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EXPLOITATION OF POTENTIALS OF ADDITIVE MANUFACTURING IN IDEATION WORKSHOPS

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Abstract: Additive manufacturing processes have become a viable alternative to conventional manufacturing for end-use products. However, designers are not sufficiently familiar with its potentials like reducing cost and time due to tool-less production or realisation of new design features. Thus, especially in traditional industries like in the automotive sector these potentials are untapped resulting from three hindering factors: Firstly, knowledge concerning potentials of additive manufacturing is lacking. Secondly, designers' creativity is blocked as they are not able to detach from established solutions. And, thirdly, organizational boundary conditions do not allow to break out of established processes. This paper presents six hypotheses on how to enable companies to implement AM into established design processes while overcoming the identified hindering factors. Based on these hypotheses, a concept for ideation workshops is proposed and demonstrated on an example from the automotive industry.

Keywords: *design for additive manufacturing, knowledge based engineering, ideation*

1. Motivation

In the last years additive manufacturing (AM) has gained a growing importance as a viable alternative to conventional manufacturing processes – even for end-use products. While in the past potentials like tool-less production were especially utilised for rapid prototyping, nowadays they are used to manufacture end-use products in order to shorten development and production time. Moreover, the realisation of new design features has been made possible by capabilities unique to AM, for instance, to design complex geometries with reduced constraints or realisation of graded materials.

The challenge of companies in traditional industries is to integrate the new design knowledge of AM into design practice. However, neither the knowledge available to designers nor the process structures of design and production are prepared for AM. Especially in industries like the automotive sector, design processes have developed over many decades without considering AM. Therefore, when designing new products, designers run the risk to fall back into old patterns. For instance, when designing new generations of structural components, designers start from predecessor products that are manufactured, e.g. in a die-casting process. In many of those cases only minor modifications on the geometry are made, e.g. by topology optimisation, to fulfil new spatial requirements. In the course of this, the manufacturing process is not questioned at any point. However, with AM, new solutions become viable that could result, for instance, in significant weight reductions or integration of new functionalities. Without considering AM, these potentials remain untapped.

Aim of the research presented in this paper is to enable companies to implement AM into design processes. Towards this aim, the paper will be guided by following three research questions (RQ):

1. What are hindering factors delaying and/or restraining the exploitation of potentials of AM that are available, but far too often not tapped?
2. Which basic preconditions have to be fulfilled to encourage designers to consider potentials of AM within the design process?
3. How can AM be implemented in companies by ideation workshops?

RQ1 will be answered based on the experience of design practices within companies in the automotive sector in Germany. The answers for RQ2 and RQ3 were developed against the background of research projects between academia and industry to implement knowledge about AM. In this context several ideation workshops where carried out providing first results for validation of the presented context.

The structure of this paper follows the stated research questions. While Sec. 2 summarises the existing state of the art in ideation processes in general and regarding the consideration of AM, Sec. 3 answers RQ1 by highlighting still existing hindering factors. Addressing these factors, Sec. 4 states six hypotheses on the encouragement of designers to consider potentials of AM in order to answer RQ 2. For RQ3 in Sec. 5 a concept for ideation workshops is demonstrated with the help of examples from the automotive industry. The paper is concluded in Sec. 6.

2. Ideation processes in product design

Ideation describes the creative process of elaborating new ideas. In product design, ideation covers an essential part of the conceptual stage. The objective of this section is to provide an overview of existing methodical approaches providing methods and tools for ideation. Therefore, a traditional general problem solving process is described initially. Afterwards, design thinking is presented as a human-centric alternative approach. Finally, approaches developed specifically for AM implementation are described.

