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Providing a knowledge-based design catalog as an approach to support the development of design for additive manufacturing skills

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Abstract

Proficiency in design for additive manufacturing (DfAM) requires training and a lot of trial and error. To support the development of DfAM skills, we redesigned 47 design artifacts from case studies and derived tacit knowledge from successful and unsuccessful redesigns. All knowledge about these artifacts was then collected in a design catalog. In a workshop with a total of 48 graduates and students, 45 participants deemed the design catalog supportive. After evaluating their designs, we concluded that the use of a knowledge-based design catalog can develop and improve individual DfAM skills.

Keywords: additive manufacturing, design for x (DfX), design knowledge, early design phase, design catalogue

1. Introduction

In the context of advanced manufacturing, additive manufacturing technologies offer the opportunity to improve existing products or even create entirely new ones. As a result, for example, we can design and manufacture more complex products that also have a reduced impact on the environment (Laverne et al., 2019).

As additive manufacturing (AM) becomes more common in design, engineering, and manufacturing, there is an increasing need for a workforce with design for additive manufacturing (DfAM) skills (Prabhu et al., 2021). These skills need to be developed and nurtured over time, reflecting lessons learned from successful product designs and design processes. It is critical to continuously incorporate these learnings into the training of our future workforce, improving their DfAM skills and maximizing the benefit of additively manufactured products.

According to design educators and researchers, future generations' comprehension of DfAM content, such as design principles and design heuristics may be the key to improving DfAM skills and maximizing the potential of additive manufacturing (Rosen et al., 2015; Blösch-Paidosh and Shea, 2022; Borgianni et al., 2022; Thomas-Seale et al., 2022). Given the benefits of simultaneously providing opportunistic and restrictive DfAM content in an early design phase (Prabhu et al., 2021), our AM-community needs an approach to provide and share DfAM knowledge, particularly to include design-specific knowledge on AM products (Schaechtl et al., 2023).

There are several ways to provide DfAM content for an early design phase: For example, Blösch-Paidosh and Shea (2022) offer design heuristics, Bin Maidin et al. (2012), Perez et al. (2015), Lauff et al. (2019), and Valjak and Bojčetić (2019) established design principles, and Weiss et al. (2016), Kuschmitz et al. (2019), Schumacher et al. (2019), Watschke et al. (2019) and Garrelts et al. (2021) provide collections of additively manufactured artifacts. What has always been missing is either the constraint-based knowledge or the tacit knowledge gained during the design process of additively manufactured artifacts. Borgue et al. (2019) provide a constraint replacement-based approach for design for additive manufacturing, but do not explicitly represent the potentials of additive manufacturing. In conclusion, existing approaches lack comprehensive knowledge of the capabilities and limitations of additive manufacturing in combination with the tacit knowledge from successful and unsuccessful designs for additive manufacturing. This poses the research question of *how to incorporate tacit knowledge from additively manufactured design artifacts and its design process into opportunistic and restrictive DfAM content to support the development of DfAM skills*.

A suitable approach could be to extract tacit knowledge from design artefacts and formalize it in a way that is intelligible to the user. This would require a redesign of each artifact and an understanding of its function and structure. A formalization of the essential tacit knowledge gained during the redesign process shall lead to a set of functional structures that are an abstracted representation of part geometries and implement a function. The term functional structure derives from the theory of “sharing in design” by Chakrabarti (2001) and is referred to by Garrelts et al. (2021) as “effect carrier” or by Kaspar et al. (2019) as “function carrier”. A knowledge-based design catalog shall capture the tacit knowledge with opportunistic and restrictive DfAM knowledge about each design artifact to provide comprehensive DfAM content. Furthermore, we shall reflect on the research question of *what designers expect from a knowledge-based design catalog*.

The aim of this work is therefore to extract tacit knowledge from design artifacts and to develop an initial version of a knowledge-based design catalog. We shall evaluate the strengths and weaknesses of this approach in a design workshop with graduates and undergraduates, as they represent our future workforce. To answer the second research question, we need to identify the user-related requirements for improving the knowledge-based design catalog. Finally, we shall reflect on the provided DfAM content and the support in developing DfAM skills.

