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# A procedure model to manage requirements for topology optimization and additive manufacturing

**Johannes Soika** [1,✉], **Felix Endress** [1], **Jakob Schenk** [2] **and Markus Zimmermann** [1]

[1] *Technical University of Munich, Germany,* [2] *AUDI AG, Ingolstadt, Germany*

✉ johannes.soika@tum.de

**ABSTRACT:** Topology optimization combined with additive manufacturing enables the creation of complex, high-performance products. However, industrial applications often involve numerous and complex requirements, making it challenging to align the design and manufacturing process to meet all demands. A particular challenge is to determine which requirements should be included in the optimization problem statement. This paper presents a procedure model to integrate requirements and feasibility constraints into the design and manufacturing process. It includes two major steps: organizing requirements and constraints in the process and identifying the problem statement. The procedure is applied to the requirements of an engine bracket of AUDI AG, demonstrating its ability to handle numerous requirements and to specify the problem statement.

**KEYWORDS:** topology optimization, design for additive manufacturing (DfAM), optimisation, complexity, requirements

## 1. Introduction

The role of engineers is evolving from meticulous detail *designers* to strategic *definers* of objectives (Brossard et al., 2020). At the heart of this paradigm shift lies the rise of generative design (GD), a powerful approach that is redefining how design challenges are addressed. Driven by breakthroughs in additive manufacturing, artificial intelligence algorithms, and cutting-edge hardware capabilities, GD has emerged as a compelling solution for modern engineering applications (Zoubek et al., 2021).
GD capabilities are increasingly integrated into modern computer-aided engineering tools (Buonamici et al., 2020; Pollák et al., 2021; Swenson, 2022). While definitions of GD vary, it is broadly recognized as a computational framework for producing one or more design solutions that meet specific requirements and constraints (Gerhard et al., 2023; Pollák et al., 2021). GD tools often utilize machine learning algorithms (Regenwetter et al., 2023) and physics-based methods such as topology optimization (TO) (Buonamici et al., 2020).
First introduced by Bendsøe and Kikuchi (1988), TO is an approach that generates designs by adding, removing, merging, or redistributing material within a given design domain. The Solid Isotropic Material with Penalization approach, short SIMP, (Bendsøe, 1989) remains one of the most widely used interpolation techniques for determining the varying material properties in the iterative process. Over the decades, this approach has evolved remarkably, becoming a robust tool for addressing structural and multidisciplinary challenges (Bendsøe & Sigmund, 2004). Today, TO is used in industrial applications, as exemplary shown by Pedersen and Allinger (2006), Klahn et al. (2018), and Endress et al. (2023).
Additive manufacturing (AM) offers flexibility in producing complex geometries, making it particularly well-suited for use in the context of GD (Kranz, 2017). While detailed insights into different AM process chains are available (Buonamici et al., 2020; Kranz, 2017; Lachmayer & Lippert, 2020), it is not addressed how to manage numerous requirements within the process chain and how to identify the problem statement. At the same time, extensive research exists on achieving desired performance through GD for specific objectives and constraints, e.g., shown by Bendsøe and Sigmund (2004) and Deaton and

Grandhi (2014) in the context of TO, or Klahn et al. (2018) and Van De Ven et al. (2021) for manufacturing constraints. However, requirements lists are often extensive and complex, and there are numerous ways to consider requirements in GD. For gradient based TO several objectives and constraints increase the challenge to find a direction that simultaneously satisfies all the requirements while maintaining efficient convergence. Therefore, not all requirements are essential for optimization; over-constraining the optimization problem can lead to suboptimal results, harms convergence, or adds conflicts of goals (Endress et al., 2023).

## 1.1. Paper objectives

A review of the existing literature reveals the lack of a systematic framework for bridging the transition from numerous requirements and constraints to an effective process organization and optimization problem formulation. This paper presents a comprehensive procedure model developed to manage diverse component requirements and feasibility constraints and organize them within the design process. Furthermore, the objective of the procedure is to provide a systematic approach to identifying an appropriate problem statement, supporting the selection of an optimizer or aligning the problem statement with the available optimizers.

