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A METHODICAL APPROACH TO SUPPORT IDEATION FOR ADDITIVE MANUFACTURING IN DESIGN EDUCATION

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Abstract

Additive manufacturing (AM) is a relatively new technology which opens the door to many new design possibilities for end-use products. However, many design engineers often are not familiar with the potentials of AM and therefore do not take advantage of them in the product development process. To overcome barriers in generation of new ideas caused by the limitations of conventional manufacturing processes particularly in the ideation stage, new design methods and tools are needed. Therefore, students as well as non-experts of AM have to be assisted to fully exploit the newly opened design potentials. This paper provides a methodical approach to enrich general design methods for ideation with AM knowledge for ensuring a user tailored support. Combinations between various methods to assist the ideation process are proposed based on the analysis of general ideation methods and existing AM-specific tools which consider potentials as well as limitations of AM. Subsequently, one of these combinations is utilized in an academic workshop and evaluated by the participants. Finally, the results of the evaluation are discussed.

Keywords: Additive Manufacturing, Design for Additive Manufacturing (DfAM), Design education, Case study

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1 INTRODUCTION

Since the further development of additive manufacturing processes and the enhancement of available materials, additive manufacturing (AM) has progressed from applications in prototyping to the facilitation of end-use product production. Compared to conventional manufacturing processes, e.g. milling or cutting, AM enables a greater design freedom in regard to the complexity, which can be achieved in part production. Because AM is a relatively new technology, AM novices and students, in particular, require a methodological guidance as well as knowledge provision to assess and systematically utilize the AM's realistic potentials. The properties of additive manufacturing processes, the tool-less working principle and the layer-wise material deposition, all result in new design potentials. This, for example, can be used to create lightweight designs inspired from bionics, hierarchical structures, part consolidation, or mass customization (Rosen, 2014, Gibson et al., 2015). Due to these new design freedoms, AM should be considered as an extension to conventional manufacturing processes in product development and, therefore, also in design education. Especially within the conceptual design stage, design engineers have to develop new ways of thinking to overcome the thought barriers which result from the habits of designing products for traditional manufacturing methods. For example, using techniques from Design for Manufacturing and Assembly in regard to additive manufacturing will limit the design characteristics of an end-product which will fail to fully exploit AM's design potential. AM-specific design education is a key factor in achieving this objective (Gao et al., 2015, Thompson et al., 2016). Therefore, inspired by the term "design for manufacturing" (DFM), supporting methods "to maximize product performance" (Gibson et al., 2015) are summarized under the term Design for Additive Manufacturing (DfAM). Different DfAM approaches have been developed to consider both potentials and limitations of additive manufacturing. Opportunistic DfAM methods aim at the exploration of the new design possibilities while restrictive DfAM methods focus on the limitations of AM processes (Laverne et al., 2015, Laverne et al., 2016).
The main objective of this paper is the identification of requirements on DfAM methods for AM novices, e.g. in design education, focussing on general design methods and their possibility to integrate specific AM-knowledge. Based on these requirements, different method combinations of general design methods and DfAM methods are introduced. For illustration purpose, one of the deduced method combinations is presented more detailed and applied in an academic workshop to generate AM-adapted solution ideas for a design task. Finally, the results of the application are evaluated and discussed.

2 STATE OF THE ART

Before deducing the research gap in Section 2.5 and setting up research questions, fundamentals of design methods focusing on ideation methods are presented with the aim to develop new solutions. Subsequently, potentials and limitations of Design for Additive Manufacturing are introduced. Different approaches as well as methods and tools which aim to provide DfAM knowledge are described. In addition, a general view on teaching within design education and the relevance of various media combinations conclude this chapter on the state of the art. The last section elaborates these ideas and formulates the research gap with a focus on design education in the field of DfAM.