2. State of research

When designers tackle a design task, they not only use methods and tools, but also their design know-how. This design know-how is referred to as tacit knowledge and is highly difficult to capture (Wong and Radcliffe, 2000). Long-term documentation, sharing, and incorporating tacit design knowledge is of great importance (Mascitelli, 2003). Design education in additive manufacturing and thus supporting the development of DfAM skills involves teaching explicit knowledge and providing an environment for the development and exchange of tacit knowledge (Prabhu et al., 2021).

An approach to perceive and share tacit knowledge is to present aggregated DfAM content in the form of design heuristics. According to Fu et al. (2016), design heuristics are based on intuition and tacit knowledge to guide the designer through a design process. Blösch-Paidosh and Shea (2017) formulated 29 design heuristics for additive manufacturing. An industrial evaluation was carried out by Blösch-Paidosh and Shea (2022) to solidify a previously reduced set of 25 design heuristics. These design heuristics are described on cards and demonstrated by printed artifacts. The universal design heuristics are structured according to generalized design potentials, e.g., part consolidation or convey information. In general, design heuristics only provide tacit knowledge about how to exploit the design freedom in additive manufacturing but disregard the design constraints that are an essential part of DfAM.

A different approach to share tacit knowledge is the provision of design principles, which however, result from the empirical investigation of design practice and experience (Fu et al., 2016). Perez et al. (2015) derived 23 crowdsourced design principles after reviewing 67 unique design artifacts. These principles have been expanded into AM design principle cards to support an innovation design process and enable exploration of additive manufacturing through design by analogy examples and design stimuli (Lauff et al., 2019; Perez et al., 2019). Valjak and Bojčetić (2019) and Valjak et al. (2022) present a function-driven repository of 32 AM design principles to systematically develop a design for additive manufacturing. Based on a functional model of a product, individual design principles can be used and adapted to the product requirements. Similarly, Schumacher et al. (2019) and Watschke et al. (2019) focus on a goal-oriented provision of design principles but start their design with a module interface graph. The design principles are categorized according to generally applicable functions and relate to the opportunities in multi-material applications.

A different research approach is the provision of additively manufactured features and artifacts. Bin Maidin (2012) collected additively manufactured artifacts from various AM processes in a feature database to inspire designers in developing new solutions. Each feature is categorized based on the type of application in AM. In comparison, Schaechtl et al. (2023) present a framework for a knowledge-driven DfAM ontology to support the semi-automated consideration of design guidelines.

The idea of providing restrictive knowledge with a design catalog was published by Weiss et al. (2016) and continued in Weiss et al. (2018). The developed internet-based design catalog is based on Roth (2001) and accessed by selecting generally applicable functions. Weiss et al. (2018) included only a few design artifacts with specified design restrictions. However, there is no allocation to design opportunities in additive manufacturing. Garrelts et al. (2021) presented a multidimensional catalog of functionally integrated additively manufactured artifacts developed specifically for laser powder bed fusion. Although tacit knowledge in the form of functional structures was included, the focus was exclusively on the design potential of integrated parts.

In summary, all approaches have their own merits, but the need to present tacit knowledge about the design process of successful designs for additive manufacturing remains. Our AM-community faces the challenge of supporting designers with little to no knowledge of DfAM to understand the design process required to achieve a DfAM. It is crucial to focus not only on the fundamentals of opportunistic and restrictive DfAM, but also to share the lessons learned from additively manufactured design artifacts in a way that allows the designer to ease into DfAM and progressively develop their DfAM skills. This work is intended to add value and extend the existing approach of a design catalog with the previously missing combination of design principles and design heuristics to serve as an educational tool for DfAM.

3. Methodology

To support designers with little to no DfAM knowledge, we first identified the necessary DfAM content (phase 1) to later extract tacit knowledge and formalize it in a knowledge-based design catalog (phase 2). We then shared the tacit knowledge in a workshop and investigated whether it supports designers in achieving a DfAM (phase 3). Figure 1 divides these three phases into individual steps.