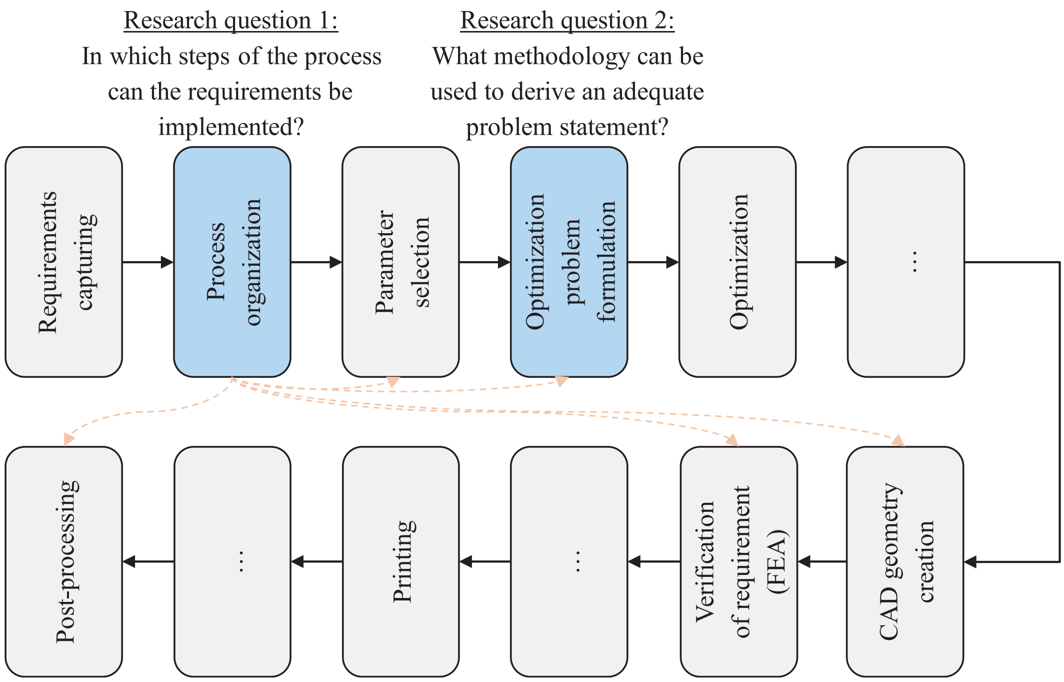


**Figure 1. Research questions within selected steps of the AM process chain**

Figure 1 highlights the research questions within selected steps of the design and manufacturing process for AM. In the following, this reduced set of steps is referred to as the *AM process chain*. There are other steps in between, indicated by the empty boxes. The structure is similar to the process chains presented by Lachmayer and Lippert (2020) and Krantz (2017). The dashed lines indicate connections between the process organization step and the steps considered for implementation.

This paper focuses on the use of TO in the context of AM, particularly Laser Powder Bed Fusion as one of the most common methods. It begins with a comprehensive review of the state of the art in requirements management in GD and design for AM, highlighting methods for addressing specific requirements and feasibility constraints in Section 2. Based on insights from previous research and industrial case studies, a procedure model is developed in Section 3. The practical application is demonstrated in Section 4, by applying the proposed procedure to an engine bracket of AUDI AG. Section 5 analyzes the opportunities and limitations of the model, and Section 6 outlines perspectives.

## 2. State of the art

### 2.1. Requirements management in generative design

Requirements can be categorized into customer, technical, functional, non-functional, performance, and process requirements (Zimmermann & de Weck, 2020). Constraints, which represent particularly rigid requirements, can also be included. In the design process, it is necessary to consider all these types of requirements in relation to each other.

Lachmayer and Lippert (2020) split the AM process chain for the development of a component into five pillars, consisting of the construction of a part, the computer aided planning, computer aided manufacturing, the post-processing and finishing. Krantz (2017) develops a methodology for designing lightweight structures optimized for AM consisting of a phase *requirements and constraints*, with the goal to identify the component requirements, the constrains, and to define the design domain. While process chains are clearly defined, the transition from the requirement list to optimization remains generally unclear. Endress et al. (2023) classify requirements in the design optimization for AM into three categories that distinct between directly considerable requirements, indirectly considerable requirements, and requirements that will not be considered in the optimization. However, a methodology on how to order the requirements into the process and how to derive the problem statement is not presented.

### 2.2. Problem formulation for topology optimization

To set up the optimization, the goal is to derive a well-defined problem formulation. A precise definition of requirements aids in identifying the objective function and constraints for the optimization problem. When a quantity does not have strict limits but is desired to be as high or as low as possible, it may be more appropriate to include it in the objective function. For example, mass is often not strictly bounded but is generally minimized. In cases where multiple objectives can be identified, the beta-method can be applied (Schumacher, 2020). This method combines and weights multiple attributes into a single objective function, allowing for simultaneous consideration of several optimization objectives.

On the other hand, requirements with strict limitations – such as those that shall exceed certain values or lie within a specific range – are better handled as constraints in the optimization or require verification after the optimization. Constraints allow for the specification of exact limits, and the optimizer ensures that they are met.

#### *2.2.1. Requirements and constraints consideration in the optimization*

Structural components are typically evaluated based on criteria such as mass, local failure, displacements, compliance, dynamic behavior, and stability issues (Schumacher, 2020). Most of these criteria can already be incorporated into the optimization process, as for example shown by Bendsøe and Sigmund (2004) and Deaton and Grandhi (2014). Requirements on these criteria can often directly be handled in optimization.