2.1 Ideation methods for developing solution ideas in engineering design

In engineering design as well as in the design education, design methods and creative techniques or methods for ideation are an important element supporting the work of engineers. Following a systematic design approach from task clarification, principal solution development, to the embodiment design and finally the detail design, methods can be applied at each phase to support the product development process (e.g. VDI, 1993, Lindemann, 2009, Pahl and Beitz, 2013). In the context of teaching DfAM knowledge, it is necessary to focus the topic as early as possible in the design process. Hence, the results of the corresponding design stage rely heavily upon conceptual design and ideation methods. In this context, a method provides an operatively applicable thinking and behavioral pattern to achieve a goal. Other authors define a method as a goal-oriented procedure in which the outcome is left open (Lindemann, 2009). However, a method serves to guide the user through a step-by-step procedure to achieve the goal. There are various methods for different goals; therefore, it is helpful to classify methods based upon their respective aims. A possible classification system places methods into the categories of: analysis methods, ideation/solution finding methods, evaluation methods and cost & economic methods as proposed e.g. in VDI guideline 2221 (VDI, 1993). As the paper focuses on the conceptual design stage and thus on ideation methods, another classification of methods that serves to generate solutions is presented. These can be distinguished between intuitive and discursive methods (Pahl and Beitz, 2013). Discursive methods divide a task into sub-tasks in order to simplify the solution generation. Intuitive methods try to solve the problem or task in one single step. This is mostly done through the intuition of the product developers. Other disciplines, like design, commonly include intuitive methods. This contribution mainly deals with intuitive methods for ideation to enrich these methods with AM knowledge.

2.2 Potentials and limitations of additive manufacturing

The potentials that AM enables can be categorized into shape complexity, hierarchical complexity, functional complexity and material complexity (Rosen, 2014, Gibson et al., 2015). Shape complexity describes the higher degree of forms, shapes, and customized geometries which can be applied to parts and are therefore easier to produce through AM processes. This could, for example, include an integration of cooling chambers or light-weight structures which increase the performance of a particular part. Similarly, light weight structures could utilize lattice structures with varying size and density to achieve weight-savings or satisfy varied tensile requirements in a product. These structures can include microstructures within the micrometer range to macrostructure with dimensions in the centimeter range. This variation in size and number of particular geometrical structures is known as hierarchical complexity. Furthermore, the ability to integrate unbound components can be integrated, adding mechanical functionality to a product. For example, a fully functional ball bearing can be produced with individual bearings and casing elements through AM processes. Due AM's layer-by-layer process, multiple material compositions can be implemented in varying degrees to achieve an optimal combination between stiffness and flexibility. This layer-by-layer production further allows a higher level of material complexity to be reached through the production of parts with both hard and soft thermoplastics.

On the other hand, different authors (e.g. Lindemann et al., 2013, Gao et al., 2015, Gibson et al., 2015) present numerous limitations for additive manufacturing. The slow production speeds of AM are one limiting factor, especially in relation to high volume production. Although build rates between various AM-machines will vary based on the material and part geometry, they generally tend to be slow in comparison to traditional manufacturing techniques. Additionally, the material choices for additive manufacturing processes are limited and can be more expensive (especially metals) in comparison. Furthermore, maximum part geometries are constrained to the build chambers of the particular AM process and machine in use. The capabilities of AM-machines also play a role in the surface roughness or qualities of final parts. Again, due to the layer-by-layer working principle of AM, smooth surface textures are difficult to achieve and result in the need for post-processing. Poor surface qualities are demonstrated by the "staircase effect" which describes the results from the additively manufacturing or curved surfaces. Sanding and polishing must be used to smooth out the stairs that occur. Lastly, AM technologies show inconsistencies in precision, especially with small geometries, which causes problems in quality and reproducibility.