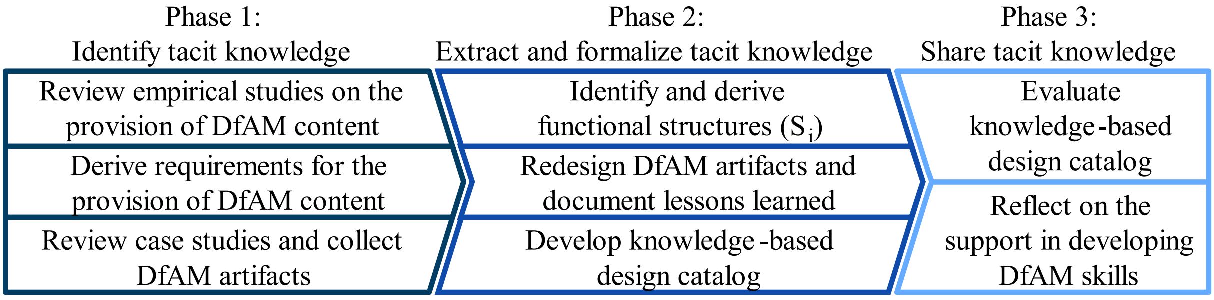


Figure 1. Methodology to identify, extract, formalize, and share tacit knowledge about DfAM

In a first phase, best practices for developing DfAM content and supporting the development of DfAM skills are derived from the existing empirical studies in section 2. This provides initial insights into what designers could expect from a knowledge-based design catalog. These insights are listed in section 4 in the form of requirements and describe the structure and content of the design catalog. The input for the knowledge-based design catalog is then created based on these requirements. This includes a systematic review of published case studies from the literature, manufacturers, and service providers of additive manufacturing to collect design artifacts. These artifacts are then analyzed in terms of their design potentials and design restrictions to identify tacit knowledge.

In the second phase of the methodology, we derive “functional structures” from each design artifact to extract and formalize tacit knowledge until saturation was reached and no new insights could be gained from the collected design artifacts. As a result, twelve functional structures were formalized, which are presented in section 5. We then establish the knowledge-based design catalog in accordance with the previous requirements. To elaborate on the case studies and extract additional knowledge about the design process, we redesigned each design artifact. The new insights gained from redesigning are incorporated into the design catalog. The design catalog is described in section 6 and consists of the

design artifacts, the corresponding functional structures, the design-related and manufacturing-related constraints, and additional information on lessons learned as well as mistakes to be considered.
In a third phase, we share our knowledge and evaluate the developed knowledge-based design catalog on its potential to support the development of DfAM skills. Section 7 describes a design workshop that serves to validate the requirements. We then discuss the findings and support in developing DfAM skills.

4. Initial requirements for a knowledge-based design catalog

Initial requirements for a knowledge-based design catalog are derived from the empirical studies on the various DfAM contents described in section 2. Table 1 summarizes the requirements for the development of a knowledge-based design catalog and divides them into the following five categories:

1. “DfAM content” comprises all necessary design inputs that shall be included into the design catalog. The focus is on the definition of design potentials and manufacturing-related design constraints to convey tacit knowledge about design for additive manufacturing.
2. “Structure” specifies the architecture of the knowledge-based design catalog. This category is about reducing the complexity of DfAM content to make it more accessible.
3. “Application” summarizes the requirements that influence the learning process comprehensiveness, intuitiveness, reliability, and the applicability of the DfAM content.
4. “Productivity” describes the effectiveness and efficiency in applying DfAM content.
5. “Flexibility” describes the iterative nature of DfAM and freedom in exploring the AM-enabled design space. It enables the DfAM content to be adapted to the respective design task.

Table 1. Requirements for a knowledge-based design catalog

No.	Requirements	Reference
1	**DfAM content**	
1.1	Present design-specific opportunities and restrictions	[1; 2; 3; 4; 5]
1.2	Provide process-specific information	[5]
1.3	Provide design artifacts and further information as stimuli	[2; 6; 7]
1.4	Implement design guidance	[8; 9]
1.5	Include information from the design process of design artifacts	[10]
2	**Structure**	
2.1	Divide content into an access section, main design section, and informative section	[11]
2.2	Divide DfAM content into presentation of design artifact and additional specification	[12]
2.3	Structure information according to the design task	[11]
2.4	Structure content so that it can be expanded or ensure completeness	[8; 11; 14]
3	**Application**	
3.1	Intuitive access of comprehensive DfAM content	[1; 15;8]
3.2	Provide reliable DfAM content	[16]
3.3	Provide comprehensive DfAM content	[14; 17]
3.4	Ensure applicable DfAM content	[8; 14; 15]
4	**Productivity**	
4.1	Simplify access by implementing function-driven access with specified functions	[11; 12; 15]
4.2	Visualize DfAM content	[12; 17]
5	**Flexibility**	
5.1	Consider universal applicability of DfAM content	[5; 8; 15]
5.2	Enable iterative/creative DfAM and exploring the AM-enabled design space	[4; 10]

