is needed as feedstock and needs to be additively welded in the layer-by-layer process. Topology optimization can facilitate extremely effective conceptual design for lightweight components. Based on the model of the available space and loading, the design can be generated automatically considering all optimization goals and boundary conditions.

So far, only few studies seek to combine topology optimization with life-cycle assessment (LCA). In [1] topology optimization and LCA for binder jetting production are coupled in a design workflow. It is proposed to iterate the topology optimization with changing the mass constraint until both mechanical as well as LCA-related goals are met. However, the described approach does not concurrently target the multiple objectives within the topology optimization but rather by altering the constraints and as such the optimization parameters. In the very recent publication [2], the coupling problem is solved with a metamodel-based approach for finding the optimized material-fabrication method pair for a given design problem, thereby, altering a multitude of parameters that are inputs or boundary conditions of the topology optimization.

In contrast, the method proposed in this paper seeks to find the most effective topology without changing other parameters (e.g., material, processing method, optimization constraints). Optimization regarding the multiple objectives, such as stiffness-to-weight ratio, part quality, and sustainability-oriented measures are made possible by a generative design framework with a 2-model topology optimization. The thereby achieved diversity of design features should facilitate the multi-objective optimization. In addition, a variety of connected analyses of the physical phenomena and domains, such as manufacturing and mechanics, are employed in a multimodal approach to the modeling and simulation. The methodical framework was developed in [3]. This paper provides additional insights regarding life-cycle assessment and how it can be integrated into the multimodal algorithm. The multi-objective formulation is changed accordingly, and the design problem solved in this way gives additional information regarding the life-cycle impact of solutions.

In this work, predictive LCA models are used to evaluate preliminary scores for environmental impact categories of intermediate topology optimization results. The collection of reliable data presents the primary obstacle in evaluating the life cycle [4]. However, to calculate meaningful relative measures for the comparison of early designs, also averaged data and simplified models could be sufficient. For the Laser Powder Bed Fusion (LPBF) process, the optimized printing orientation can be identified with calculating related measures on basis of the intermediate topology result. Those are the build time, thermal deformation tendency, support structure volume and post-processing effort. Many orientation options are evaluated using the commercial software Amphyon with its assessment module. The process-related models are discussed in detail in [5], and results with detailed description using the same method for assessing the build orientation are presented in [3]. In this paper, the LCA is integrated with modeling the LCA for the best orientation that is selected for each intermediate topology result.

With the generative design including LCA, the sustainability-oriented objectives can for the first time be optimized in topology optimization. The most promising solutions can then be selected for further development. The proposed workflow for the Design for Additive Manufacturing is illustrated in Fig. 1.

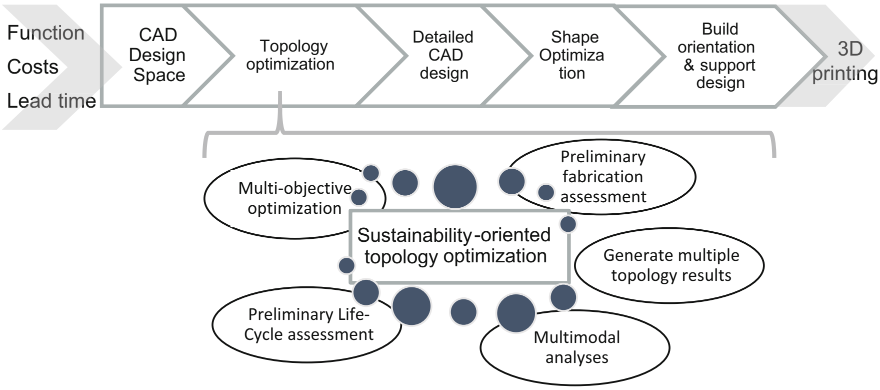

Fig. 1. Illustration of the complete workflow for the Design for Additive Manufacturing, starting with the design requirements and ending by the final 3D printing with integrating sustainability-oriented topology optimization in the early stage

The results of the topology optimization frequently require interpretation and clarification to satisfy all fabrication and usage requirements. After selecting the most promising topology, the design can optionally be designed in CAD and shape optimized. In the further progression towards manufacturing, the final build orientation is determined in conjunction with the design of support structures for overhanging surfaces and potentially allowances for milling or other features. A detailed thermal simulation of the deformation tendencies can be carried out, e.g., with the Amphyon software simulation module (see [6] for the modeling description) to validate the configuration. The build direction and support structure design can be altered if excessive deviations are discovered. Manufacturing failures have been shown to be reduced by this strategy, see e.g. [9].