2.3 Existing methods and tools in design for additive manufacturing

The term "Design for Additive Manufacturing" (DfAM) was developed based on the ideas of "Design for Manufacturing" (DFM) and "Design for Assembly" (DFA), which are often discussed in context of one another as "Design for Manufacturing and Assembly" (DFMA). The main objective of DFMA operations is to "eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs" (Gibson et al., 2015). In relation to AM, the barriers laid out by conventional design rules of DFMA are broken down and new design opportunities are revealed. In order to harness these new opportunities to the fullest potential, new design process approaches and design practices are necessary (Thompson et al., 2016). DfAM research presents different approaches, methods, and tools to consider the new design potentials as well as the limitations in relation to the product development process (Laverne et al., 2015). Additionally, Tang and Zhao (2016) distinguish methods which provide a general guidance (necessary for non-experts of AM) and consider both multiple and individual objectives. On the one hand, the so-called opportunistic DfAM methods and tools aim at a systematically exploitation of the new freedom in design. On the other hand, restrictive DfAM supports the fulfillment of design rules and ensures manufacturability.

2.3.1 Opportunistic DfAM approaches

Opportunistically driven methods and tools range from checklists with general recommendations for the utilization of AM´s design possibilities to modified design methods which support the generation of creative solution ideas. Bin Maidin et al. (2012) developed a DfAM Design Feature Database, which contains and categorizes AM-specific design solutions considering different goals. This database supports design engineers in the development of basic solution ideas by providing a goal-oriented access to different design features. Furthermore, Laverne et al. (2016) propose a method for developing innovative solutions through the provision of a procedure model and tailored AM knowledge. In creativity workshops, sort, amount, and point-in-time within the product development process are evaluated with regard to the quality of the results. They point out the importance of specific AM-knowledge for creativity, especially in the early design stages. Another approach for representing new design potentials enabled by AM is provided by Watschke et al. (2016). They developed physical AM-models with different additive manufactured components that present examples of the numerous design features that are possible. Additionally, AM-novices can be inspired and supported in developing AM-adapted solution ideas by physically interacting with example models (see Figure 1). In addition, a catalogue-system provides more detailed information about the displayed design features and their resulting benefits.

2.3.2 Restrictive DfAM approaches

Although there are many design opportunities offered by AM, there are limitations which need to be considered. Restrictive DfAM subsumes general design guidelines, e.g. part orientation to avoid support structures or reduce surface roughness as well as more specific quantitative design rules, for example minimal hole diameters or wall thickness. A number of research institutions investigate process and material specific design rules inter alia for Fused Layer Modeling, laser sintering, and laser beam melting (Adam and Zimmer, 2014, Kranz et al. 2015). The results of this research has partly been transferred into guidelines such as the VDI 3405 Part 3 (VDI, 2015). Kumke et al. (2016) further categorize different published design rules, deduced general process-specific guide values and prepared the knowledge in an interactive system. Furthermore, Lindemann et al. (2015) developed a two steps system with a so called Trade-Off-Matrix that supports product developers in evaluating and identifying promising part candidates for an AM-redesign. Parts can be evaluated based on analyzed key and Knock-Out criteria, for example, size limitations based on a machine's build chamber, the necessary post-processing effort or the estimated material consumption. Additionally, a worksheet developed specifically for AM-novices to avoid manufacturing failures is proposed by Booth et al. (2016). The worksheet is divided into eight weighted categories like complexity, functionality, tolerances, and geometric exactness and evaluates the manufacturability as well as it recommends a possible redesign or a change of manufacturing process.

2.3.3 Combined DfAM approaches

Further DfAM research combines these above approaches with a procedural model which supports and provides guidance for the development of AM-adapted products with both opportunistic and restrictive methods and tools. This model is based on the general product development process of VDI Guideline 2221 Kumke et al. (2016) developed as a methodological framework that integrates existing opportunistic as well as restrictive DfAM methods. The proposed framework facilitates a systematic AM-specific product development independent of specific design goals and industrial sectors. In addition, the modular approach of this framework enables the integration of AM-specific methods and tools as well as general design methods, e.g. for ideation, and connects them within a holistic procedure. Yang and Zhao (2015) proposed a design method for developing redesigned structures that focus on both on function integration and structure optimization by considering AM-specific process constraints as well as design specifications.