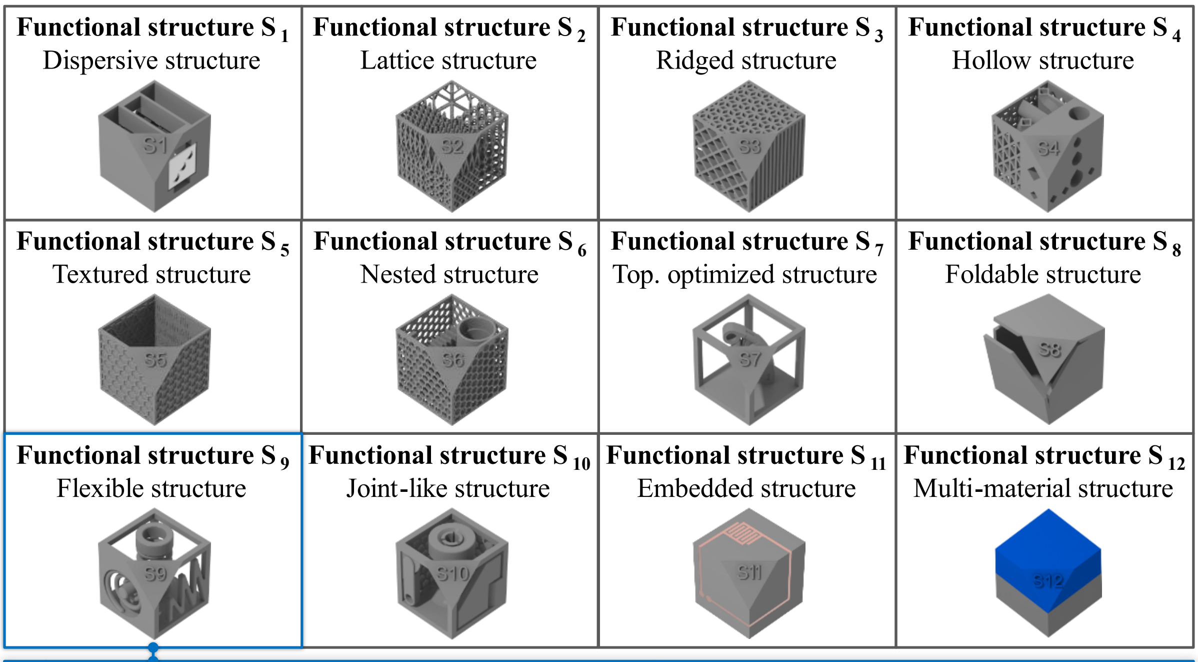
[1] Valjak and Bojčetić (2019); [2] Schumacher et al. (2019); [3] Watschke et al. (2019);
[4] Kaspar et al. (2019); [5] Prabhu et al. (2021); [6] Roth (2001); [7] Lauff et al. (2019);
[8] Blösch-Paidosh and Shea (2017); [9] Perez et al. (2019); [10] Bin Maidin et al. (2012); [11] VDI (1982);
[12] Weiss et al. (2016); [13] Kuschmitz et al. (2019); [14] Blösch-Paidosh and Shea (2022);
[15] Valjak et al. (2022); [16] Schaechtl et al. (2023); [17] Perez et al. (2019)

5. Extraction of tacit knowledge as functional structures

Based on the overall objective and the requirements, we assume that accessing knowledge through a knowledge-based design catalog of additively manufactured artifacts that combines restrictive and opportunistic DfAM is a suitable approach to support the development of DfAM skills.

In order to generate input for the design catalog, it was necessary to systematically review design artifacts tailored to DfAM. The design artifacts were extracted from published case studies from the literature, manufacturers, and service providers of additive manufacturing. The manufacturers and service providers were retrieved from Wohlers Report (Wohlers et al., 2021). The focus was on DfAM artifacts produced by fused filament fabrication (FFF), laser sintering (LS), stereolithography (SLA) or similar additive manufacturing processes. We have limited ourselves to these three processes, as their desktop printers are commercially available. Graduates and undergraduates are more likely to have access to desktop printers as these printers are either used privately or in makerspaces, allowing students to improve their DfAM skills independently.

