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A proposal for guiding the selection of suitable DfAM support based on experiential knowledge

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Abstract

Unlocking additive manufacturing's (AM) potential requires designer expertise. Design for additive manufacturing (DfAM) addresses this need but faces barriers, such as uncertainty in scope of integration, design support selection, result validation or time investment for incorporating design support. This paper proposes a framework aligning SCRUM (agile framework) to aid designers in overcoming those barriers. The goal is to pave the way for a better exchange between academia and industry and fostering iterative development of DfAM support tailored to designer needs.

Keywords: *additive manufacturing, design for additive manufacturing (DfAM), agile development, design support, design methodology*

1. Introduction

The potential of additive manufacturing (AM) is currently not being fully exploited (Stavropoulos et al., 2023). Design supports in this area, which are often summarised under the term Design for Additive Manufacturing (DfAM), aims at improving this situation by highlighting capabilities and potentials of AM as well as supporting designers in using additive manufacturing (Gibson et al., 2021). Although new technologies such as generative design can significantly support designers in the realisation of AM-compatible parts, the full utilisation of the potential requires adaptation at a functional level. Design supports are therefore not limited to support modelling, but the entire development process. The high number of DfAM such as methods, tools and guidelines that come up every year is interpreted as an indicator for the demand by practitioners and is also reported by researchers, e.g. Liu *et al.* (2019). However, those approaches often do not find their way into design practice. Research about trends and industry needs in the field of AM related design support shows a lack of trust and willingness to adapt AM but also a lack of understanding about the suitability of AM for specific companies and products. (Guertler et al., 2022; Kumke et al., 2016; Stavropoulos et al., 2023). This is to some extent caused by the lack of formalised DfAM knowledge (Guertler et al., 2022). An increased awareness of the AM practices will likely grow in future generations of designers. In fact, designers will be increasingly familiar with additive manufacturing processes, as there is already more content on AM and DfAM being systematically taught in universities (e.g. Murray *et al.*, 2022; Thomas-Seale *et al.*, 2023). Still, the implementation of those topics in industry will remain a hurdle as long as basic requirements are not achieved. Only design supports that are believed to add value will be actively implemented into the design process. However, many of the existing design supports are still in the development phase and vary widely regarding their level of maturity (Guertler et al., 2022). Given the large spectrum of context dependent factors that can affect the efficacy and usability, a proper evaluation thereof is extremely

challenging. Case studies, as currently often used for evaluation of design supports, will probably not be sufficient to address the large spectrum of real-world use scenarios of the proposed design support.
In addition to the need to further improve design supports (Guertler et al., 2022), there is also a need to further assist designers in integrating design support into the design process. This includes the selection of the right design support (or even a set of design supports, called method ecosystem (Gericke et al., 2022)), according to the respective development phase. The importance of these phases becomes clear, in the highlighted fact that considering additive manufacturing during early design stages, gives the opportunity to utilise the potential of AM as the greatest. Existing approaches to integrate the design supports into the design process are mainly based on conventional design processes (e.g. Renjith et al., 2020) or (Kumke et al., 2016). However, AM and agile approaches offer common advantages, such as the strong involvement of customers in the process through customisation or the rapid adaptability within the process through rapid prototyping. The following research therefore presents a framework, with an analogy to the agile approach called Scrum. In particular, it is aimed at actors that want to explore the role of AM in the formation of the product architecture and are open to methodological approaches. It covers the whole process of identifying AM-potentials, choosing a suitable design support for solving a certain problem, utilising a design support and evaluating the output against pre-set criteria. The aim is to provide information about the usability of a design support for individual use cases and to create a base for benefiting from the experience of other companies and designers. The development of this framework, was guided by the following research questions:

1. How can designers be guided in selecting AM related design support?
2. How can designers be supported in assessing the suitability of the used design support?
3. How can the transfer of knowledge and experience be improved?

The paper will present a design support repository and its development before the focus is shifted onto a framework for selection of design support and transfer of experiential knowledge.