2.4 The role of different media in design education

As the focus in this paper is laid on providing DfAM knowledge within design education, it is fruitful to consider the different modes of (physical) media which support the transfer of knowledge. Dealing with additive manufacturing techniques along with their respective opportunities and challenges, physical models can supplement the presentation of necessary knowledge through classic media forms like texts, pictures, and animations. The question remains, however, which medium is the one that presents AM knowledge and illustrates its advantages best. According to Recker et al. (1995), research focused on this topic rather concludes contradictory results. The research has shown that one media form's superiority over another's cannot be shown, which implies that there are various factors that play an influence on students' learning process. Possible influencing factors may stem from relevant background knowledge, a students' motivation and interests as well as their learning strategies and goals (Recker et al., 1995). Hence, research in this field focuses rather on the learner than on the media itself (Mayer, 2003).

Within university context, the student diversity can be quite high, thus resulting in a varied preference for learning media. It can therefore be assumed that the use of various media forms improves the knowledge transfer to the students. This assumption is based on the Vester's theory concerning different learners or learning types. Vester (1998) distinguishes between a visual, an auditory, a haptic and an intellectual learner. There is not a strict distinction between learning types, but rather a spectrum between them. Concerning this, the proposition to use different media forms to transfer knowledge would appeal to a variety of learning types. The media considered for this contribution is defined by the methods and tools that already exist and were introduced in chapter 2.3. The knowledge on additive manufacturing is represented via texts, pictures and images in an analogous or digital format. Some media, like models (digital and physical) or databases, can provide interactive elements which allow a more detailed examination and an intellectual learning.

2.5 Research methodology

As mentioned, since AM is a relatively new technology, there is a strong deficit of knowledge about the subject area. Therefore, DfAM methods and tools have to be introduced and taught during design education to fully explore the new design freedoms and to consider AM as an extension to conventional manufacturing processes in product development. By introducing the appropriate knowledge at the qualification stages for new engineers, thought barriers caused by the traditional fundamental knowledge in design education can be overcome. In addition, existing and established products and technologies normally affect engineers in practice. New mindsets in product design and an openness for the design opportunities of new manufacturing processes result in a systematic investigation and implementation of the design and optimization potentials. Thus, new methods and tools are needed for an appropriate design education. A combination of existing general design methods enriched by AM-specific knowledge could be a promising approach for novices to take AM's design potentials into account. The following research questions are investigated:

1. Which requirements should DfAM methods for design education fulfill?
2. How can AM design potentials and limitations be provided to AM novices in education?
3. Which methods or combinations of methods, media, and AM knowledge are appropriate for improving the utilization of AM in the product development especially for AM novices?

The contribution tries to answer the research questions by proposing a first methodical approach to support ideation for AM in design education. Therefore, requirements of DfAM methods for AM novices are deduced in Section 3 as they are related to question 1. Subsequently, different combinations of general ideation methods and various representation media for AM knowledge are presented in Section 4.1. For illustration, a method combination is then evaluated in a workshop within an academic setting (Section 4.2), and the results are discussed regarding research questions 2 and 3 (Section 4.3).

3 REQUIREMENTS FOR ADDITIVE MANUFACTURING METHODS

Analyzing and deducing requirements for DfAM methods is the aim of this section in relevance to the first research question. It is assumed that the classic methods for ideation presented in 2.1 require fundamentally similar or even the same conditions and knowledge as specific DfAM methods used in the conceptual design stages. The additional challenge of the later methods included the consideration of the potentials and limitations for novices to AM. To deal with this challenge, the focus is laid on the combination of various media during application of the method. In the following, existing methods and tools for ideation as well as for DfAM are analyzed and used to deduce the requirements for teaching knowledge to enhance ideation methods as they relate to AM product design.