The case studies were then analyzed to understand their implementation of opportunistic and restrictive DfAM. The result yielded a total of 47 different case studies, which consist of either practical applications or design artifacts that are explained in detail. Only case studies that reveal the design features and restrictions applied were considered. Case studies that do not describe the iterative design process or do not address the insights gained from non-manufacturable (failed) designs were excluded. As part of the review, all case studies were analyzed in terms of their exploited design potential and restrictions. Consecutively, tacit knowledge was extracted and formalized as design principles according to Fu et al. (2021). These design principles were then supplemented by generalized functional structures (S_i, $i \in [1;12]$) that represent AM-specific and function-based design principles and physical structure to implement the design principle. Each functional structure is illustrated in Figure 2, whereby the visualization is based on Garrelts et al. (2021). For example, S_9 represents flexible structures that are used in additive manufacturing to enable relative movement of the connected parts (Valjak et al., 2022).



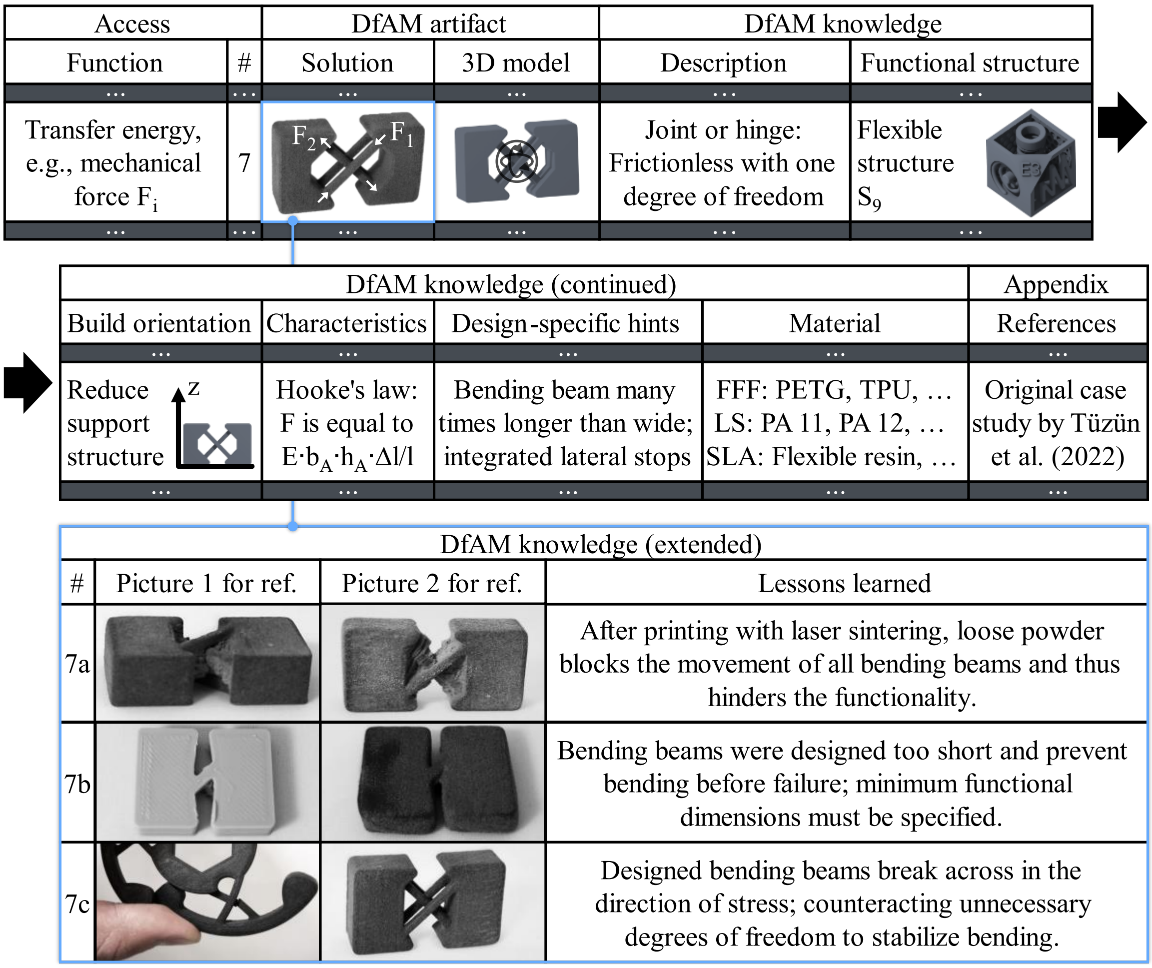
#	Design principle for functional structure	Design restrictions
S_9	Use **flexible structures** to store, transfer, convert or distribute energy. Flexible structures such as bending beams are used in elastic or compliant areas of a part. These areas are to be loaded with bending stresses.	Flexible structures should be several times longer than they are wide. However, this can easily lead to deformation of the components and protruding overhangs should be avoided.

