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ON THE TREATMENT OF REQUIREMENTS IN DFAM: THREE INDUSTRIAL USE CASES

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ABSTRACT

Optimization-driven design offers advantages over traditional experience-based mechanical design. As an example, topology optimization can be a powerful tool to generate body shapes for Additive Manufacturing (AM). This is helpful, when (1) load paths are non-intuitive due to complex design domains or boundary conditions, or (2) the design process is to be automated to minimize effort associated with experience-based design. However, practically relevant boundary conditions are often difficult to put into a formal mathematical language to, for example, either feed it into a topology optimization algorithm, or provide precise quantitative criteria for CAE-supported manual design. This paper presents a survey of three industry use cases and identifies three types of requirements: the first can be directly cast into parts of an optimization problem statement (~ 40%), the second is considered indirectly by adapting the optimization problem without explicit reference to the requirement (~ 20%), and the third is only assessed after the design is finalized (~ 40%). For categories 2 and 3 we propose directions of improvement to support formulating complex design tasks as unambiguous design problems.

Keywords: Requirements, Optimisation, Design for Additive Manufacturing (DfAM), Product Development, Topology Optimisation

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1 INTRODUCTION

Advances in numerical methods and increased manufacturing potentials, provided by fabrication techniques such as additive manufacturing (AM) or detailed manufacturing process simulations, have greatly encouraged the use of optimization methods in technical product development over the past few years. Results obtained from algorithms searching for optimality (with respect to certain objectives), often outperform designs based on intuition and experience. However, in the industrial practice of optimization-driven product development, it would appear that only a relatively limited number of requirements are explicitly considered in optimization formulations. Usually, just a few selected requirements are translated into a problem statement (also called an optimization statement), that can be formulated by mathematical means, consisting of a minimization or maximization as an objective, combined with single or multiple constraint(s). Other requirements are taken care of in previous or later development steps. Difficulties matching requirements with (mathematical) optimization problem formulations arise on both sides, requirements and optimization formulations.

Requirements. Eliciting requirements is an essential process step when developing products that can be supported effectively by several methods and techniques categorized and listed by (Zimmermann and de Weck, 2020). Although requirements should be formulated unambiguously, representing the needs and wishes of stakeholders, they often remain vague. Whereas, for example, mass is an attribute that is per se a quantity that can be subjected easily to a requirement, other product characteristics such as operational safety, manufacturability, lifetime, aesthetics or even cost may be more difficult to formalize, but are frequently of interest when designing a new product. This poses a challenge in optimization-driven development approaches, where requirements must be transformed into precise mathematical language. Furthermore, requirements formulated for different levels of a system may exacerbate the translation from requirements into numerical optimizations. In some cases, requirements can be considered somewhat indirectly. For example, overall cost (a quantity of interest on the system level) are typically subject to requirements, even though quantitative and precise cost models that can be used to design the part are rarely available. A satisfactory compromise, which generally works well in lightweight design problems, is to simply associate cost with mass. As has been illustrated by (Zhu et al., 2016), reducing the weight of a Boeing 787 by 20% would result in an improved fuel efficiency and thus, a reduction of costs during operation by 10-12%.

Optimization formulations. There are various reasons why it is not easy to find an intuitive mathematical formulation for many requirements. In many cases, the relation of a quantity of interest, which is subject to a certain requirement, to the design variables, which in the context of mechanical design typically define the geometric layout of the part, can only be described qualitatively or is not known at all. In addition, the mere existence of a mathematical description is not sufficient. For numerical optimization in particular, it is important that the problem can still be solved efficiently and that the necessary software functions and computational resources are in fact available to the designer. Thus, whether to make a requirement part of the design optimization problem or not, is not just a question of theoretical feasibility, but rather a complex trade-off that also has to consider cost and time budgets, as well as available tools and methods.

Research gap. The importance of a requirement formulation in complex real-world scenarios is widely accepted. Unfortunately they are often not considered in formal problem formulations that are necessary for a precise clarification of the task and an unambiguous assessment and verification. In order to derive improvement measures, we have to ask the question: *What requirements in industry-practice are cast into formal design problem statements? What requirements are not, because of a lack of methods?*

In answer to this question, this paper presents a collection of three industrial use cases (UC). Three metallic components were designed for AM and manufactured. In the use cases, the task was to develop an optimized design using either numerical or manual optimization and design techniques. The selection is a result of a research project together with industry partners where we wanted to cover a range of relevant industrial design problems. We do not claim that this is exhaustive, we have only taken these use cases to argue the relevance of introduced categories. The objective of this paper is to find out where automatic design is limited with respect to requirement treatment. Some requirements can be easily be expressed in formal problem statements, e.g. as constraints, and treated accordingly. Some cannot because it is either numerically too expensive, or associated with too much modelling effort.