2.1. Problem solving in traditional design methodology

Starting point for any design activity is an unsolved problem regarding the fulfilment of a need that should be addressed by a technical system. For this purpose, the designers carry out two main activities (Weber, 2007): Firstly, analysis to derive the technical system's properties (e.g. weight, costs and functionalities) from its characteristics. Secondly, synthesis to determine characteristics (e.g. material, geometry and colour) in order to ensure the fulfilment of the required properties. The challenge for designers is that for both analysis and synthesis the relations between properties and characteristics must be known. However, mostly these relations are not transparent and design tools are needed. For this purpose, various means of product representation – product models – exist providing relevant information on the relations between characteristics and properties for decision-making (Roth, 2000).

Several traditional approaches of product design like Pahl & Beitz (2007) build on this theory and provide procedures guiding designers step by step through a proposed amount of product models, like function structures, effect structures, working structures and building structures. The types of product models vary between the different approaches. However, most traditional approaches have in common that the same idea of a general process of problem solving is followed. It can be described by three phases:

1. The initial description of the task or the predecessor product is formulated as a product model describing the problem (abstraction).
2. The product models serve as a basis for the generation of solutions for the problem whereby new product models are created (ideation).
3. The ideas are elaborated to a realisable product description (concretisation).

2.2. Design thinking

Design thinking is an alternative human-centric approach for product design that puts the focus on the integration of expertise from design, social sciences, engineering, and business (Plattner et al., 2011). It is built on following three core elements (HPI, 2016; Gericke et al., 2010):

- Multidisciplinary teams: People from technical and non-technical disciplines are collaborating in teams in order to integrate different perspectives to the process.

- Variable spaces: The work spaces for design thinking contribute essentially to the designers' performance and creativity. Opportunities for different activities like brainstorming or prototyping should be available when needed.
- Iterative process: The process comprises the steps understand, observe, point of view, ideate, prototype and test that are passed through in a flexible way.

The application of design thinking in ideation processes in product design can be carried out in different ways. A well approved approach is studied at ETH Zurich by carrying out workshops with small and medium sized enterprises (Heck, 2017). These workshops are set up in three phases:

1. "Right questions are identified" by analysing the design challenge and clarifying the goals.
2. New hypotheses, ideas and prototypes are generated by ideation.
3. The implementation of the ideas is prepared by focusing on challenges in the organisation.

Generally, the procedure of these workshops is similar to the process of problem solving described above. The key differences become apparent in its execution, whereat design thinking allows more freedom following the above mentioned core elements, and traditional approaches follow closely a defined sequence of product models.

2.3. Methods and tools considering additive manufacturing in ideation

The knowledge available to designers plays a key role within ideation, especially, when new technologies like AM are introduced. Hatchuel & Weil (2003) highlight in their C-K theory that innovations arise due to the elaboration of new concepts (C) in the concept space. The concept space is thereby connected to the knowledge space containing propositions that "have a logical status for a designer". They follow that creativity and innovation come from what is already known in the knowledge space. Therefore, a great challenge in *Design for Additive Manufacturing* is the provision of knowledge about the unique capabilities of AM. In literature several approaches exist categorising (Gibson et al., 2015) or systemising AM's new freedom of design (Kumke et al., 2017). A systematisation as well as a linkage of design goals like part count reduction or improvement of stiffness with AM-specific design potentials like internal graded lattice structures foster creativity in rethinking the conceptual design and facilitate a wide application of the new design freedom.
However, a comprehensive exploitation of potentials of these capabilities requires a rethinking of conventional design processes. Therefore, several process-oriented approaches are proposed in literature. For instance, Kumke et al. (2016) provide a methodological framework based on traditional design methodology incorporating existing AM-specific methods, for instance, in development of solution ideas and tools in the different design phases. Similarly, Rias et al. (2017) propose a 5-phase Creative-DFAM method specific to concept generation for AM. Their framework is inspired by design thinking (c.f. Sec. 2.2) and contains two ideation and two decision-making steps.

3. Hindering factors for the consideration of additive manufacturing

Aiming on the integration of AM to design processes, the industry faces several hindering factors resulting in a poor exploitation of its potentials. This section describes *lack of knowledge*, *restrained creativity*, and *processual barriers* as three main hindering factors that were identified in literature and practice in the automotive industry.