Figure 2. Tacit knowledge visualized by functional structures with S_9 as an example

6. Development of a knowledge-based design catalog

The knowledge-based design catalog was implemented as a digital tool. It is subject to a function-oriented access, which was derived from the requirements in section 4. The intention of providing a knowledge-based design catalog is to introduce designers to DfAM, find existing solutions for DfAM and help them to gradually develop their DfAM skills. This approach serves as a first stimulus for pursuing a DfAM. However, the overall objective is to provide support in sharing and comprehending tacit knowledge on existing DfAM artifacts.

The design catalog is structured as shown in Figure 3 and an example is given with a frictionless joint (Tüzün et al., 2022). All DfAM artifacts are numbered and categorized according to a function-driven access (e.g., transfer energy) (Weiss et al., 2016), further specifying the functions (e.g., transfer mechanical force) (Valjak et al., 2022). It helps to access the design catalog for a given design task and to find suitable solutions or at least suggestions. For some functions, no or only a few design artifacts were derived from case studies.



Access		DfAM artifact		DfAM knowledge	
Function	#	Solution	3D model	Description	Functional structure
…	…	…	…	…	…
Transfer energy, e.g., mechanical force F_i	7	F_2 F_1		Joint or hinge: Frictionless with one degree of freedom	Flexible structure S_9
…	…	…	…	…	…

DfAM knowledge (continued)				Appendix
Build orientation	Characteristics	Design-specific hints	Material	References
…	…	…	…	…
Reduce support structure z	Hooke's law: F is equal to $E \cdot b_A \cdot h_A \cdot \Delta l/l$	Bending beam many times longer than wide; integrated lateral stops	FFF: PETG, TPU, … LS: PA 11, PA 12, … SLA: Flexible resin, …	Original case study by Tüzün et al. (2022)
…	…	…	…	…

DfAM knowledge (extended)			
#	Picture 1 for ref.	Picture 2 for ref.	Lessons learned
7a			After printing with laser sintering, loose powder blocks the movement of all bending beams and thus hinders the functionality.
7b			Bending beams were designed too short and prevent bending before failure; minimum functional dimensions must be specified.
7c			Designed bending beams break across in the direction of stress; counteracting unnecessary degrees of freedom to stabilize bending.

Figure 3. Structure of knowledge-based design catalog

The DfAM content is comprised of an interactive 3D model of each design artifact, which can be rotated or scaled. In addition, an implemented functional structures S_i is assigned to each design artifact. When accessing a design artifact, the user can view the respective design restrictions based on the selected material and additive manufacturing process. Furthermore, the optimal build orientation (z-axis) is visualized in relation to the design objective. Finally, characteristics and design-specific hints conclude the DfAM content. A link to the corresponding publication or the original case study is provided in the appendix.

Based on the redesigns, the lessons learned and flawed designs were grouped into subordinate variants for each design artifact (see Figure 3, variants are highlighted in blue). This approach allowed to include both successful and unsuccessful design artifacts.

The intuitive search and selection of design artifacts is supported by filters and text search functions for each column in the design catalog to balance out the complexity of the design catalog. For the sake of simplicity, filters and search functions are not shown in Figure 3. In addition, it is possible to constantly expand the design catalog, which at the same time anticipates its disadvantage.

Due to the increasing possibilities in the field of AM (e.g., through new technologies or new materials), the number of design artifacts is growing. However, the scope of the artifacts presented is limited, as the availability of published case studies is restricted.