However, certain criteria are more challenging to incorporate directly and may require alternative approaches. Examples are connection elements, such as screw connections. These can be considered by defining non-design spaces with void and solid regions that reserve space and provide contact surfaces for the screw (Endress et al., 2023). Ambrozkiewicz and Kriegesmann (2021) extended this approach by considering connection failure and flexible connection positions, while Wanninger et al. (2024) introduce an implementation strategy method for screw connections that identifies the optimal contact points between the connected structures.

Manufacturing constraints can also be incorporated into the optimization process. For AM, common constraints are the minimum feature size and overhang limitations. Minimum feature size can be controlled through appropriate filter sizes or discretization methods, while overhang constraints can be managed using specialized algorithms (Van De Ven et al., 2021). Overhangs are handled with support structures; however, in geometries such as tubes, these support structures may not be removable and should be avoided (Klahn et al., 2018). In addition, consideration of anisotropic materials, manufacturing defects, connectivity, and cost constraints are further areas of research (El Khadiri et al., 2023; Li, 2024).

### 2.2.2. Utilizing computer-aided engineering tools for optimization

Several computer-aided engineering tools are available for GD and TO. For example, Buonamici et al. (2020) analyze the GD workflow implemented in Autodesk® software. The process begins by defining the objective, focusing on either minimizing the structure's mass or maximizing its stiffness. Subsequent steps include geometry definition, load application, and selecting the manufacturing process. Finally, the material is chosen before the design is generated. However, the workflow does not address how to handle various requirements.

*Altair Inspire® 2024.1* allows for selecting three primary optimization objectives: maximizing stiffness, maximizing frequency, and minimizing mass (Deacon, 2024). Each objective can be combined by a range of customizable constraints. For instance, when maximizing stiffness, users can define a mass target and apply frequency and thickness constraints. Similarly, minimizing mass allows for the inclusion of stress constraints with a safety factor, as well as optional frequency and thickness constraints. The latter can be used to consider minimal thickness constraints due to the manufacturing process. Overhang constraints can also be implemented. For this purpose, the build direction and a maximum overhang angle are specified.

## 3. Development of a generic procedure model

This section derives a procedure model based on the presented literature. In this paper, a desired state of a product, including performance, is referred to as a *requirement*, while measures to ensure physical feasibility, including manufacturing constraints, are denoted as *feasibility constraints*. The procedure is intended to organize numerous requirements within the AM process chain and to identify the problem statement. It consists of two major steps *organizing requirements and feasibility constraints in the AM process* and *identifying the problem statement for topology optimization*. The process organization is conducted after the requirements are collected, shown in Figure 1. The following section describes these major steps.

**Table 1. Implementation of the requirements and feasibility constraints in the AM process chain of different industrial use cases of (Endress et al. 2023)**

| Step used for implementation | Aero Engine Bracket | Screw Gripper | Exhaust Rake |
|---|---|---|---|
| Parameter selection | | #4: Hardness | #5: Temperature resistance;<br>#8: Creep strength;<br>#9: Oxidation resistance |
| Optimization problem formulation | #1: Design domain;<br>#2: Loads;<br>#3: Enable machining;<br>#6: Displacement;<br>#8: min. wall thickness;<br>#9: Mass;<br>#10 load introduction | #1: Mass;<br>#2: Compliance;<br>#5: Design domain;<br>#6: Contact surfaces;<br>#8: Costs;<br>#9: Functional surfaces | #1: Design domain;<br>#2: Flange attachment;<br>#6: Eigenfrequency;<br>#7: Channel distance;<br>#13: Costs |
| CAD geometry creation | | #7: Machining effort | |
| Verification | #3: Dimensional tolerances;<br>#4: Stresses;<br>#7: max. wall thickness | #3: Stresses;<br>#4: Dimensional tolerances | #3: Aerodyn. Drag;<br>#4: Temperature gradient;<br>#10: Tip tolerances;<br>#12: Eigenstresses |
| Post-processing | | | #11: Surface roughness |

### 3.1. Organizing requirements and feasibility constraints in the AM process

The first major step is to order the specific requirements and constraints into steps of the considered AM process chain, for example the process in Figure 1. The process chains consist of the design and manufacturing steps for AM, as presented by Lachmayer and Lippert (2020) and Krantz (2017). Some steps focus on creating the hardware, such as printing of the part, or steps that are necessary for the realization of a component, such as the creation of support structures. However, in these steps of the

process chain, the designer cannot specify the design according to a requirement. An example for a step at which a specific requirement can be implemented is the formulation of the problem statement in which, for example, a mass requirement can be considered.
In the following, these steps are derived from the use cases of Endress et al. (2023). In Table 1, all requirements of the use cases are assigned to the respective step in which they are realized. All process steps without a requirement entry are not listed. The hashtag indicates the requirement number, while the keyword indicates the topic of the requirement. From Table 1, five steps of the process chain are used to implement different requirements and feasibility constraints. These will be referred to as *implementation steps*:

1. **Parameter selection:** In this step, parameters are selected before the optimization is performed. At this stage, certain attributes are fixed in accordance with the prescribed requirements and will not vary during optimization. For example, the material may be predetermined due to specific requirements, such as hardness, corrosion resistance, or other material properties essential to the design's functionality.
2. **Optimization problem formulation:** The requirements and feasibility constraints identified as relevant to the optimization are incorporated into the problem statement. The objectives and the constraints are identified. After this step, the optimization can be initiated.
3. **CAD geometry creation:** Once the optimization process has generated a result, a CAD geometry is created according to the result. This step also enables the fulfilment of requirements that cannot be addressed in the optimization process by modifying the geometry. For instance, additional structures may be added to facilitate machining processes after the printing job. The structure can also be adjusted, particularly if FEA indicates the need for reinforcement in specific areas.
5. **Verification:** This step involves verifying the design against the defined requirements, for example by using FEA. It is particularly useful for verifying requirements that were not directly considered during optimization. If a requirement is not fulfilled, the part can be iteratively improved by modifying the CAD or by changing the problem statement.
6. **Post-processing:** This step is conducted after the part is printed and involves hardware post-processing, such as machining or milling. It contains requirements that cannot be met through printing alone, e.g., precise tolerance requirements that exceed the capabilities of the printer.

It is important to note that there are several other AM process steps between the identified implementation steps, as indicated in Figure 1. According to the procedure model presented in this paper, all requirements and feasibility constraints are sorted into the implementation steps.

## 3.2. Identifying the problem statement for topology optimization

Once the requirements are ordered into their respective implementation steps, the requirements relevant to implementation step (2) can be filtered. This provides a clear overview of which requirements are considerable in the optimization phase. In addition to the objectives and constraints, the definition of the design space is an important part of the problem formulation and optimization setup (Buonamici et al., 2020; Kranz, 2017).
The requirements suitable to be part of the objective function and included as constraints of the optimization are identified. To determine the appropriate objectives and constraints, available software and optimization tools can be analyzed towards their ability to incorporate various objective functions and handle specific constraints within a single optimization process. By comparing these capabilities with the needs identified for implementation step (2), the problem statement can be adjusted to align with the capabilities of the available software, or alternatively, the software that best matches the problem statement can be selected.
If requirements prove incompatible or impractical to integrate into the optimization problem, they are reassigned to another implementation step. This ensures that these requirements are still addressed elsewhere in the process, even if they are excluded from the optimization. This can be achieved by integrating them into later stages, such as verification in implementation step (4) or iterative modifying the CAD model in implementation step (3).
The derived procedure model is depicted in Figure 2 as a flow chart, arranged from left to right. The procedure model is applied directly after the requirements and feasibility constraints have been collected, as illustrated in Figure 1. For practical application, a spreadsheet is used as an efficient working

environment. The spreadsheet can be populated with all relevant requirements and feasibility constraints, which are then evaluated based on the procedure model presented in Figure 2.