2. DfAM knowledge basis

The DfAM Design Support Repository is based on a literature study of the Database Scopus. Academic sources that deal with supporting designers in exploiting AM potential. All publications with the terms "Design for additive manufacturing" and "Additive manufacturing" in the title, keywords or abstract were reduced to relevant hits. Publications that include methodological support for designers were filtered using direct keywords such as "design support" or "method". Indirect search terms such as "product architecture" or "function" were used to detect research that may not contain a completed method but can still serve as design support. In addition, those research results were compared and supplemented with design supports listed in established literature in the field of DfAM (e.g. Gibson *et al.*, 2021; Lachmayer and Lippert, 2020). The study, while not being exhaustive, resulted in a total number of around 50 design supports, each categorised complemented with references to academic publications. It has to be mentioned that there are several classifications of DfAM approaches. The term (DfAM) therefore covers different spectrums.
A widespread consensus distinguishes between opportunistic DfAM and restrictive DfAM. Opportunistic DfAM emphasises the opportunities offered by the use of AM and neglects restrictions. Restrictive DfAM on the other hand primarily refers to those restrictions (Kumke et al., 2018). However, Schaechtl (2023) points out that approaches usually contain elements of both groups. These are referred to as dual DfAM in other publications (e.g. Cayley *et al.*, 2022). Ponche (2018) differentiates between approaches that have a small influence on the product architecture and only make minor modifications for the use of AM (spatial approach) and those that significantly influence the product architecture (global approach). Other classifications are less binary and distinguish between common types of design support categories that are listed in Table 1, left-hand column (cp. Pradel *et al.*, 2018). This subdivision will be used later to categorise the different design supports. In addition to approaches explicitly developed for AM (e.g. checklists), design supports from other research areas can also serve the purpose of exploiting the potential of AM (e.g. TRIZ). As there are often variants of the approaches that focus on different aspects, e.g. on a specific area of application, materials, AM processes, etc., it is therefore

not possible to show all of them here. Examples of the repository's design supports are listed in Table 1, right-hand column.

Table 1. DfAM categories (left) and examples of AM related design supports (right)

DfAM categories (Pradel et al., 2018)	**Examples of AM related design supports**
AM heuristics	Mood boards (Lang et al., 2021)
AM principles	Bionic (Lachmayer and Lippert, 2020)
AM guidelines	Topology optimisation (ZHU et al., 2021)
AM rules	Agile development (Reichwein et al., 2020)
AM process guidelines	Checklists (Kumke, 2018)
AM specifications	Axiomatic design (Toguem et al., 2020)
AM process selection tool	TRIZ (Mazlan et al., 2022)
	Methods for modifying the product architecture, e.g. one-part device (Schmitt et al., 2022) (according to Ehrlenspiel (2007))

3. Selecting design support

The last section showed the diversity of design supports aiming at utilising AM potential. However, it has already been mentioned that these remain largely unexploited in industry. This following chapter deals with challenges in the selection of design support with focus on AM. Access to such design support and similar content is usually provided to designers by using textbooks, archival publications, web repositories and community-based design support platforms (cp. Gericke *et al.*, 2016).

Compared to textbooks and other publications, web repositories have the potential to be dynamically updated. However, the resources required for supporting such repositories or databases, which are often provided by rather small teams, are limited. On the other hand, content in textbooks is generally more controlled in terms of quality. Descriptions in textbooks about different methods or other forms of design support tend to show a consistency that supports comparing and choosing one of them. Scientific publications in particular, often focus on a single method and a very specific scenario of application. The focus is not on the effort required for the method, which makes it difficult for designers to estimate its applicability (Gericke et al., 2016). The integration of a design support without context comes with challenges (Gericke et al., 2016). Several researchers in the field of DfAM met this need by integrating a set of design supports into a methodology. These sets serve as guidance for designers. Such frameworks are usually based on established design methodologies such as the four phases of the traditional design process (according to Gericke and Bender, 2021) (e.g. Renjith *et al.*, 2020) or the VDI 2221 framework (Kumke et al., 2016). In contrast to community-based web platforms, where the aim is to share knowledge with other practitioners, these methodologies for AM are also largely based on autodidactics.

4. Capturing and transfer of experiential knowledge

Assessing the suitability of AM and the respective design support requires knowledge and experience. This section presents some of the approaches and difficulties in dealing with this subject. Knowledge is required to determine whether the effort of implementing AM is adequate and adds value to the product and can be supported by selecting a design approach. There are a great number of approaches guiding the selection of AM support that cover a wide spectrum of activities of the development process. There are approaches that assess the environmental performance by examining design and process parameters that affect the environment, e.g. compiled in (Naser et al., 2023). Other approaches help evaluating design decisions in terms of cost according to the level of complexity of the components and different options of manufacturing processes. Tlija and Al-Tamimi (2023) use DfAM as one of the DfX approaches which serve as a base for cost calculation. Each design support is based on the knowledge and experience of other researchers and practitioners, which is transferred into a design support. While evaluation of a new design support is an important step during development, which is described in the Design Research Methodology (according to Blessing and Chakrabarti, 2009), it is often not considered