The results show that the provision of tacit knowledge from DfAM artifacts can be standardized. Novice designers are given the opportunity to find predefined solutions for given functions without in-depth knowledge of AM or DfAM. As opportunistic and restrictive DfAM are combined, this approach serves on the one hand as inspiration and on the other hand for the (limited) adoption of existing solutions.

7. Evaluation and discussion

An evaluation was carried out to validate the requirements for the knowledge-based design catalog, to reflect on the impact of a knowledge-based design catalog on supporting the development of DfAM skills and to identify possible improvements to the knowledge-based design catalog from a designer's view. The evaluation took place in a 2.5-hour supervised workshop with a total of 48 graduates (n = 38) and undergraduates (n = 10) with different levels of experience. 23 participants (approx. 48%) had no experience with AM processes or DfAM. Twelve participants (approx. 25%) were already involved with DfAM and AM processes and a further twelve participants (approx. 25%) only had experience with DfAM. Only one participant (approx. 2%) was familiar with the AM processes but not DfAM. The evaluation was conducted according to the procedure shown in Figure 4 and compared the results of different design tasks with and without the support of a knowledge-based design catalog:

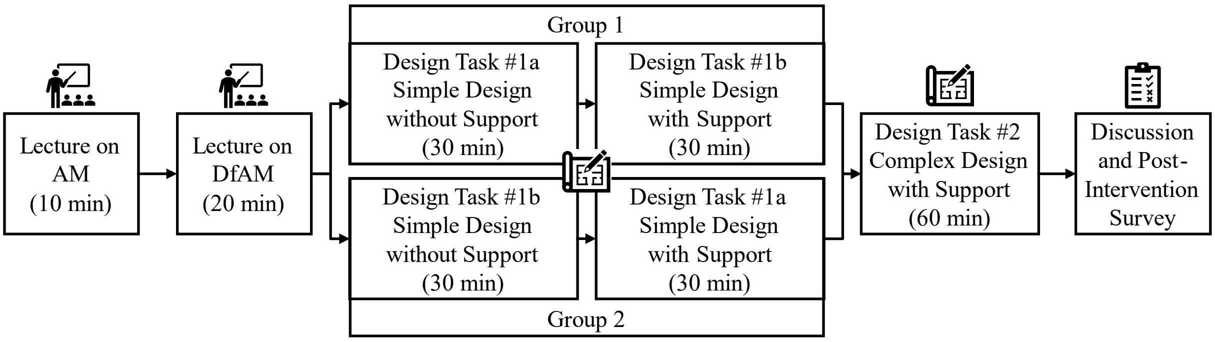


Figure 4. General evaluation procedure

After a brief introduction on AM and DfAM, participants were asked to solve the predefined design tasks and develop a DfAM. For their first design task, the participants had to design an original solution for a given product function. Without the support of a knowledge-based design catalog, group 1 had to design a clothespin (design task #1a) and the second group a bottle opener (design task #1b) with the overall objective to achieve a DfAM. The specific design objectives were to optimize the shape of the original design and to reduce the number of components needed. The knowledge-based design catalog was explained immediately afterwards, and the design tasks alternated without discussion or showing possible solutions.

In the second design task (design task #2), the participants had to pursue the same design objectives. However, the participants were given the functional structure of a pen-shaped hot glue gun as well as specific product requirements, e.g., material and manufacturing-related constraints. Another product requirement was the actuating force that feeds the glue stick into the nozzle. These requirements were set to motivate the participants to find solutions that, for example, transfer energy from the actuator to the glue stick and push it into the nozzle. In turn, the design catalog was used to solve the design task.

Shifting from a standard hot glue gun to a pen-shaped version required some rethinking of the participants. Despite the increased complexity within the task, around a third of the participants succeeded in finding a feasible solution by exploiting the design potentials and considering all design constraints. The lower success rate in conjunction with the feedback from the participants suggests that the number of suitable solutions offered by the design catalog is too low. The participants therefore selected suboptimal solutions and adapted them according to the design-specific hints.

With methodological support and comparing all design tasks based on the DfAM worksheet by Booth et al. (2017), the participants progressively achieved the required design objectives and designed a solution that was tailored to AM. One criticism was that the use of a design catalog requires a high degree of abstraction and could impair the intuitive development of solutions for particularly simple design tasks. The participants expressed the opinion that the design catalog is worthwhile if the design tasks are more complex. The function-based access to the design catalog was rated as particularly positive, as it enabled a focused search for solutions and targeted knowledge transfer.