It could happen that the final design steps (detailed CAD, final printing direction, support design etc.) do not give good results for the best selected design from topology optimization and deviate from the predictions. In this case, the generative concept has the advantage that further alternatives have been generated, so that the next best solution could be selected for the detailed design phases. However, further use-case studies will be needed for validating the quality of the predictions with respect to the final design.

The sustainability-oriented topology optimization is based on the multimodal topology optimization concept for generative design that has been conceptually presented in [7], published in an early 2D-version in [8] and firstly developed for 3D and in a sustainable design context in [3], however, not yet with LCA integration. The concept of integrating predictive LCA models was first presented in [9] as a foresight of ongoing work. In the meantime, the implementation and formulation have been re-worked and extensively tested. Some results are presented below.

2 Method Description

The workflow of the sustainability-oriented topology optimization is illustrated in Fig. 2. The standard (std.) topology optimization serves as a reference and starting point for the 2-model topology optimization. Both are performed with the OptiStruct® finite element code with the Solid Isotropic Material with Penalization (SIMP) method. The concept for the 2-model topology optimization with inverse-damage models is introduced in [3]. The optimization is iterated with adjusting the weighting between the two inversely damaged models as a design variable. For all generated topology results multiple analyses are performed. Prior to this, each topology result, which is calculated in the finite element domain, is transferred to a geometry representation with a distinct boundary surface using a threshold value for the material utilization in a given area.

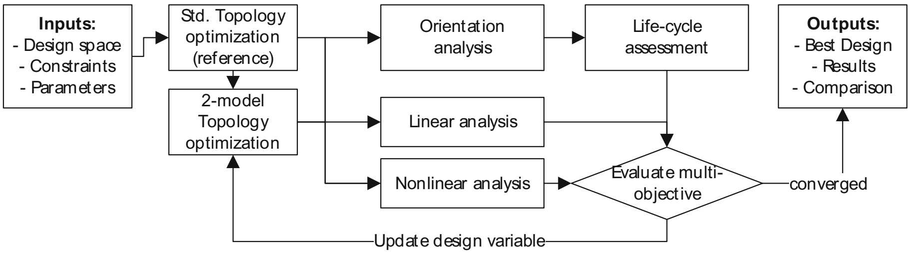

Fig. 2. Workflow of the sustainability-oriented topology optimization with multimodal analyses and integrated LCA

With respect to the mechanical performance, the same static loading case as in the topology optimization is reevaluated by a more detailed linear analysis on a new, more accurate finite element mesh representation of the geometry with its bounding surface. Additionally, the performance regarding an overloading scenario is evaluated by nonlinear analysis. The LPBF-process-specific measures are evaluated in an orientation analysis of multiple possible configurations. The latter is performed with the Amphyon software with the same method described in [3]. For the selected best orientation, the life-cycle impact assessment (LCIA) is performed to evaluate a preliminary score regarding environmental impact categories.

For the topology optimization, the two most common objective and constraint configurations are possible. Those are the optimization of stiffness with a mass (or volume) constraint, as well as minimizing mass (or volume fraction) with a stiffness constraint (e.g., local displacement, or the global measure being compliance). They can also be combined in that the reference topology optimization can have a different setup than the 2-model topology optimization, if the constraints can be enforced. The latter could be achieved by adjusting the threshold of material utilization in generating the topology result in the geometry domain. Thereby the topology and effectiveness are not changed, but the values for mass and compliance change within certain limits because the structures become slightly slimmer or thicker.