The focus here is on proposing areas of improvements with respect to methods and algorithms motivated by practical use cases. The collection of use cases and resulting designs that are presented serve only as a documentation of how the design was performed. Alternative design approaches and opportunities are not presented or discussed (e.g. different objective functions).

This paper is organized as follows. Subsequent to the introduction in Chapter 1, we briefly present the state of the art (Chapter 2) of considering requirements within optimization-driven design. This will be done exemplary for topology optimization, which is the most suitable tool for this purpose. In Chapter 3 we introduce three uses cases, list the requirements for each of them and present the achieved optimized part designs. We introduce three categories to cluster the different requirements from the use cases in Chapter 4. This paper ends with a conclusion and summary in Chapter 5.

2 STATE OF THE ART

Formulated as the objective function or constraint(s) in topology optimizations, there are many examples where requirements were directly cast into optimization problems. Frequently considered quantities of interest are eigenvalues or -frequencies (Tsai and Cheng, 2013; Ma et al., 1994; Pedersen, 2000), mass (Larsson et al., 2022), stiffness or compliance (Bruggi and Duysinx, 2012), displacements (Rodriguez et al., 2020) or stresses (Da Silva et al., 2021). In addition to the aforementioned quantifiable requirements, requirements on the design itself, its manufacturability or functionality can also be considered in (numerical) optimizations. Fail-safe designs (Zhou and Fleury, 2016), overhang constraints for AM (van de Ven et al., 2021), fatigue (Holmberg et al., 2014), buckling (Yi et al., 2019), or minimum length scales and wall thicknesses are requirements, that can be satisfied by appropriately formulating and solving optimization problems. However, often only one requirement (mostly a quantity of interest) is taken into account, whereas a vast array of requirements must be considered in industrial applications. Moreover, it generally takes a while for new optimization methods to achieve a sufficient level of robustness before they can be adopted in commercial software solutions.

In practice (and in the use cases presented in Chapter 3), not all requirements can be cast into optimization formulations or described by mathematical means. The level of detail of different requirements often does not match one single numerical optimization. For example, fine structural details of a surface are usually much too small to be considered in a macroscopic single scale optimization. Also other areas, such as stress constraints in topology optimization are also under constant investigation, but still pose challenges when it comes to delivering robustly sound results. This is partly due to the local nature of stress, making it difficult to solve a naive constraint-based formulation efficiently, and partly due to failure criteria, singularities and artificial stress-concentrations (Da Silva et al., 2021).

In practice, there are usually various ways to pose, approach and solve a design problem using optimizations. However, results generated by topology optimization algorithms depend to a large extent on decisions a designer takes when formulating the optimization problem (Tyflopoulos and Steinert, 2019). Variations in design domain, load or boundary conditions may lead to ’drastical changes in the “optimal design”’ (Bendsøe and Sigmund, 2004, p. 47). In addition, other parameters related to requirements, such as the granularity of the spatial discretization or filtering approaches to ensure minimum length scales, can significantly influence resulting topologies (Sigmund, 2022). Therefore, the formulation of complex engineering problems into mathematical optimization statements poses a challenge.

In the context of Design for Additive Manufacturing (DfAM) the elicitation of requirements is often part of the development process. Nevertheless, optimizations are not usually capable of considering (all) manufacturing requirements and result more in drafts and concepts than detailed designs (Klahn et al. (2018), S. 44). Moreover, in other exemplary AM development approaches, requirements are not fully translated into optimization problems (e.g., see examples in Lachmayer et al. (2021)). However, different approaches exist for grouping requirements into categories to systematically facilitate a purpose-driven development of complex parts and systems. For example, the NASA Systems Engineering Handbook classifies requirements into functional, performance, interface and cross-cutting (e.g. environmental, safety, etc.) requirements (Hirshorn, S. R., 2016). Pahl et al. (2007) proposes a division into basic, technical performance, and attractiveness requirements. This categorization is not helpful for structural optimizations, because the latter cannot be formulated and a distinction between the first two is not related to optimization formulations. Categories of functional, performance, specific quality, and constraint requirements introduced by Glinz (2007) may be misleading when translating requirements into optimization problems. What's more, the separation by Koelsch (2016) into functional and non-functional requirements does not provide a categorization related to optimization problems. In the light of the aforementioned categories, it becomes clear that existing categories do not support the formulation of precise optimization statements.