A post-intervention survey asked the participants about any noticeable changes in their DfAM skills. The participants evaluated the approach in terms of whether it helped them to exploit design potentials and consider design restrictions. Overall, the verdict was positive, as shown in Figure 5.

This was confirmed by the results from the first design tasks, as most participants achieved a DfAM much more effectively with support than without. In a few individual cases, no change was observed between supported and unsupported design task. Yet no decrease in DfAM skill was noted.

In addition, it was necessary to validate whether the knowledge-based design catalog fulfills the requirements in section 4. The result was very good, even if the reliability of the design catalog should be improved (cf. Figure 5).

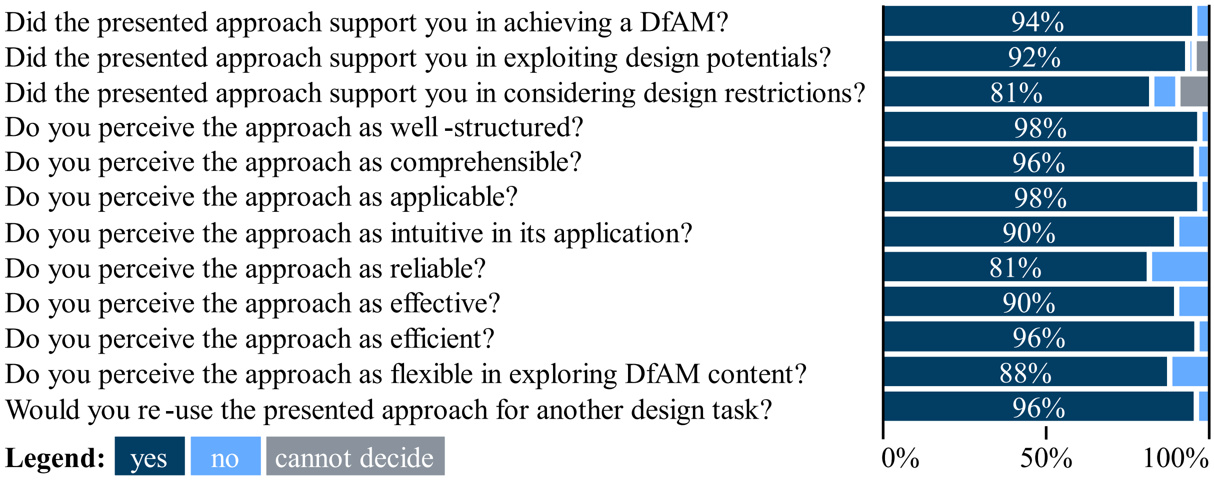


Figure 5. Validation and results of the knowledge-based design catalog (n = 48)

However, unsolved questions remain. As additive manufacturing technologies continue to evolve, the number of application examples is also increasing. It is difficult to estimate the extent to which new design options will arise in the future. This will not affect the structure of the design catalog, but the content of the DfAM could change. However, due to the nature of the design catalog, changes can be made quickly.

The workshop duration of only 2.5 hours was also too short to measure long-term effects. Hence, the aim is to integrate the knowledge-based design catalog into the existing curricula to provide medium- to long-term observations.

8. Conclusion

While the basic training of our future workforce provides general knowledge in design, engineering, and manufacturing, it is important to support the designers' needs in developing DfAM skills.

In order to develop the lack of or limited experience of graduates and undergraduates in DfAM, opportunities and restrictions of additive manufacturing must be communicated together. It is necessary to present explicit DfAM knowledge and create a platform for the exchange of tacit DfAM knowledge. A knowledge-based design catalog can be used as such a platform. In contrast to existing approaches, the design catalog vividly illustrates the best practices and lessons learned of existing design artifacts that are tailored to additive manufacturing. This supports immersion in the basic design-through process of DfAM. An initial design workshop with a total of 48 graduates and undergraduates shows that 93.75 percent perceive the support for the development of DfAM skills as beneficial.

The knowledge gained will be used to further expand the design catalog and implement it in an industrial context. In general, DfAM content may not be decoupled from real case studies. Therefore, future research should compare the success in developing DfAM skills with different presentation of DfAM content. Further observations are necessary to ensure that it is not self-efficacy but the influence of the presentation of DfAM content that is decisive for the development of DfAM skills.

Acknowledgments

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