The overall objective is formulated to be largely independent from the topology optimization configuration and is clustered by three categories. The first one is the mechanical performance with respect to the volume of the part. Additionally, to the static stiffness, here represented by the compliance c, also the maximum bearable load before breakage in an overloading scenario is evaluated. The latter is modeled by calculating the maximum reaction force of the structure for a prescribed progressive displacement at the same load application point as in the static scenario. The objective for mechanical performance is formulated as follows

$$F_{Mech.} = w_{stiff} * \frac{c_{stat,X}}{c_0} \frac{V_X}{V_0} + w_{Fmax} * \left(2 - \frac{F_{max,X}}{F_{max,0}} \frac{V_0}{V_X}\right) \quad (1)$$

In Eq. (1) the subscript X stands for the value of the current design and *0* for the reference solution. Two factors w_{stiff} and w_{Fmax} are introduced to weigh between the contributions. To maximize the static stiffness, the compliance is to be minimized. Contrary, the maximum reaction force F_{max}, that counteracts an excessive deformation in overloading, is to be maximized. The objective $F_{Mech.}$ takes on the value *1.0* for the reference and is better for topology results with smaller values.

A process-related objective is formulated in the same manner with modeling the fractional deviation to the reference design and comparing measures for the deformation tendency *def* and for the post-processing effort for downward facing surfaces *pp*, which is strongly correlated with surface quality for the LPBF process. The objective $F_{Process}$ can be seen as a model of reliability and quality of the processing and is formulated with

$$F_{Process} = w_{def} * \frac{def_X}{def_0} + w_{pp} * \frac{pp_X}{pp_0} \quad (2)$$

The third objective models the impact of the design regarding ecological categories, which are here represented by the climate change potential and metal depletion, both calculated in the LCA. The respective objective F_{LCA} is formulated as follows

$$F_{LCA} = w_{CC} * \frac{CC_X}{CC_0} + w_{md} * \frac{MD_X}{MD_0} \quad (3)$$

In Eq. (3), the *CC* represents the values calculated in the life cycle impact assessment for the climate change potential in *kg CO2-eq./unit* and the metal depletion *MD* in *kg Fe-eq./unit.*

All three objectives are combined in one top level multi-objective function being

$$F_{Obj} = w_M * F_{Mech.} + w_P * F_{Process} + w_P * F_{LCA} \quad (4)$$

The life cycle assessment model for additively manufactured components, which was incorporated into the topology optimization within the scope of this work, is presented in the following section.

The AM product system is illustrated in Fig. 3. Most common post-processing steps are included. It is known from [9] and [11] that the AM process with LPBF likely has a high influence, however, this strongly depends on the used machine and setup. The raw material, energy, such as that used to heat the powder, and other utilities, such as compressed air, are the primary inputs to the process chain. Only a small portion of the

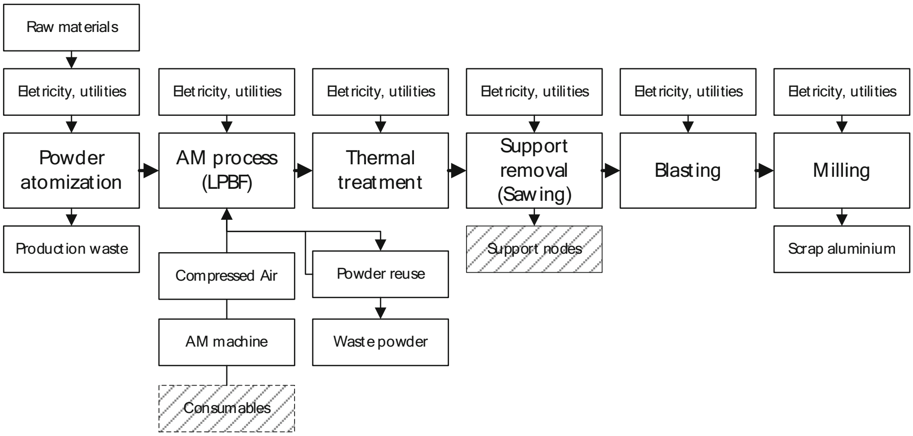

Fig. 3. AM product system used in the study. Common post-processing steps are included. Consumables of the AM process as well as the support nodes that could potentially be recycled after removal are cut-off.

feedstock is used for the additively laser-melted raw structure, and a lot of the powder is used again after each manufacturing cycle.

The product system is implemented in Brightway 2, an open-source software for life cycle assessment. The IPCC 2013, GWP 100a, and ReCiPe Midpoint (Hierarchist) V1.13 methods are used to calculate the impacts. For the AM process, a predictive resource model that was developed and experimentally validated in [3] is used to calculate the electricity consumption, compressed air and powder used. For all other processes the ecoinvent 3.8 market data with cutoff is employed to represent averaged data from the industrial system.