3.1. Lack of knowledge

Conventional manufacturing processes like die casting have been used and analysed for more than a hundred years. Therefore, a lot of experience and knowledge exist especially in the development departments of the OEM in the automotive industry. Due to the novelty of AM processes and its profound differences to conventional processes, most designers do not have the required knowledge about potential benefits, capabilities and limitations of AM (Kumke et al., 2017). Already existing AM design rules, guidelines and experience concerning possible geometries, materials, mechanical specifications as well as the process immanent limitations are still limited to research facilities and a few specialist. This can result in the selection of parts that are not suitable for AM, the elaboration of unrealisable concepts, or the limited exploitation of the potentials.

3.2. Restrained creativity

Cognitive barriers represent one of the main challenges with regard to the full exploitation of AM potentials. For the most design tasks, solutions from preceding projects with similar or even identical tasks are available. During ideation those preceding solutions can prevent designers from exploring alternative solutions. Literature refers to this barrier as design fixation. Examples for factors that have an influence on the occurrence of design fixation are designers' expertise, instructions, design methods, group work, timing and prototyping (Alipour et al., 2017; Jansson, 1991). It is necessary to minimise design fixation and, therefore, consider the mentioned factors in order to get novel designs exploring potentials of AM comprehensively.

3.3. Processual barriers

The decision on most suitable manufacturing processes for designed parts is usually made at a relatively late stage within the design process. However, when considering AM (as a manufacturing process) at a late stage, it is often not possible to revise the product concept in order to implement then noticed beneficial capabilities of AM. The integration of neighbouring components, for instance, needs to be assessed during conceptualisation since a later consolidation of already designed parts is time consuming and costly. Hence, existing discrepancies between conventional design processes and AM-suitable design processes lead to the utilisation of AM for parts that are conventionally designed. Beyond that, conventional design processes often do not allow designers to invest additional time to revise already proven concepts from preceding projects. Mostly, the redesign of existing parts results only in the optimisation of shape (e.g. topology optimisation) in contrast to variation of working principles (e.g. use of lattice structures). Reasons for that are that the application of new capabilities often result in necessary additional investments as well as potential risks in the industrialisation (Albers et al., 2015). Towards the exploitation of the imminent AM potentials it is crucial to reassess the concept and, therefore, adapt the existing design processes.

4. Enhancing the exploitation of potentials of additive manufacturing

In order to address the challenges described in the preceding section a comprehensive approach needs to be elaborated for implementation in companies. In this section, a basis for the approach will be laid by formulating six hypotheses (H) on the inducement of designers to consider AM. The hypotheses are derived from established methodical approaches in product design. Thereby, especially concepts of the conventional design methodology (c.f. Sec. 2.1) and design thinking (c.f. Sec. 2.2) are considered.
An overview of the six hypotheses in alignment to the three basic factors from Sec. 3 is given in Fig. 2. Thus, H1, H3 and H5 are assigned directly to one main factors each. H2, H4 and H6 address two factors each. In the following the general idea of the hypotheses will be described in brief. A closer look on how to implement the hypotheses in practice will be demonstrated in Sec. 5.

Hypothesis 1: Provision of Solution Principles

Knowledge about capabilities of AM, provided as solution principles, enhance the designers' ability to implement AM to design activities.
The provision of knowledge plays a key role in product design, as new concepts arise due to the combination of the known, c.f. Sec. 2.3. Especially, when new technologies like AM are introduced designers require knowledge about new possibilities. This knowledge can be provided as solution principles comprising the description of capabilities of AM, like realisable design features. In order to ensure its integrity to design processes, it is essential to include descriptions of solution principles explaining of how to change characteristics as well as how product properties can be affected (c.f. Richter et al., 2017). Design principles for AM can be provided, for instance, in principle databases (c.f. Kumke et al., 2017).