3 USE CASE ANALYSIS

Three different industry use cases are presented in this chapter. In addition to a problem description, i.e. a design task, and accomplished results, detailed requirement lists are presented. For the first two use cases, the objective is to minimize mass aimed at the overall goal of reducing cost. The third case study deals with maximizing the first natural frequency. Software tools used include Altair OptiStruct, Inspire and Autodesk Inventor. While defining the objective function does not pose a problem, dealing with other requirements turns out to be less straightforward. The consideration of requirements during the optimization process is documented in the column "Treatment" in Table 1. Further, requirements are clustered into three categories, which will be explained in Chapter 4. Only completed use cases are presented, so all requirements are satisfied. The development of the parts is not reported in this paper, but was performed based on the state of the art approaches. For each requirement, the verification was either simulation-based (S), provided experimentally by hardware testing (T), based on experience and prior knowledge, gained in comparable design processes (E) or a combination of these.

3.1 Use Case 1: Gripper for automatic screwing

3.1.1 Problem description

The first use case is a customized screw gripper for a handheld or robot-guided screwdriver from Stöger Automation GmbH. The gripper consists of two articulated pairs of jaws which hold the screws in place and release them once the screwdriving process is completed. The jaws are closed by a pre-stressed spring. The expected service life of a gripper is considerable and may cover more than a million cycles. The goal is to achieve a lightweight design which can also be fabricated conveniently using AM. The requirement list for the design problem of the screw gripper is shown in Table 1.

3.1.2 Results

The optimized gripper is shown in Figure 1. Compared to the conventional design, mass savings of 30% were achieved while retaining the original stiffness. The final design is closely based on the topology optimization result created. Minor modifications were carried out to realize a self-supporting design which can be printed without sacrificial support structures.

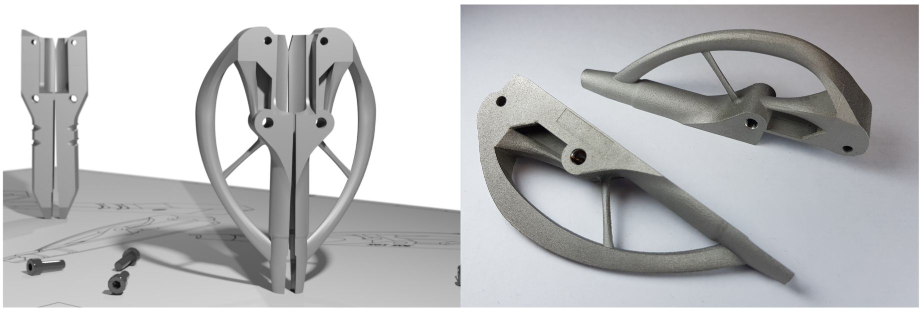

Figure 1. Conventional design of the screw gripper (left), optimized redesign (middle) and parts of the manufactured prototype (right).

3.2 Use Case 2: Aero engine bracket

3.2.1 Problem description

The second use case is an archetypal aerospace bracket. The case study was conducted in collaboration with MTU aero engines AG. The bracket serves as a mechanical fixation to connect an individual

Table 1. Requirement lists for design problems of a screw driver, an aero engine bracket and an exhaust rake.