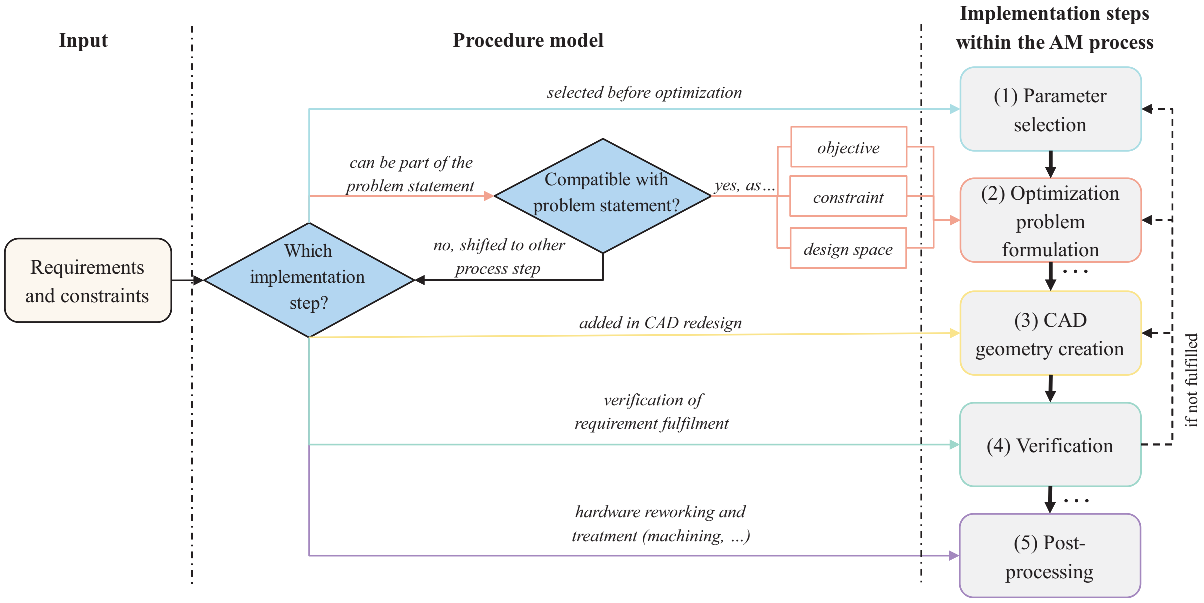


Figure 2. Procedure model for requirements and constraints management

## 4. Application to a use case

The proposed procedure is applied to a case study involving an engine bracket, analyzed in collaboration with AUDI AG. The goal is to systematically apply the procedure model to organize all requirements and feasibility constraints within the implementation step and to identify the problem statement. In the following section, the component requirements are initially identified to provide background. Next, the requirements and feasibility constraints are ordered according to the procedure model in Figure 2, finally leading to the identification of the problem statement.

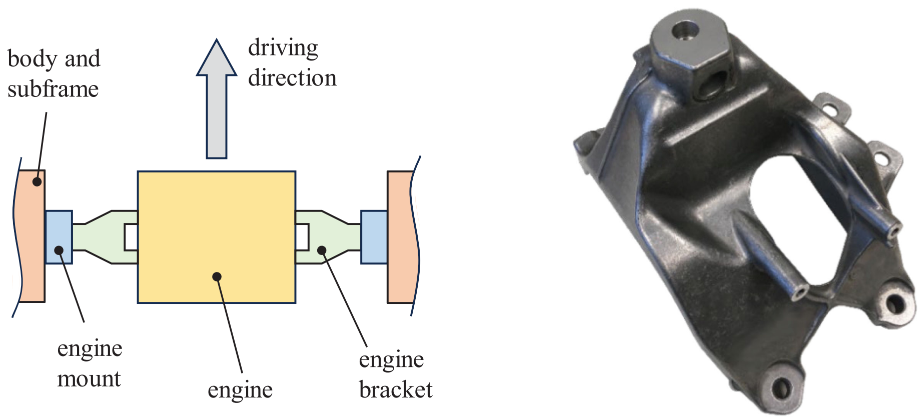


Figure 3. Left: components of an engine mounting system; right: example of an engine bracket used in series of an EA888 engine by AUDI AG

### 4.1. Requirements identification

A spreadsheet is used to collect the requirements and feasibility constraints, presented in Table 2 in the first columns in grey. Figure 3 right shows an example of an engine bracket that is used in series. The engine bracket is connected on one side to the engine mount, which consists of two separate damping elements, and on the other to the engine, as illustrated in Figure 3 left. The primary objectives are to achieve high dynamic stiffness and strength while minimizing mass. A critical factor in the design is

the dynamic frequency, which shall be limited to avoid increased noise levels in the passenger cabin. The design domain is restricted to a specific area to prevent interference with other components in the powertrain system. A safety factor is considered to ensure structural strength. Plastic deformations shall be avoided, and the interaction with surrounding components shall be considered in the optimization and verification. The material shall be corrosion-resistant, especially at the contact surfaces to other components, and cables shall be attached to a lug at the side of the engine bracket, represented by the lugs on the upper right side of the engine bracket in Figure 3 right.
Furthermore, the constraints arising from the manufacturing process shall be addressed during the design phase. For AM, these include overhang constraints, minimum feature sizes, and considerations for post-processing, particularly for the screw connections. The component shall be easy to assemble to the other components. Overall, economic interests shall be considered, for example minimal part costs.