Hypothesis 2: Reassessment of problem definition

Since AM enables solutions for design tasks that conventional manufacturing does not allow, a reassessment of the design problem increases the possible degree of potential exploitation.

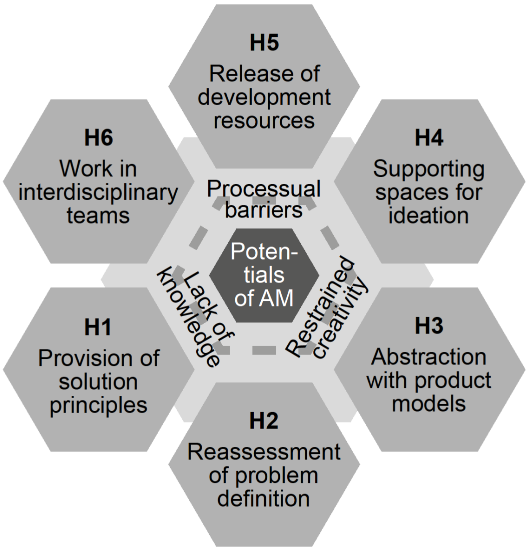

Figure 1. Hypotheses on the enhancement of the exploitation of potentials of AM in product design addressing the three main hindering factors

The driver for design activities is the fulfilment of required properties of the product. As often the starting point for a design task is a predecessor product, the required properties like the functional scope or the prescribed maximum weight are predominantly taken over from the former design project. However, AM provides new capabilities, for instance, to integrate additional functionalities to parts or radical improvements of weight, see Sec. 2.3. Therefore, when designing products for AM, it is essential to reassess the problem definition by clarifying benefits that can be generated.

Hypothesis 3: Abstraction with product models

Potentials of AM are aligned to different levels of abstractions, and therefore, can only be exploited by describing the product to be developed with different product models.

According to traditional design methodology (see Sec. 2.1) problem solving is carried out by generation of abstract product models of the design problem that provides the basis for ideation. Thus, product models like function structures or working structures provide the means to implement new ideas. Solution principles for AM can be described with different levels of abstraction like additional functions to be integrated, different topologies for working principles or new freedoms in the embodiment design. Therefore, the generation of various abstract product models as proposed by established methodical approaches can enhance the exploitation of potentials.

Hypothesis 4: Supporting space for ideation

Ideation activities regarding the design of products manufactured with AM are supported by spaces allowing the creation of intermediate representations of the solutions.

Design thinking propagates that, especially, space can modify the designers' intrinsic motivation and enhance their creativity, c.f. Sec. 2.2. Therefore, several authors, e.g. Heck (2017), propose to carry out ideation activities in external spaces that allow designers to escape from daily business, provide supporting facilities like catering. Creativity is also encouraged by supporting visualisation and prototyping of intermediate objects. Thus, divergent thinking (abstraction of problem, generation ideas) can be supported by an open environment (Rias et al., 2017).

Hypothesis 5: Release of development resources

The implementation of AM in design processes requires at least initially more development resources compared to the development of conventionally manufactured products.

Nowadays, as AM is not established in design processes, the exploitation of AM potentials is not possible entirely. In order to change that, additional development resources for initial training, idea generation and prototyping (trial and error) are necessary. An approach for the release of the necessary resources can be supported by makerspaces. The idea of makerspaces is to provide individuals with design software, manufacturing tools that are generally not available for non-professional users and the necessary knowledge through trained personnel (Wilczynski et al., 2015). Thus, designers of companies can be allowed to spent time in those environments to generate new ideas besides the daily business.

Hypothesis 6: Work in interdisciplinary teams

AM ideation is enhanced by the interdisciplinary teamwork of stakeholders (designer, manufacturer, product user, etc.) with different knowledge background and personality characteristics.