#	Requirement	Symbol	Minimum	Maximum	Nominal	Unit	Treatment	Verification	Category
	Use Case 1: Screw Gripper								
1	Mass shall be as low as possible.	m				g	Objective function	S	1
2	Compliance shall be equal to the compliance of the conventional design.	c		2.3		Nmm	Constraint on c	S	1
3	Von-Mises stress shall remain below the allowable limit (per load case).	s_{vM}				MPa	Checked in post-processing	S	3
4	Material hardness on guiding surfaces shall exceed ...		*			HRC	Material selection, heat treatment	E	3
5	Design domain of 100x20x15 mm^3 shall not be exceeded.						Modelling: Design domain	S	1
6	Part shall withstand wear to prolong lifetime.						Offsets were added locally to compensate wear	E	2
7	Effort for post-machining shall be low.						Considered during CAD geometry creation.	T	3
8	Cost shall be below that of the conventional design.						Coupled with mass (AM specific) and post-machining effort.	S	2
9	Functional surfaces for the screw guiding surface, a bearing, and spring-load introduction shall be present and comply with specified tolerances.						Modelling: passive and solid elements	T	2
10	Printed part shall remain within dimensional tolerances.	Δd		0.1		mm	Manufacturing process simulation, 3D laser scanning	S, T	3
	Use Case 2: Aero Engine Bracket								
1	Design domain of 150x75x70 mm^3 shall not be exceeded.						Modelling: Design domain	S	1
2	Shall withstand static and dynamic loads as specified.						Modelling: Loads	S	1
3	Printed part shall remain within dimensional tolerances.						Manufacturing process simulation, 3D laser scanning	S, T	3
4	Von-Mises stress shall remain below the allowable limit (per load case).	s_{vM}				MPa	Checked in post-processing.	S	3
5	Effort for post-machining shall be as low as possible.						Enable fixation of part and accessibility for post-machining using passive elements (elements that remain void) in design domain.	E	2
6	Displacements at specified locations shall not exceed specified values.	u		*			Displacement constraint	S	1
7	Wall thickness shall not exceed ...	t_{max}		20		mm	Visually confirmed after optimization	S	3
8	Wall thickness shall exceed ...	t_{min}	1			mm	Modelling: Spatial discretization	S	2
9	Mass shall be as low as possible.	m				g	Objective function	S	1
10	Sufficient material shall be provided where load is applied.	t_{int}				mm	Modelling: Design domain with solid elements/ non-design region	S	1
	Use Case 3: Exhaust Rake								
1	Design domain of 250x250x250 mm^3 shall not be exceeded.						Modelling: Design domain	S	1
2	Attachment to customized flange shall be maintained as is.						Modelling as solid elements following the reference design	E	1
3	Stresses due to aerodynamic drag shall be below the allowable limit.						Experience-based evaluation, validation by testing	E	3
4	Shall withstand temperatures up to ...	T_{max}		900		°C	Material selection	E	3
5	Stresses due to thermal gradient from room temperature (attachment) to T_{max} shall be below the allowable limit.						Comparison to a conventional solid rake design.	S, E	3
6	Eigenfrequency (1st) shall exceed ...	f_1	320			Hz	Iteratively checked	S	1
7	Pressure channels shall be clear of clogging and free of unwanted openings linking to adjacent channels.						Minimum spacing between channels and minimum diameter chosen based on experience.	T	1
8	Sufficient creep strength (at T_{max}) required.						Material selection.	E	3
9	Resistance to oxidation at T_{max} required						Material selection.	E	3
10	The position of the tips must remain within the specified tolerance.	u_{mag}		0.5		mm	Manufacturing process simulation, 3D laser scanning	S, T	3
11	Surface roughness shall be as low as possible.	R_a					Manufacturing process parameter and post-machining	E	3
12	Eigenstresses shall be as low as possible (heat treatment).						Manufacturing process simulation	S	3
13	Cost shall be below that of conventional reference design.						Design according to DfAM principles (avoiding overhangs to reduce sacrificial support structures)	E	2

subcomponent firmly to the surrounding structure of the aero engine. The bracket must operate safely in a harsh environment with strong vibrations at elevated temperatures. The design goal is to reduce the mass as much as possible while satisfying a number of requirements related to functionality, cost and manufacturing. The requirements documented in Table 1 indicated by * are not shown in detail for reasons of confidentiality.

3.2.2 Results

The optimized bracket is shown in Figure 2, featuring a smoothened truss-like structure. Significant mass savings could be realized. For the topology optimization, mass was taken as the objective function while constraints were imposed on the displacements at selected positions as specified by the industry partner.

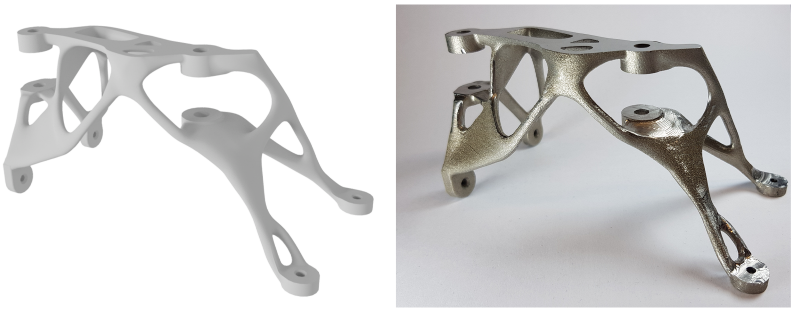

Figure 2. CAD representation of the optimized aero engine bracket (left) and manufactured prototype (right).