The integration of the LCA with Brightway 2 into the topology optimization is established and automated via python. An excel file is generated and updated with each new topology as an input for the LCA. The data includes the predicted resources in the AM process and other relevant measures with respect to each intermediate topology. Those are e.g., the electricity used by the AM machine per part, the build time, the volume of the part, the volume of the support structure and the batch size, which depends on the occupied space on the build platform. After creating the life cycle inventory (LCI), as a final step, the life cycle impact assessment (LCIA) regarding the climate change potential and the metal depletion are calculated. In addition to the fabrication, also mobile use-phase modes can be considered. E.g., in the Ecoinvent database, there is data stored for "market for transport, passenger" which can represent the use-phase for a passenger car in a simple manner. The driven kilometers (e.g. *150,000* km) are allocated with the weight ratio between the part and the vehicle and the lifetime of the part is assumed to be the same as for the car.

3 Results

The sustainability-oriented topology optimization is performed for a cantilever beam problem for a mobile mode of a passenger car and a production of *100,000* parts. The dimensions of the design space are $60 \times 60 \times 180$ mm^3. The beam is loaded at the dropout with a force of *500* N. The finite element model is built with uniform cubic elements with a length of *3* mm. The std. Topology optimization is performed as a reference with a min. Compliance formulation subject to a volume constraint with *15%* utilization of the design space. Minimum structural member size control is applied with *10* mm. The iteration count is set to *75*. The 2-model topology optimization is performed using a minimum mass with compliance constraint setup. The constraint value is taken from the reference. This represents the design logic of generating alternative solutions to the reference, featuring at least the same stiffness, however, if possible, with lesser mass. If the compliance in the more detailed reanalysis significantly differs from the constraint, the density threshold for generating the geometry is automatically varied such that the compliance is equalized while changing the mass. In doing so, all topology results have the same stiffness, but the more efficient topologies feature a smaller mass. The material used is Scalmalloy© with Young's modulus 70 GPa, Poisson's ratio 0.33 and density 2.67 g/cm^3. For the nonlinear analysis, a Johnson-Cook material and damage model is used to model Scalmalloy© in a relatively ductile material state with ca. 12% elongation before breakage.

For this study, the EOS M400 system with a single *1* kW laser unit is adopted. The nitrogen inert gas atmosphere for the process is produced within the AM machine, however leading to a relatively high consumption of compressed air. The modeling parameters are the same as stated in [3]. For the example, all weighting factors are set equally and thereby model no preference by the designer. The result of the sustainability-oriented topology optimization run is illustrated in Fig. 4. Design 0 is the reference solution and 10 alternative solutions are generated with the 2-model topology optimization. The individual objective values as well as the overall inclusive objective function $F_{obj.}$ are stated in the graph. The progression of the design solutions is calculated based on the golden section search. It is clearly visible that this optimization algorithm can find the local minimum represented by the design 7. The design solutions 4, 8, 9 and 10 have the same topology and vary only very slightly in their shape. The design 7 has the best individual value for the LCA objective and is a good compromise for the other two individual objectives leading to the best overall value. The best mechanical performance is shown by design 6, however compromised with less good ratings for the other objectives. The best performance with respect to the process criteria is represented by design 2.

While some objectives correlate, like mass reduction in $F_{Mech.}$ also improving impact aspects in F_{LCA} due to lower material use, Fig. 4 shows also non-correlating aspects between the two (see e.g. design 2 and design 6) related e.g. to the LCA impact of support structures or differing batch size. The proportions of the individual objectives to the inclusive objective are changing, so that different preferences, expressed by different weightings, would lead to different solutions. This suggests that the objective formulation is appropriate, and the LCA-related objective is significant to the selection. However, this needs further review in use cases.