Ideation in teams can enhance both the available knowledge about customer wishes, neighbouring systems, manufacturing requirements, boundary conditions etc. as well as the diversity of personality characteristics. Therefore, design thinking proposes to carry out ideation in interdisciplinary teams. For the conceptualisation of products considering AM several authors highlight the advantage of collaborative design between designers and other stakeholders to share their knowledge and expertise (Laverne et al., 2016; Rias et al., 2017).

5. Ideation workshops for addressing design

In order to put the hypotheses of Sec. 4 into practice, a concept for ideation workshops was developed that can be implemented to design tasks in companies. In this section, at first, the objectives of these workshops will be outlined, before the procedure and applied methods and tools are described. In the last section, experience from workshop execution will be summarised.

5.1. Objective of ideation workshops

Traditional approaches describe the design process in phases from the clarification of the task (abstract problem model) until preparation of complete documentation of the product (concrete solution model), see Sec. 2.1. The focus of the ideation workshops lies within the general process of problem solving in the first and second step. Therefore, the conducted activities comprise activities to

- describe the problem in abstract product models (H3),
- diverge the problem space by reassessing the problem (H2) and
- generate possible solutions inspired by AM solution principles (H1).

The starting points for workshops are conventionally manufactured products. Objective is to carry out the above mentioned activities to develop a number of alternative solutions to be manufactured additively. A further evaluation and concretisation of these concepts is not part of the workshops, but is planned for subsequent steps.

5.2. Procedure and applied methods and tools

The workshops are divided into the three phases: *abstraction of the problem*, *goal setting* and *ideation by inspiration* (see Fig. 2). To explain the used methods and tools within these three phases, an example from the automotive industry will be explained, on that the workshop concept was applied. The goal of this workshop was the redesign of an air breather (see Fig. 2) by considering neighbouring systems, for instance, the charging socket and windscreen washer reservoir, and realise additional functions, for instance, the integration of sensors for the park distance control. Therefore, an interdisciplinary team of eight people from several departments (embodiment, aerodynamics, acoustics, industrial design etc.) are brought together for 2.5 hours into an external workspace (c.f. H4, H5 and H6).

Within the first step, the predecessor product of the air breather is abstracted by describing its functions in a function structure, c.f. H3. By means of the abstract problem formulation, the access to AM capabilities and the extension of the problem space and therefore the consideration of neighbouring systems is facilitated (e.g. for functional integration).

In the second phase, the problem formulation forces a wider goal setting, c.f. H2. The goal setting is supported by a *potential model* containing several areas of product properties that can be addressed by AM, like weight, size, functionality as well as production costs and process durations. In case of the air breather, the improvement of the aerodynamic performance, the reduction of design space, and the minimisation of number of parts are primarily focussed.