3.3 Use Case 3: Exhaust rake

3.3.1 Problem description

The third use case is a probe rake used for flow measurements, that is developed and manufactured by vectoflow GmbH. The probe rake is immersed in the hot exhaust jet of a gas turbine engine to gather information on velocity and pressure. For that reason, small-diameter, internal pressure channels run through the interior of the rake, connecting the fifty measurement openings with the connector panel at the base plate of the rake. The goal was to find a new rake design with a certain minimum first natural frequency to make the rake less susceptible to vibrations under operation. Since any outer surface of the existing solid rake design had to be retained, the challenge was to achieve this by only redesigning the inner mechanical structure.

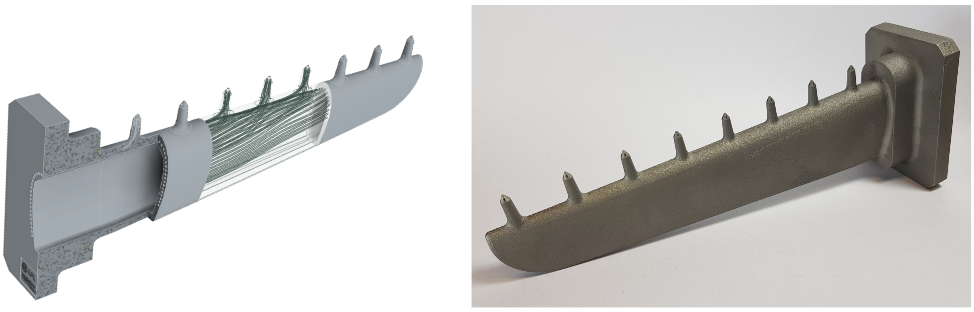

Figure 3. Cross-sectional view of the manually optimized measurement rake showing details of the internal pressure channels (left). Printed prototype (right).

3.3.2 Results

A cross-sectional view of the redesigned gas turbine engine emissions rake is shown in Figure 3. The lightweight design features a single-cell hollow section with the internal pressure channels embedded in the walls. The first natural frequency of the final design is 50% larger than the required minimum value. Mass was reduced by one third compared to the existing solid design.

4 TYPES OF REQUIREMENTS FOR THE OPTIMIZATION-DRIVEN PRODUCT DEVELOPMENT

Chapter 3 presented the requirement lists of three AM industry use cases. In the requirement lists in Table 1, the treatment, i.e. realised consideration of the present requirements, is marked in the column "Category". Treatment means here to take a measure that will ensure that the requirement will be satisfied. This can be accomplished, e.g. by the actions listed in Table 1. We propose three categories to classify requirements for optimization problems, as described in Table 2, as a contribution towards the automatization of design. Topology optimization and manual redesigns were applied in the use cases. However, a problem statement is also required for other optimization types, such as parameter optimization, and this does not affect the type of categories that we identified. The comprehensive requirement lists in Table 1 are shown in detail to document how specific requirements were treated, for example by including them in formal, mathematical problem statements. Those requirements that cannot be treated this way show potential directions of improvement, either methodical or algorithmic.

Based on the use cases that were analysed, we observe that the number of requirements in categories 1 ($\sim$ 40%) and 3 ($\sim$ 40%) is high, whereas only a few requirements were indirectly considered (Category 2, $\sim$ 20%). Each category contains several examples, so it is plausible that every category is relevant. We do not claim that the percentages are representative for other use cases. Directions of future research can be derived from the analysed distribution of requirements among the categories in the use case examples. The use cases presented include requirements specifically written for AM, as some prescribe the underlying manufacturing method, such as minimum wall thicknesses (UC2, Req. 8) or the reduction of overhangs (UC1, Req. 7). Other requirements could be considered indirectly by defining the manufacturing method as AM, such as reduced costs for reduced overhang support structures (UC3, Req. 13).

Requirements that can be formulated by mathematical means (allocated to category 1) require skilled personnel and tool availability to practically formulate and solve optimizations. However, a trade-off against category 1 type requirements is often also required, because the more objectives and constraints that are considered, the more complex it becomes to solve design problems. In practice, external factors and individual circumstances (including tool availability, a-priori knowledge of system- and part responses to loads, experience, numerical cost, required robustness, etc.) influence the decision, if a quantitative requirement is considered in category 1.