**Table 2. Requirements and constraints ordered according to the procedure model**

| Design Task Definition | | Consideration in AM Process | | | | | Identifying Problem Statement | | | | Final Implementation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID-Nr. | Description requirement/ constraint | (1) Parameter Selection | (2) Optimization problem formulation | (3) CAD geometry creation | (4) Verification | (5) Post-processing | Objective | Constraint/ setting | Design Space | Shifted to another implementation step | Implementation comment 1 | Implementation Comment 2 |
| 001 | The domain of the design space shall not exceed … | | X | | | | | | X | | Design domain can directly be provided | |
| 002 | The component shall be as light as possible. | | X | | | | X | | | | Minimize mass | |
| 003 | The dynamic stiffness shall be more than … for a frequency range … | | X | | | | | | | (4) Verification | Verified with FEA | |
| 004 | The component's strength shall be as high as it withstands all loadcases. | | X | | | | | X | | | Strength constraint in optimization | |
| 005 | A factor of safety must be applied as the general factor of safety of … | | X | | | | | X | | | Considered by lower stress limits | |
| 006 | In crash, the component shall deform according to crash requirements … | | | X | X | X | | | | | Verification checkt; if not fulfilled, modifying geom. | |
| 007 | The component shall be connected at … points to the motor with bolts of type …. | | X | | | X | | | X | | Indirectly considered with void & solid areas | Re-drilling of the hole |
| 008 | The component shall be connected at one point to the hydraulic mounting with bolts of type …. | | X | | | X | | | X | | Indirectly considered with void & solid areas | Re-drilling of the hole |
| 009 | The component shall be connected at two points to the auxiliary mounting with bolts of type …. | | X | | | X | | | X | | Indirectly considered with void & solid areas | Re-drilling of the hole |
| 010 | The component shall not deflect plastically under the loadcases. | | | | X | | | | | | Checked via FEA | |
| 011 | The component should be corrosion-resistant according to the surrounding conditions and the contacting components. | X | | | | | | | | | Material choice | |
| 012 | The costs shall be as low as possible. | | X | | | | (X) | | | | Indirectly minimized by minimizing mass | |
| 013 | The stiffness of the surrounding components shall be considered in the optimization. | | X | | | | | X | | | Considered in simulation environment | |
| 014 | A lug shall be added at the … side of the component. | | | X | | | | | | | Added in CAD geometry creation | |
| 015 | Overhang constraints. | | X | | | | | | | (4) Verification | Verified before printing job | |
| 016 | The minimum feature size shall not exceed …. | | X | | | | | X | | | Selection a minimum feature size | |
| 017 | A post processing of the component shall be ensured. | | X | X | | | | | X | | Indirectly considered through void/ solid areas | Adding of feature in CAD geometry creation |
| 018 | The component shall be easy to assemble. | | X | X | | | | | X | | Indirectly considered through void/ solid areas | Adding of feature in CAD geometry creation |

## 4.2. Application of the procedure model

### *4.2.1. Organizing requirements and feasibility constraints in the AM process*

The first task is to order the requirements and constraints into the implementation step. In Table 2, the orange columns with headline "Consideration in AM Process" are used to mark the respective implementation step with an "X". The design domain distribution (ID-Nr. 001), the component mass (ID-Nr. 002), strength (ID-Nr. 004 & 005), and dynamic stiffness (ID-Nr. 003) are typical candidates for direct consideration in the problem statement. They are the primary objectives of the optimization and therefore assigned to implementation step (2), having strict requirements on the strength and stiffness, while the mass shall be as low as possible.

Requirement ID-Nr. 006 addresses the crashworthiness of the structure, specifying a defined deformation in the event of a crash. This requirement is considered in implementation steps (3), (4), and (5). Achieving the desired deformation may require minor adjustments both in the digital design phase and during post-processing. This is verified through FEA or requires physical testing.
The screw connections (ID-Nr. 007, 008, & 009) are considered in several steps, as implementation step (2), where the connection points are modelled via void and solid non-design regions. In step (5) the screw holes are drilled precisely, and threads that exceed the printing quality are cut. The requirement on plastic deformation (ID-Nr. 010) is not considered in the optimization and is verified via FE analysis in implementation step (4). Corrosion resistance (ID-Nr. 011) is addressed by an appropriate material choice before the optimization in step (1). Costs (ID-Nr. 012) are indirectly addressed by considering mass in step (2) mass. The surrounding components of the engine mounting system (ID-Nr. 13) can be considered directly in the optimization. The lug (ID-Nr. 014) can be added in step (4) in the redesign process, as it is not useful to consider the lug in the optimization.
Manufacturing constraints, as overhang (ID-Nr. 015) and minimum feature sizes (ID-Nr. 016) can be considered in the optimization, therefore ordered to step (2). Finally, support structures for post processing (ID-Nr. 017) and consideration of the assembly process (ID-Nr. 018) are added either via void and solid areas in step (2) or with a modification of the CAD geometry of the component in step (3).

### *4.2.2. Identifying the problem statement for optimization*

Once all requirements and feasibility constraints are organized within the AM process, the ones considered in implementation step (2) are sorted in the green columns with headline "Identifying Problem Statement" of Table 2. The goal is to identify the objective(s), constraints, the design space, and which entries are shifted into different implementation steps. For easier identification, the software capabilities of *Altair Inspire® 2024.1*, presented in Section 2.2.2, have been marked as yellow cells. Comparing the yellow marked cells to cells with an "X" in implementation step (2), the mass is selected as the objective. The structure's strength, which has a defined limit, is treated as a constraint. Minimum feature size can be considered in optimization, while screw connections, assemblability, and other considerations are handled by non-design regions.
However, not all entries are suitable for inclusion, as some are incompatible with the used software. In this case, the dynamic stiffness (ID-Nr. 003) is excluded from the optimization and deferred to the verification in implementation step (4). The overhang constraint (ID-Nr. 015) has been moved to the verification step to reduce the number of active constraints. Defining an overhang constraint requires selecting a printing direction, which adds more restrictions and might lead to suboptimal results. If the structure is found to be not manufacturable or requires excessive support structures, the constraint can be included in the next optimization loop. This iterative approach allows the designer to get a first idea of the structure's shape, making it easier to choose an appropriate printing direction in the next iteration. Finding a suitable problem statement may require multiple iterations. Generally, if there are many conflicting requirements, a prioritization of the requirements can be added in an additional column to distinguish between mandatory and optional requirements.
After organizing all entries within the process, a comment section is used to specify the implementation of each requirement and constraint. The comment serves as a check if all entries are considered and specifies the intended implementation.
Finally, the spread sheet provides all information over the problem statement, and the organization of the requirements in the AM process. The following problem statement is identified:

- Objective: Minimize mass
- Constraint: Stress constraint with safety factor, minimum thickness constraint

## 5. Discussion

The strength of the proposed procedure model lies in its simplicity in organizing requirements. It is easy to implement and ensures that all requirements and feasibility constraints are systematically considered throughout the design process. The procedure therefore addresses the research questions 1. This procedure can be implemented in the process chain of Lachmayer and Lippert (2020) and Krantz (2017) at the very beginning of the process. Regarding research question 2, the procedure facilitates the formulation of the optimization problem by identifying objectives, constraints, and potential conflicts. It

therefore goes beyond the presented case study of Endress et al. (2023). As highlighted in Section 4.2, the model also supports in selecting the most suitable solver by aligning problem formulation entries with the solver's capabilities, as demonstrated with *Altair Inspire® 2024.1* (Deacon, 2024).
However, effective use of the procedure requires knowledge of optimization principles to properly assign the requirements and feasibility constraints into the implementation steps. A clear understanding of the capabilities of the chosen optimization software is recommended to determine what can be incorporated into the optimization and what needs alternative handling. This creates a challenge in verification step (4). While some requirements can be verified, unmet requirements may leave uncertainty about how to adjust the design or problem formulation to satisfy all criteria. Furthermore, the process does not guarantee to find the best design, it rather helps to handle numerous requirements. A convergence of the optimization is not ensured applying this procedure. It might be an iterative approach to find a suitable problem statement, and there is not just *one* solution.

## 6. Conclusion and outlook

This paper introduces a procedure model for systematically incorporating requirements and feasibility constraints into the design process of AM parts for industrial applications. First, the requirements and feasibility constraints are sorted into the steps of the AM process where the design can be changed to obtain a desired performance or to include features. These implementation steps include *(1) Parameter selection*, *(2) Optimization problem formulation, (3) CAD geometry design*, *(4) Verification* and *(5) Post-processing*. Some requirements may be treated with multiple steps. Entries relevant to step (2) are evaluated to determine whether they function as objectives, constraints, design space, or, if incompatible with the optimization software, need to be shifted to other implementation steps.
The procedure is applied to designing an engine bracket of AUDI AG, demonstrating a systematic organization of the requirements and feasibility constraints, and a problem statement is derived. The procedure provides clarity in the design process, allowing rapid organization of requirements and feasibility constraints within the AM process. It ensures that all requirements are adequately addressed and helps in formulating a viable problem statement for optimization that matches available software capabilities. It is recommended that the designer has experience in TO and AM when applying the procedure model.
While the model is tailored for TO and AM, it is versatile enough to be adapted to other manufacturing processes and GD methods. The main variation would be in which step requirements and manufacturing constraints are considered, while the overall procedure remains unchanged.
Further, the procedure model can be automated, for example by using machine learning algorithms. The algorithms can translate requirements into problem statements, which are then forwarded to an optimizer to generate designs. Combined with large language models proposed by Gräßler et al. (2023), this approach would enable fully automated component design, requiring only "spoken" requirements as an input.

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## References

Ambrozkiewicz, O., & Kriegesmann, B. (2021). Simultaneous topology and fastener layout optimization of assemblies considering joint failure. *International Journal for Numerical Methods in Engineering*, 122(1), 294–319. https://doi.org/10.1002/nme.6538
Bendsøe, M. P. (1989). Optimal shape design as a material distribution problem. *Structural Optimization*, 1(4), 193–202. https://doi.org/10.1007/BF01650949
Bendsøe, M. P., & Kikuchi, N. (1988). Generating optimal topologies in structural design using a homogenization method. *Computer Methods in Applied Mechanics and Engineering*, 71(2), 197–224. https://doi.org/10.1016/0045-7825(88)90086-2
Bendsøe, M. P., & Sigmund, O. (2004). Extensions and applications. In M. P. Bendsøe & O. Sigmund (Eds.), *Topology Optimization: Theory, Methods, and Applications* (pp. 71–158). Springer. https://doi.org/10.1007/978-3-662-05086-6_2

Brossard, M., Gatto, G., Gentile, A., Merle, T., & Wlezien, C. (2020). How generative design could reshape the future of product development | McKinsey. https://www.mckinsey.com/capabilities/operations/our-insights/how-generative-design-could-reshape-the-future-of-product-development

Buonamici, F., Carfagni, M., Furferi, R., Volpe, Y., & Governi, L. (2020). Generative Design: An Explorative Study. *Computer-Aided Design and Applications*, 18(1), 144–155. https://doi.org/10.14733/cadaps.2021.144-155