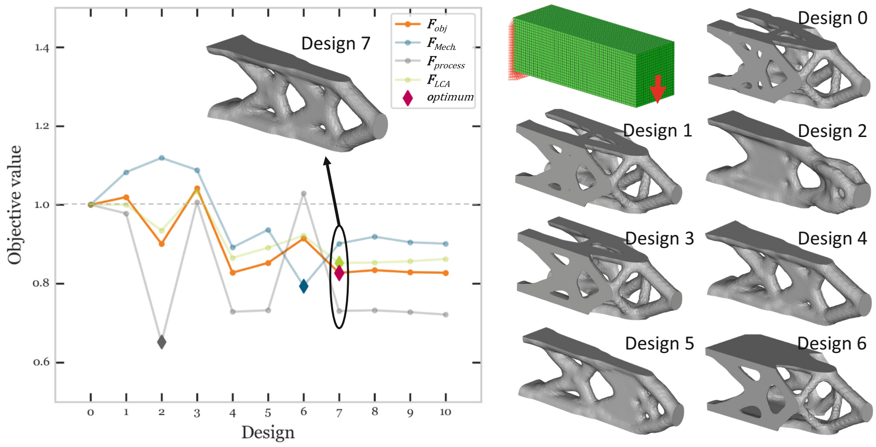

Fig. 4. Generated topology results for the design problem (design space and loading: middle, green, red). Individual and inclusive objectives (left) and respective design solutions (right).

In the following, the reference (design 0) and the best overall solution (design 7) are compared in more detail. The static compliance is equal because it is set as a constraint for the algorithm. However, the mass of design 7 achieving the same stiffness is reduced by ca. *6.4%*. In addition, even with using less mass, the reaction force in the overloading scenario is significantly increased with ca. *6.5%* higher maximum loading capacity before breakage. The latter is illustrated in Fig. 5 (left). The reason for this is that the load and resulting stresses are distributed more evenly over the component during the overloading scenario, as depicted in Fig. 6 for the displacement (*7.2* mm) shortly before the breaking event. The mechanical performance of design 7 is calculated to be ca. *9.9%* better than the reference, which also accounts for the reduced mass.

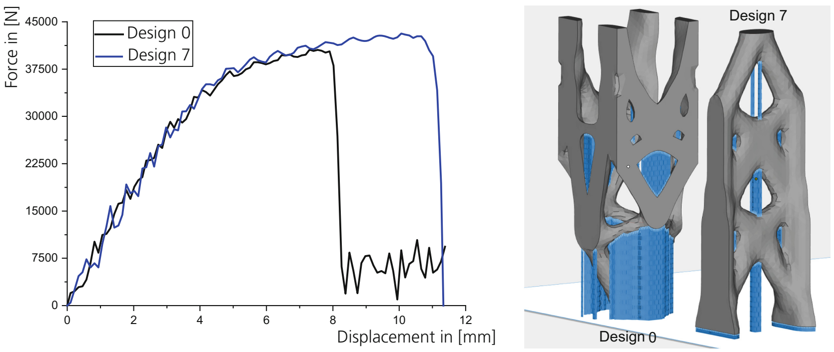

Fig. 5. Reaction force in the overloading scenario of progressive prescribed displacement at the dropout (left). Exemplary support structure design (blue, right) for the two designs, each in their respective best printing orientation.

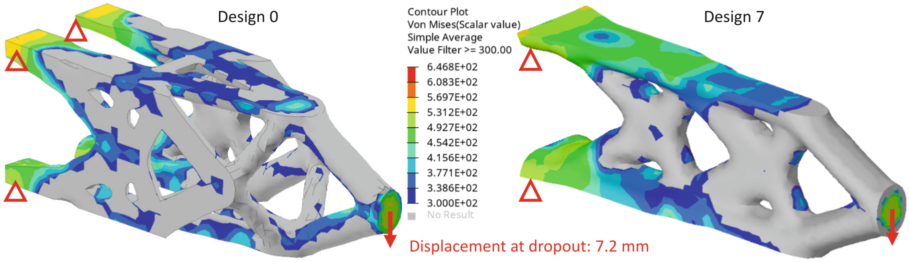

Fig. 6. Plot of the von Mises stress distribution for design 0 (left) and design 7 (right) with a threshold on higher values that could lead to plastic strains for a displacement at the dropout of *7.2* mm, shortly before breakage occurs.