3.1 Analysis of ideation and AM-specific methods and tools

There are a number of ideation methods which fulfill most of the above mentioned requirements. Hence, those methods were analyzed regarding their suitability to integrate specific AM-knowledge (see Table 1). The criteria were evaluated using a three-point scale from "fully fulfilled" to "not fulfilled." Hereby, "partly fulfilled" means there need to be modifications or there are restrictions for the fulfillment. Part of the analysis reviewed the flexibility of each method in the predefined structure; that is to say, the degree of flexibility to change the structure or the procedure of the method without compromising its final goals was reviewed. The ways each method/tool is perceived during its application was also considered to help identify gaps or suitable supplementary media. The main portion of this analysis reviews the possibility to integrate AM-knowledge. For each method, a suitable adaption was developed and evaluated with concern for the integration quality and simplicity (general integration). As an example, Brainstorming only allows a medium level of integration (Table 1). This results from the idea that knowledge has to be provided during the whole process or in an additional step which would cause a disruption in the ideation phase. Another example is the Reizbild method in which AM-specific pictures can be integrated with little effort resulting in a high mark within the "general integration" category.

Table 1. Excerpt of analysed ideation methods regarding the integration of AM-knowledge

	Required Method Knowledge	Flexibility of Predefined Structure of Method	Perception within Ideation (based on types of learner)			General Integration Possibilities of AM Knowledge	Time or Way of Integration	Suitable Media for Knowledge Integration		
			Haptic	Visual	Auditory			Analog	Digital	Interactive
Brainstorming	low	◒	○	◒	●	◒	simultaneously to Method or Break	●	◒	◒
Method 635	medium	○	○	●	○	◒	simultaneously to Method or Break	●	○	○
Synectics	high	○	○	◒	●	●	during/before Force Fit phase	●	◒	◒
Reizbild	low	●	○	●	○	●	adding AM pictures	●	●	○
Gallery Method	medium	◒	○	●	●	◒	proposing during ideation phase	●	◒	◒
Six Thinking Hats	medium	●	○	◒	●	●	including or changing a hat	●	◒	◒
Disney Method	medium	●	○	◒	●	●	potentials as dreamer, limitations as critic	●	◒	◒
Legend	low, medium, high					● fully fulfilled ◒ partly fulfilled ○ not fulfilled				

The next step of the analysis is the evaluation of the AM-specific methods and tools described in Section 2.3. Again, the aim is to deduce requirements for how to present the knowledge in a design educational context. Table 2 presents an excerpt of the analysis, starting with a classification concerning the representation of potentials and limitations within the individual methods and tools.

Table 2. Excerpt of analysed DfAM methods and tools

	AM-Potentials	AM-Limitations	Perception		Media		
			Haptic	Visual	Analog	Digital	Interactive
Physical AM-Models *Watschke et al. (2016)*	●	◒	●	○	●	○	●
Interactive design rule catalogue-system *Kumke et al. (2016)*	○	●	○	●	○	●	●
DfAM Design Feature Database *Bin Maidin et al. (2012)*	●	◒	○	●	○	●	●
Design Rules *Adam & Zimmer (2014), Kranz et al. (2015)*	○	●	○	●	●	○	○
Design Guidelines *VDI (2015)*	◒	●	○	●	●	○	○
Trade-Off-Matrix *Lindemann et al. (2015)*	◒	●	○	●	●	○	○
Support Tool *Laverne et al. (2016)*	●	◒	○	●	○	●	◒
DfAM worksheet *Booth et al. (2016)*	○	●	○	●	●	○	○
Legend	AM-Potentials	AM-Limitations	● fully fulfilled ◒ partly fulfilled ○ not fulfilled				

The way of perception and the used media type are also considered. For example, physical AM-Models as presented by Watschke et al. (2016) can represent the potentials of AM, but the limitations are only approached partly. The user can perceive the knowledge haptically and visualy by directly interacting with the physical models. The Support Tool by Laverne et al. (2016) is a digital tool which allows less direct interaction and only is a visual representation of the AM potentials. The possibility to display potentials and limitations is similar to the models presented by Watschke et al. (2016).