sufficient in the research literature. (Gericke et al., 2016). Studies show that the methods are often only evaluated theoretically and not in an industrial context (Beckmann et al., 2016; Ellsel et al., 2021). This situation reflects the general challenge of knowledge exchange between industrial companies and academic institutions (Gericke et al., 2016). Challenges are knowledge management (especially intellectual property) and the willingness to deal with AM, because it is seen as too time-consuming even when being supported by using methods (Gericke et al., 2016; Guertler et al., 2022).
This paper aims at addressing those challenges because knowledge and its evaluation is an important step to increase quality and effectiveness. In order to enable a fast-track feedback loop and the chance to identify assumptions that lead to value as well as most helpful changes that impact the product, a technique from project management shall be used as a base for further development. For the challenges of selecting and applying AM design support, the structure of an agile framework called Scrum represents a promising approach for this project as this is the most established agile approach for physical components, which can increase acceptance for its use (Cooper and Sommer, 2018). In addition the general concept of iterative development rather than sequential phases (as with other agile approaches) makes it suitable for this purpose As well as the structure of the framework. The following section presents some of the artefacts of the framework that are particularly important for an analogy of the framework to be developed. In terms of the evaluation of design support in particular, the retrospective provides a good base for evaluating the outcome.

An analogy for capturing experiential knowledge - the Scrum framework

Agility is a paradigm in product development that promotes short iterations, time-boxed events and collaboration to enable more flexibility, responsiveness to change and satisfied customers. The agile paradigm has its origin in software development where it has been successfully implemented in the last years. Agile design methodologies and methods are based on the agile manifesto, determined in 2001, which outlines certain principles such as customer collaboration being more valuable than negotiating contracts (Beck., 2000; Schwaber and Beedle, 2001).
One agile methodology is Scrum, which shall serve as the base of this research. The Scrum framework contains personas, events and artefacts, which are displayed in figure 1. The personas and the respective tasks are not relevant for this research. Scrum artefacts represent work or value and intend to enable transparency of key information. The product backlog is a list of actions needed to improve the product. The sprint backlog contains the sprint goal, the tasks chosen to be dealt with during a sprint and the plan for delivering the increment (an increment is some kind of outcome). Events are the sprint, sprint planning, daily stand-up sprint review and sprint retrospective. During a sprint, ideas are turned into value and the work necessary to achieve a goal is done. Sprint planning is a time-boxed event that initiates the sprint by laying out the work to be performed and results in a sprint plan. The purpose of the daily stand-up is to display progress and enable quick adaptations to the sprint backlog. During a sprint review, the outcome of a sprint and future adaptations are discussed. A Sprint retrospective opens the opportunity to increase quality and effectiveness of the process (Schwaber and Sutherland, 2017).

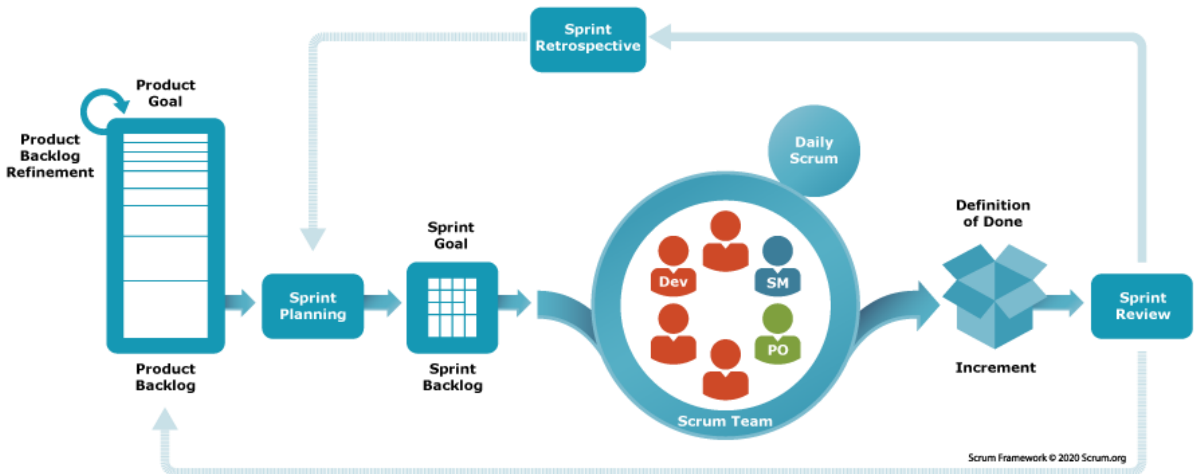

Figure 1. Scrum framework (Schwaber and Sutherland, 2017)

The retrospective as a method to improve collaboration among teams as well as procedures and content, offers great potential for gaining experience and knowledge management. Therefore, it should be used not only at the end of development phases that cover longer periods of time but also after certain other activities to benefit from fast feedback such as the implementation of design support.