The process performance is modeled from the estimated values for deformation tendency and post-processing effort. Thereby, design 7 achieves ca. *14%* less deformation tendency and up to *40%* less post-processing effort. The former mainly refers to the size and gradients of the cross-sections in printing direction. Sudden cross-section changes can lead to geometric deviations. The post-processing effort is correlated with the amount of support structures and their accessibility. The Amphyon software estimates a reduction for support structure volume of up to *70%* for design 7 in comparison with design 0.

Even though the calculated values are rough estimates, they are quite plausible when looking at the topologies with their proposed best building direction. In Fig. 5, the support structure design in the Magics software is illustrated as a type of validation. Here, even a reduction of *85%* of support structure volume is achieved. With slight shape adaptions they could be further reduced for both designs, however, an experienced look can comprehend that the overall printability could be much better for design 7.

The LCA score is calculated from the contributions of climate change potential and metal depletion. The climate change potential is calculated to be *14.9%* less and the metal depletion to be *14.7%* less for design 7 in comparison with design 0. The two main inputs that lead to the improvement are the reductions in part mass and support structure mass. In addition, comparing the space taken on the building platform, design 7 occupies much less, leading to an estimation of up to *78 parts* that can be printed per batch in comparison to only *36 parts* for design 0.

In Fig. 7 and Fig. 8, the calculated values and listing of contributions by the constituent processes for the climate change potential and metal depletion categories are depicted. Even if the absolute values are rough estimates and some of the input parameters like the estimation of support structure mass can lead to significant tolerances, the relative importance resulting from the compilation can provide interesting insights. The use-phase contribution is only influenced by the mass of the part in relation to the vehicle mass and scales with the number of parts and the number of kilometers driven. In both categories, the use-phase takes up ca. *25%* of the impact. Second most important is the contribution of the AM process and third the production of the Scalmalloy© feedstock.

Both AM process and production of feedstock correlate with the amount of material that is printed for the parts and supports. In the metal depletion category, the AM process is more dominant, as the production of the AM machine takes up a significant portion.

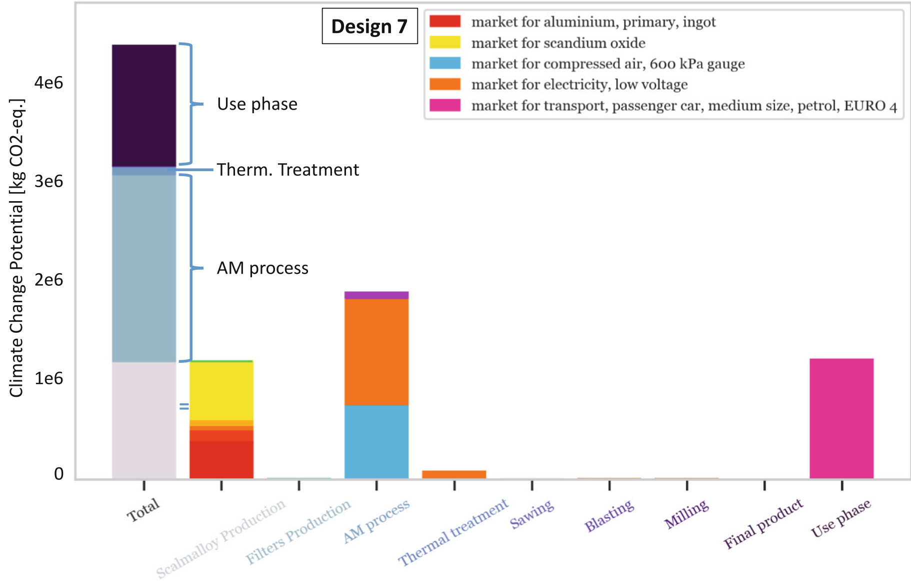

Fig. 7. Listing of contributions by the constituent processes of the product system regarding the climate change potential for the best design 7. Estimation for fabricating 100,000 parts and a use-phase as a passenger car component.

For both categories, the amount of compressed air is quite significant and looking at other machine setups, e.g., with inert gas cylinders, could be promising. For the Scalmalloy© production, the contribution by the alloying elements to the overall impact changes strongly between the two categories. In any case, the choice of alloy and its components have a great influence, and the overall impact of the feedstock production could change significantly for a different aluminum alloy or other lightweight materials like titanium.