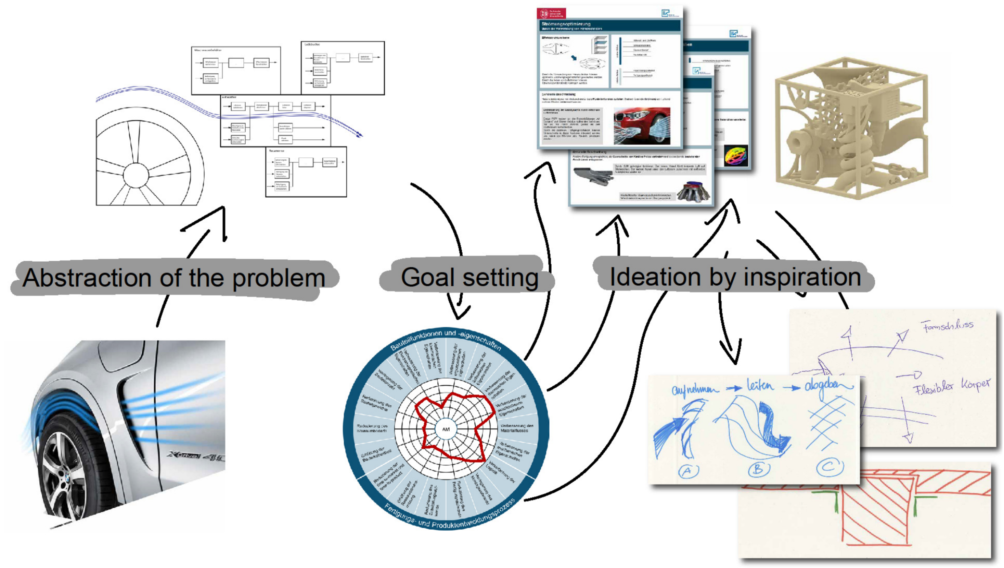

Figure 2. Procedure of the ideation workshop

Based on this, a goal-oriented identification of suitable AM solution principles is conducted, c.f. H1. To shape the ideation process in regard to AM, the ideation is supported by solution principle cards on paper and related additively manufactured illustrative models. The principle cards show AM-specific solution principles, for instance, the improvement of the aerodynamic performance with internal shape optimised channels. An assignment to the goals of the potential model helps to systematically access appropriate solution principles. The illustrative models encourage inspiration by a haptic interaction and support the understanding of the solution principles by demonstrating the capabilities.

As a result, the participants generated ideas, for instance, for a minimisation of part numbers and the integration of sensors. Due to the reduction of design space, the aerodynamic performance could be improved by a maximisation of the height of the air breather. Moreover, concepts for improvements in design were developed, for instance, with an adaptive design that morphs depending on driving speed between a maximal aerodynamic performance and an optimal aesthetic appearance.

5.3. Experience and further research

The workshop concept shows how to generate alternative concepts for redesigning conventionally manufactured products for AM with improved product properties. It was noticed that the abstract model of the product facilitated the consideration of neighbouring systems and the extension of the problem space. This lays the basis for the access to and utilisation of AM potentials. In addition, the combination of general design methods and AM-specific tools like solution principle cards and illustrative models could systematically support the ideation.

Based on the workshop results, further workshops for detailing the air breather concepts are planned. Finally, selected designs will be manufactured and tested. The identification of appropriate products for the redesign with AM in a workshop like it is described above is a challenging task. Therefore, in order to support and to automatise the selection process a fuzzy logic will be developed. Thus, the application of AM-specific solution principles will also be facilitated.

6. Conclusions

This paper was motivated by the increasing importance of AM becoming more and more a viable alternative to conventional manufacturing for end-use products. However, often designers do not consider the capabilities of AM sufficiently. Thus, potentials remain untapped. The aim of the research presented was to enable companies from traditional industries to implement AM into their established design processes.

Therefore, towards understanding current challenges (RQ1), it was shown that three main hindering factors delay and/or restrain the exploitation of potentials of AM. These are, first, *a lack of knowledge*,

second, *restrained creativity*, and third, *processual barriers*. In order to overcome these barriers (RQ2), six hypotheses were postulated. Three of these hypotheses are focussing the ideation activities, and support a *systematic reassessment of the problem definition* and the *use of product models* to enhance abstract thinking. Therefore, it is possible to provide *AM solution principles* appropriately. Three further hypotheses call for *supporting spaces for ideation*, the *release of additional development resources* and *collaboration in interdisciplinary teams*. Finally, an approach was demonstrated on how these hypotheses can be implemented into a company by executing workshops (RQ3). The workshop concept comprises three phases starting with the abstraction of design tasks, followed by the goal setting for redesigning products and, finally, the ideation with inspiration of AM solution principles.
Overall, the presented paper gives insights into the design practice in industry and proposes an approach to overcome barriers that are often neglected when AM is introduced to companies. The results can be implemented beneficially to other methodical approaches as well as design processes in practice. The hypotheses provide a general basis for transferring the key claims of this paper, although further effort need to be invested to test the hypotheses in various contexts. So far, an application only was executed in few workshops. The results were described in this paper in brief. Therefore, further workshops are planned, which will contribute to a comprehensive evaluation, based on long-term experience.

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