For requirements in category 2, new methods and guidelines are required to enable a consideration in optimization problem statements. As shown in the use cases, the indirect consideration of requirements requires general engineering knowledge or partial knowledge of the solution to the design problem so as to include the requirement appropriately in an optimization problem. For example, in use case 2 (bracket), the effort of post processing (Req. 5) was implicitly considered by using passive elements in the design domain. Passive elements combined with engineering knowledge (here: how to fix a part for subtractive machining) hereby allows an implicit consideration of the requirement in the topology optimization. Generally, the category to which a requirement is assigned to depends on the individual use case. For example, the surface roughness of a part is not subject to a topology optimization. However, for certain manufacturing technologies, such as metal AM, it is known that downward-facing surfaces will be of low quality (i.e. characterized by a great roughness), whereas upward-facing surfaces are rather fine. This means that for this special case, requirements on the surface characteristics may be satisfied by prescribing the orientation in a printer as part of the loading and boundary conditions, as well as appropriately modelling the design domain (category 2).

New tools or algorithms are required to include requirements of category 3 in optimization formulations. Since they are not formulated as problem statements, verification is required to check if a requirement from category 3 was met (but this is not always possible). In contrast, requirements in category 1 and 2 do not necessarily need verification, as some optimization methods can guarantee good designs (no violation of requirements). Thus, both testing and simulation effort as well as the optimization could be reduced, when including requirements into optimization problems. With more powerful tools and algorithms, e.g. considering stress constraints, more requirements could be considered in optimization formulations.

Table 2. Types of requirements in optimization-driven product development

Category	**Requirement type**	**Examples from the use cases** Quantity of interest: Treatment
1	Directly considered in problem formulation. Can be treated with little numerical or modelling effort.	Mass: Objective function (UC1, Req. 1; UC2, Req. 9) Compliance/ stiffness: Constraint (UC1, Req. 2) Design Domain: Modelling and spatial discretization (UC1, Req. 5; UC2, Req. 1, UC3, Req. 1) Displacement: Constraint (UC2, Req. 6) Material where load is introduced: Design domain modelling with solid elements (UC2, Req. 10) Compatibility with geometry of initial design: Design domain modelling with solid elements (UC3, Req. 2) Eigenfrequency: Objective in (manual) optimization (UC3, Req. 6)
2	Indirectly represented in problem statement.	Cost: Volume/ mass as objective function (UC1, Req. 8) Accessibility (effort for post-machining): Design domain modelling using passive elements (UC2, Req. 5) Functional surfaces: Modelling of passive and solid elements to achieve defined surfaces (UC1, Req. 9) Minimum length scales and minimum wall thicknesses: Spatial discretization and filter radius (UC2, Req. 8) Cost: Reduction of overhangs (AM-specific) (UC3, Req. 13) Wear: Offsets were added locally to compensate for wear (UC1, Req. 6)
3	Not considered in problem statement.	Surface characteristics and material hardness: Level of detail not applicable in optimizations (UC1, Req. 4; UC3, Req. 11) Stresses: Analysis after optimization (UC1, Req. 3; UC2, Req. 4; UC3, Req. 3) Dimensional accuracy: Measured after manufacturing (UC1, Req. 10) Maximum wall thickness: Requirements were always fulfilled (UC2, Req.7) Withstanding high temperatures: Material selection (UC:3, Req. 4) Creep strength: Material selection (UC3, Req. 8) Oxidation: Material selection (UC3, Req. 9) Surface roughness: Manufacturing process parameter and post-machining (UC3, Req. 11) Eigenstresses: Manufacturing process simulation (UC3, Req. 12)

5 SUMMARY AND CONCLUSION

Complete and unambiguous problem formulations help in successful design work. More specifically, casting requirements in precise formal problem statements supports automatic design based on optimization algorithms. This paper reviews three industry use cases to analyse how requirements were expressed in explicit problem formulations. Three categories were introduced: the first represents requirements that can be directly formulated as quantitative constraints or objectives that can then be further processed by numerical optimization, for example. The second is considered indirectly, such as cost. The third is not considered and verified after the design or optimization process, possibly necessitating further design measures. The introduced categories offer guidance for a further automation of the design process. Requirements of category 2 can be treated with improved guidelines, whereas those of category 3 require new algorithms. The contribution of this paper is to show how requirements are addressed in three industry-relevant use cases. Conclusions drawn are not exhaustive, however relevant.

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