3.2 Deduction of requirements in the context of design education

As previously considered, the right combination of media for the purposes of teaching has a heavy impact on the uptake of information. Thus, the AM development methods or the combination of these methods should contain elements that address different types of learners. Therefore, the involvement of auditory, visual, and haptic elements is preferred. Independent of the method, moderators should accompany the method's application to allow users to focus on the ideation process rather than on how to apply the method itself. General elements of methods for ideation are a direct result of team diversity and creativity. Thus, the team should be interdisciplinary and diverse to generate a greater range of ideas. To yield a productive creativity session, a level of discipline and structure is necessary to keep the group focused on the end goals. The aforementioned moderator provides this structure. Furthermore, the setting in which the creative session occurs would augment creativity through the integration of flexible elements and possibilities to easily write down and structure ideas or to build up first concept models. All of the ideation methods presented in Table 1 contain the main elements that support creativity. The team composition that is proposed by the moderator is also generally applicable for ideation methods and the subsequent method combinations to develop. The AM tools and methods described above mainly provide knowledge; thus, they can be integrated into ideation methods to enhance the solution generation while laying a focus on AM driven solutions. Based on the analysis of the methods in Table 2, possible combinations can be selected to create new AM specific ideation methods that bring together advantages of different methods and tools. Ideation methods can offer a procedural structure while the AM tools and methods deliver the necessary knowledge for the appropriate solution generation.

4 DFAM METHOD COMBINATION

Based on the results of Section 3, method combinations for optimal ideation considering DfAM prepared especially for AM novices and students in design education may now be built. For illustrating the integration of AM knowledge into an ideation method, one of the method combinations is presented in detail and applied in a workshop setting (Section 4.2). However, further combinations are mentioned but not discussed in detail.

4.1 General development of method combinations

The procedure to identify suitable combinations starts with the analysis of the ideation methods and their opportunity to integrate AM knowledge or AM tools. As presented in Section 3, the Synectics, Reizbild, Six Thinking Hats, and Disney Methods were suited best to enhance the original method procedure. Each of these methods can be enriched with opportunistic AM knowledge, for example, the combination of the Six Thinking Hats and Disney Methods allows the integration of AM limitations, which results from the steps that include the critical consideration of the previously developed ideas. For example, the critique phase in the Disney Method can be supported with restrictive AM knowledge. However, during the ideation stage, the additional provision of DfAM tools could become overwhelming for AM novices as it may be too much information to process. Synectics, in particular, helps to formulate the problem statement in different levels of abstraction. Due to focus on the main problems, the transfer and integration of AM knowledge is facilitated. Furthermore, Synectics, with its three phases for problem analysis, analogy finding, and solution development, forms the framework for the integration of e.g. the AM-Models that are shown in Figure 1.

The Reizbild method, a method to inspire participants of the ideation method by showing a number of images from different fields, supports the finding of analogies. To shape the ideation process in regard to AM, a slide show can be presented with general pictures (showing nature, e.g.) and AM-specific design opportunities (e.g. bionic light-weight and internal lattice structures). Finally, during the development of solution ideas, the physical AM-Models can be used to haptically and visually demonstrate the new design opportunities for AM novices in particular. Along with the selection of design potentials, the models also present limitations, for example, the resultant surface roughness or feature sizes. The additional catalogue system contains a description of the displayed design features and allows a goal-orientation through an allocation of design objectives.