4 Discussion and Conclusion

Topology optimization and LPBF-based additive manufacturing are potent technologies for lightweight design and sustainability. By incorporating the predictive life cycle assessment (LCA) into topology optimization, a novel workflow for generative design is created that directly targets environmental impact categories as design objectives. It is demonstrated that with the presented implementation of the sustainability-oriented topology optimization a multitude of design criteria from different domains can be evaluated in an automated and coherent fashion. In addition, the results show that significant improvements can be achieved in comparing different design solutions leading to a more holistic design.

Both evaluated ecological impact categories and all main contributors to the footprints benefit significantly with a strict lightweight design and an optimized build direction for fewer support structures to reduce the amount of fabricated material. The relevant parameters of the LPBF-based additive manufacturing production are incorporated

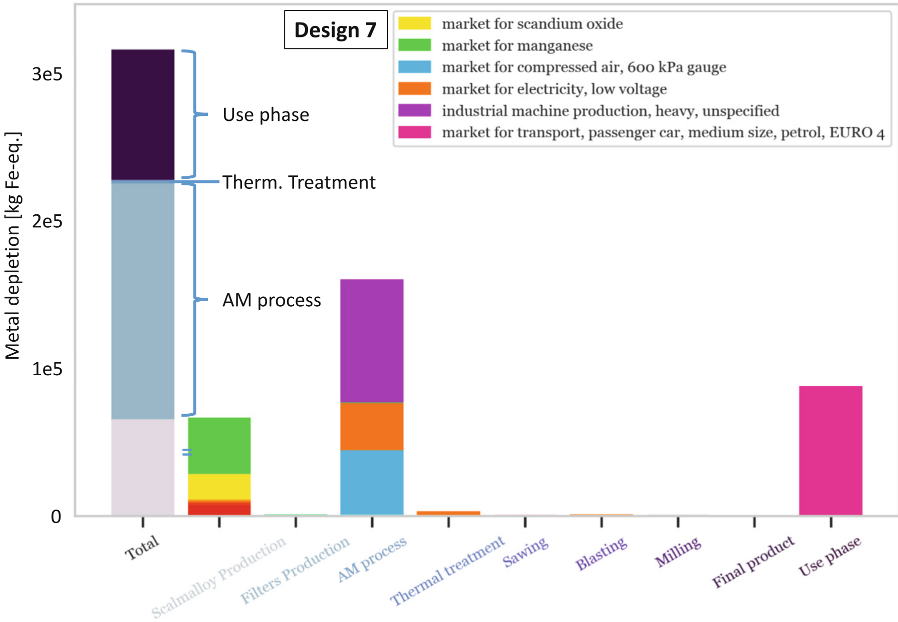

Fig. 8. Listing of contributions by the constituent processes of the product system regarding the metal depletion for the best design 7. Estimation for fabricating 100,000 parts and a use-phase as a passenger car component.

based on calculating relative, predictive measures with respect to the intermediate topology results. In doing so, the most promising topology results can be selected from the multimodal optimization towards completing the detailed design phases for the final fabrication.

The exemplary result showed that without the need for experiments, it is possible to predict the ecological impact. Even though the absolute values can have large tolerances, the relative significance for a specific design problem can be very informative for taking design decisions. The overall optimization took ca. *3* h with each additional generated design taking ca. *20* min. on a desktop PC with *4* CPU cores employed. However, so far, the implementation is only demonstrated for a plain 3D geometry and relatively simple loading conditions and must be demonstrated for more complex design problems, e.g., with multiple loading scenarios. In addition, the comparison of lightweight materials like suitable titanium alloys with aluminum alloys and different fabrication setups like LPBF machines with other print envelope or multi-laser would be interesting.

When comparing machine setups or different alloys, the accuracy of the used models for the process and footprint estimation become more important. For such extensions the modeling of resources in the AM process and process-specific measures like the support structures need to be reworked and be validated with a wider scope and more experimental data. In addition, other approaches for generating the design diversity needed in the generative design could be thought of. They could extend the here employed inverse-damage model of the 2-model topology optimization. Especially specific implementations that steer the design features towards the chosen target objectives, e.g., with adjusting manufacturing constraints, would be beneficial. Currently no manufacturing constraints are used in the topology optimization. E.g., it could be beneficial to limit the number of overhanging surfaces with constraint functions to further reduce the amount of support structures.

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