Deacon, A. (2024). Structural Optimization (Optimization) [Task]. https://help.altair.com/inspire/en_us/topics/inspire/structure/optimization_inspire_c.htm

Deaton, J. D., & Grandhi, R. V. (2014). A survey of structural and multidisciplinary continuum topology optimization: Post 2000. *Structural and Multidisciplinary Optimization*, 49(1), 1–38. https://doi.org/10.1007/s00158-013-0956-z

El Khadiri, I., Zemzami, M., Nguyen, N.-Q., Abouelmajd, M., Hmina, N., & Belhouideg, S. (2023). Topology optimization methods for additive manufacturing: A review. *International Journal for Simulation and Multidisciplinary Design Optimization*, 14, 12. https://doi.org/10.1051/smdo/2023015

Endress, F., Rieser, J., & Zimmermann, M. (2023). ON THE TREATMENT OF REQUIREMENTS IN DFAM: THREE INDUSTRIAL USE CASES. *Proceedings of the Design Society*, 3, 2815–2824. https://doi.org/10.1017/pds.2023.282

Gerhard, D., Köring, T., & Neges, M. (2023). Generative Engineering and Design – A Comparison of Different Approaches to Utilize Artificial Intelligence in CAD Software Tools. In F. Noël, F. Nyffenegger, L. Rivest, & A. Bouras (Eds.), *Product Lifecycle Management. PLM in Transition Times: The Place of Humans and Transformative Technologies* (Vol. 667, pp. 206–215). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-25182-5_21

Klahn, C., Meboldt, M., Fontana, F., Leutenecker-Twelsiek, B., & Jansen, J. (2018). Entwicklung und Konstruktion für die Additive Fertigung: Grundlagen und Methoden für den Einsatz in industriellen Endkundenprodukten. https://publikationen.bibliothek.kit.edu/1000142320

Kranz, J. (2017). Methodik und Richtlinien für die Konstruktion von laseradditiv gefertigten Leichtbaustrukturen. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-55339-8

Lachmayer, R., & Lippert, R. B. (2020). Entwicklungsmethodik für die Additive Fertigung. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-59789-7

Li, Y. (2024). Advances in 3D Printing Research Based on Topology Optimization. *Highlights in Science, Engineering and Technology*, 120, 210–220. https://doi.org/10.54097/8zdja488

Pedersen, C. B. W., & Allinger, P. (2006). Industrial Implementation and Applications of Topology Optimization and Future Needs. In M. P. Bendsøe, N. Olhoff, & O. Sigmund (Eds.), *IUTAM Symposium on Topological Design Optimization of Structures, Machines and Materials* (Vol. 137, pp. 229–238). Springer Netherlands. https://doi.org/10.1007/1-4020-4752-5_23

Pollák, M., Kočiško, M., & Dobránsky, J. (2021). Analysis of software solutions for creating models by a generative design approach. *IOP Conference Series: Materials Science and Engineering*, 1199(1), 012098. https://doi.org/10.1088/1757-899X/1199/1/012098

Regenwetter, L., Srivastava, A., Gutfreund, D., & Ahmed, F. (2023). Beyond Statistical Similarity: Rethinking Metrics for Deep Generative Models in Engineering Design. *Computer-Aided Design*, 165, 103609. https://doi.org/10.1016/j.cad.2023.103609

Schumacher, A. (2020). Optimierung mechanischer Strukturen: Grundlagen und industrielle Anwendungen. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-60328-4

Swenson, K. (2022, February 23). Generatives Design – was ist das? https://www.autodesk.com/de/design-make/articles/was-ist-generatives-design

Van De Ven, E., Maas, R., Ayas, C., Langelaar, M., & Van Keulen, F. (2021). Overhang control in topology optimization: A comparison of continuous front propagation-based and discrete layer-by-layer overhang control. *Structural and Multidisciplinary Optimization*, 64(2), 761–778. https://doi.org/10.1007/s00158-021-02887-2

Wanninger, T., Frank, J., & Zimmermann, M. (2024). Topology optimisation of multiple robot links considering screw connections. *Proceedings of the Design Society*, 4, 1879–1888. https://doi.org/10.1017/pds.2024.190

Zimmermann, M., & de Weck, O. (2020). Formulating Engineering Systems Requirements. In A. Maier, J. Oehmen, & P. E. Vermaas (Eds.), *Handbook of Engineering Systems Design* (pp. 1–52). Springer International Publishing. https://doi.org/10.1007/978-3-030-46054-9_33-1

Zoubek, M., Poor, P., Broum, T., Basl, J., & Simon, M. (2021). Industry 4.0 Maturity Model Assessing Environmental Attributes of Manufacturing Company. *Applied Sciences*, 11(11), 5151. https://doi.org/10.3390/app11115151