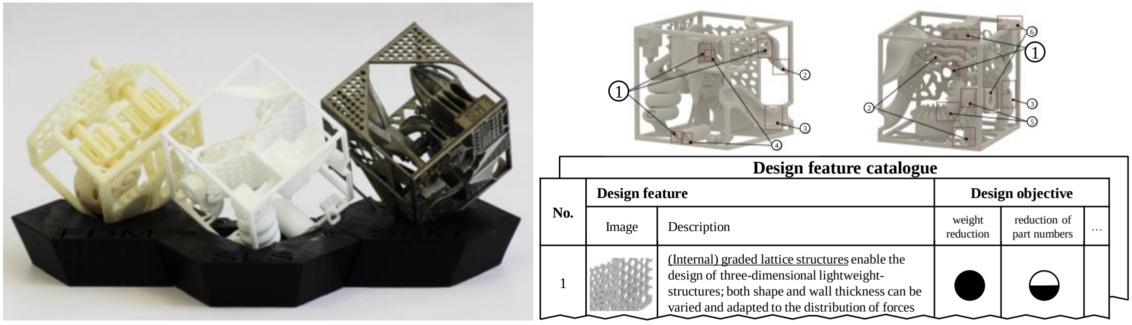

Figure 1. Physical AM-Models with the design feature catalogue

Furthermore, several other ideation-method combinations and DfAM tools are possible. As described above, the Six Thinking Hats and Disney Method can be enriched with restrictive AM knowledge to not only allow the user to generate ideas, but to also allow them to evaluate these ideas in regard to the final production capabilities of AM processes. Therefore, a design rule catalogue or interactive system (cf. Kumke et al., 2016) would be suitable for such integration. The Design Feature Database developed by Bin Maidin et al. (2012) could supplement the physical AM-Models in ideation for users who are more familiar with AM design potentials. This would be particularly appropriate since this tool could be expanded to contain more detailed design features and provide goal-oriented feature identification, but would require no haptic interaction as the users would be familiar with AM production possibilities.

4.2 Application of an exemplary method combination

The final portions of this research project intend to show how to present AM knowledge to non-experts of AM with regard to design education and to the suitability of a method combination derived above. The combination of Synectics and Reizbild along with the physical AM-Models was carried out because Synectics helps to divide the problem into less complex sub problems and therefore build a framework for the integration of the specific opportunistic AM knowledge provided by the AM-Models. In addition, the combination of Synectics and Reizbild method facilitate the ideation, in particular for bionic design, due to abstraction, analogy and inspiration, which was very fitting concerning the design task.

The application was done in an academic setting at the Institute for Engineering Design at the Technische Universität Braunschweig. Seven participants with little and advanced experiences in engineering design from various technical backgrounds (automotive engineering, mechanical engineering and design) took part. Two additional people served as moderators to keep the Synectics session structured and focused on the end task and goals. The workshop lasted 1.5 hours with the first 20 minutes being dedicated to an introduction of the creative techniques. The introduction included a video tutorial of how Synectics can be used to generate roundabout solutions which was followed by a discussion of the time table, the goals and tasks for the workshop. The workshop was divided into the three Synectics phases: first phase "identification and definition of problem", second phase "disassociation from the problem through analogies" and third phase "solution generation" (Figure 2).

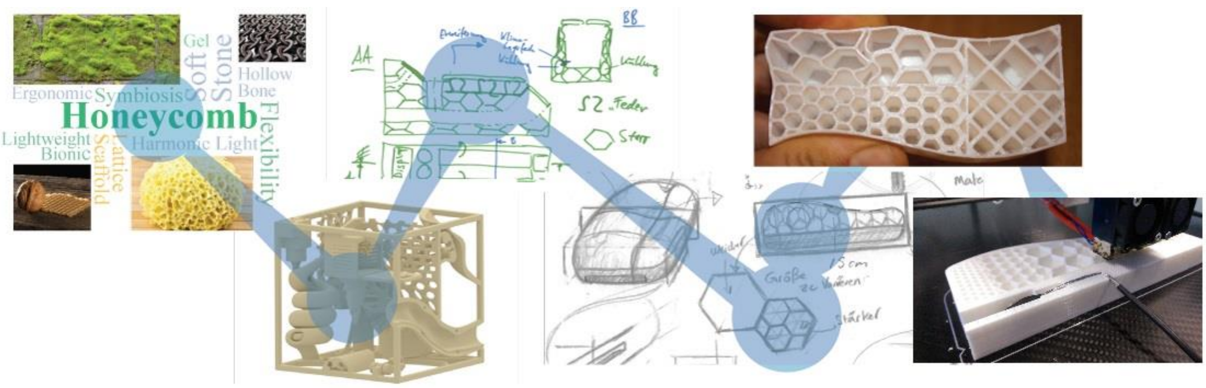

Figure 2. Ideation-process from the workshop up through solution implementation

The goal of this workshop was the modification and redesign of an armrest to improve comfort along with adding functionality. Within the second phase of the workshop, the Reizbild was used to provide participants with inspiration from nature and from AM relevant technologies through a slide show presentation of images. Examples of such images can be seen in the upper left area of Figure 2 along with a selection of the generated analogies.

Based on these images, participants generated analogies from nature as well as technical and personal areas. Finally, the participants were asked to adapt these analogies onto technical solutions based on the initial problem statement. During this phase, participants were allowed to interact with the AM-Models that help to systematically depict AM's design potentials. One result from this workshop was a flexible graded honeycomb structure which is divided into softer and stiffer areas; this was achieved through a variation in form and wall thickness to facilitate the individual passive adaption of the armrest's shape to a user's arm. In addition, the integration of electrical functionality was implemented with a smartphone docking area. A test model was designed, based on the resulting ideas of the workshop.

4.3 Evaluation and discussion

An evaluation questionnaire of the workshop was requested of the participants. Participants answered questions about their design and AM experiences. This was done to gain insight for the postulated research questions of Section 2.5; these are concerned with "how AM's potentials and limitations can be support AM novices in design education?" and "which methods or combinations of methods, media, and AM knowledge are appropriate for improving the utilization of additive manufacturing in the product development especially for AM novices?" The general feedback of the survey was positive referring to the suggested combination of general well-known design methods and both AM-specific tools and knowledge by 7 of 7 participants. Thus, all participants were able to produce useful results during the workshop. The non-experts of AM mentioned the inspirational ideation supported by interaction with the physical AM models in particular. However, due to the necessary familiarization period in the introduction, there was not enough time to investigate all of the represented design features. As for the third phase of Synectics, 4 of 7 participants stated they would have preferred additional knowledge about AM's general limitations to better transfer the ideas into technical solutions. On the contrary, only 2 participants asked for more knowledge about design potentials.

The selected combination of the design methods Synectics and Reizbild was also rated as positive by 5 of 7 participants. The method's video introduction (7 of 7) and the visual support through inspiration images (5 of 7) were highly favored. However, some participants noted some concerns with regard to the tight time line of the workshop and along with the quantity of images per time that were provided. Furthermore, the interdisciplinary team composition of AM experts and non-experts was appreciated in relation to a creative working atmosphere. Since a greater portion of the participant were non-experts of AM, the integration of DfAM methods and tools into design education was required.

In summary, through the combination of methods with AM-tools and knowledge, here Synectics and Reizbild method with AM-Models, innovative ideas and interesting solutions were generated more quickly, which maybe would not have been possible without this mix of ideation methods supported by tailored AM-specific knowledge. However, the evaluation results are based on a single case study with a single method combination, so that this method combination could only be investigated in relation to one team and one task. In addition, the time for ideation and utilizing the AM-Models was strictly limited. Especially for the participants that are unaware of DfAM, a general introduction into the unique capabilities of AM and the specific tools would be useful to improve the created solution ideas.

5 CONCLUSION AND FUTURE RESEARCH

In this paper, a methodical approach to support ideation for additive manufacturing, especially in design education, is proposed. Based on the previous research of ideation methods as well as different DfAM methods and tools, requirements for DfAM methods are deduced focusing on design education for AM novices. For illustration, a method combination was applied in an academic workshop to investigate the potential of developing new and more innovative solutions. The workshop results showed that a combination of general design methods and DfAM methods enable even non-experts of AM to consider AM-specific design potentials in ideation. However, to transfer solution ideas to detail design both general experiences in design and additional knowledge about AM limitations are needed.

In future research, further workshops will be carried out and other method combinations (in particular with restrictive AM knowledge) will be investigated to confirm these evaluation findings. Subsequently, the method combinations will be transferred into the industry to analyze the acceptance of their utilization and effects on an AM-adapted product development. Finally, application specific method sets could be developed to support the consideration of both AM-specific design potentials and limitations in product design as well as the establishment of additive manufacturing processes.

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