5. Framework for selecting design support via experiential insights

The following chapter provides an initial stage for solving the problem of maintaining knowledge and experience during the application of design support in AM. The first section contains a framework that displays the process of choosing, implementing and validating a design support. The second section describes a repository that is part of the process and whose intention is to help designers in choosing the right support according to a design question and the respective development phase. The third and last section proposes an approach to validate the output generated from implementing a design support.

5.1. Adapting the Scrum framework

An analogy of the Scrum framework described above was used to model a framework that helps choosing, executing and evaluating design support for additive manufacturing. It represents a procedure and can be seen as a single "sprint" when being compared to Scrum. The "backlog" contains a project's criteria derived from the requirements list that determine whether additive manufacturing is suitable. The criteria then need to be compared with design parameters indicating a high potential for additive manufacturing (e.g. defined by Renjith et al. (2020)). For example, if a requirement limits the maximum weight of a product to be 5 kg, the appropriate design parameter would be to reduce weight, which can be realised using AM through infill modification, lattice structures and material choices. If one or more of those criteria indicate a potential, the next step is to choose from a variety design supports, which one is suited best to solve a certain problem (e.g. reducing weight).
The DfAM repository is intended to aid designers during this step to realise a guided selection. The fundamental functionality of the DfAM repository is described in Section 5.2 After that, the use of the selected design support needs to be planned, realised and tested. In the end, there should be some kind of output, which could be for example a cost prediction or a three-dimensional object, depending on the applied design support. The output has to be validated against pre-defined criteria (cp. 5.3) to determine whether using the design support additive manufacturing adds value to the product. The purpose of the retrospective is to increase quality and effectiveness. The advantages and disadvantages of the used design support are discussed to determine the most helpful changes to improve the product. During the retrospective, it should be considered whether the generated output fulfils the project criteria and it must be decided whether another method would be better suited to generate the preferred solution or if additive manufacturing is not the right way to pursuit. This framework refers to the use of design support. As these relate to the entire design process, there is no limitation on the time of use but due to the advantages mentioned, an application is already suggested in or before the conceptual phase.
The process described above is presented in Figure 2.

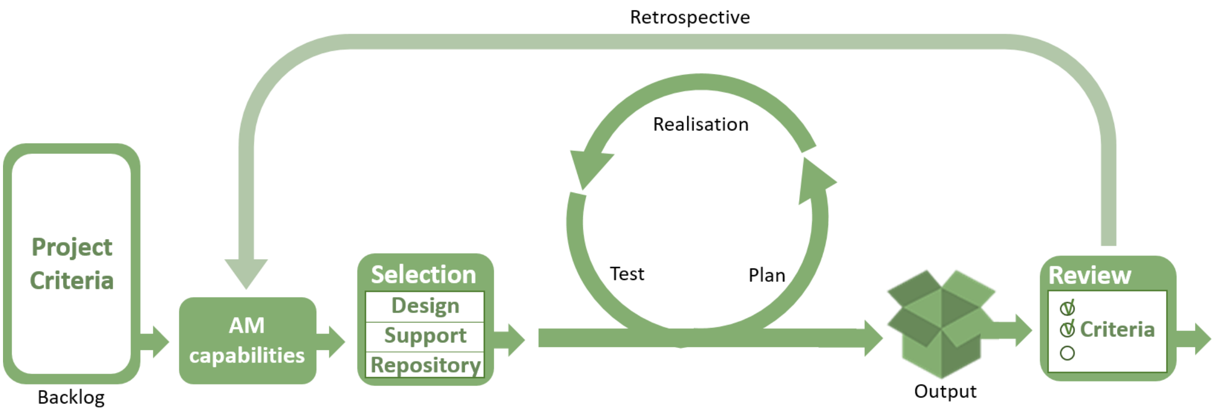

Figure 2. Framework for choosing and evaluating DfAM design support

5.2. Design support repository

This repository summarises scientific content that can serve as design support. It also includes approaches that are not listed in other overviews (e.g. DfAM catalogues). The different categories of design support (see Table 1, left-hand column) serve as an initial filter for a suitable design support to address a certain challenge. These are evaluated for effectiveness with regard to different criteria. Those criteria include the four design stages planning and clarification of the task, conceptual design, embodiment design and detailed design according to Gericke and Bender, (2021). Other criteria include the specific reference to material or process method or the established classification into opportunistic and restrictive design support. When applying the filters to the criteria, users can rate the conformity (of their own needs) and less suitable design support can be excluded further on.
The next step is to take a closer look at the results. Zooming into the remaining design support categories provides information about design supports assigned to the respective category. These include information concerning scope, purpose, coverage, benefit and conditions that are required. Access to one (or more) scientific source(s) is then presented in the form of a DOI.

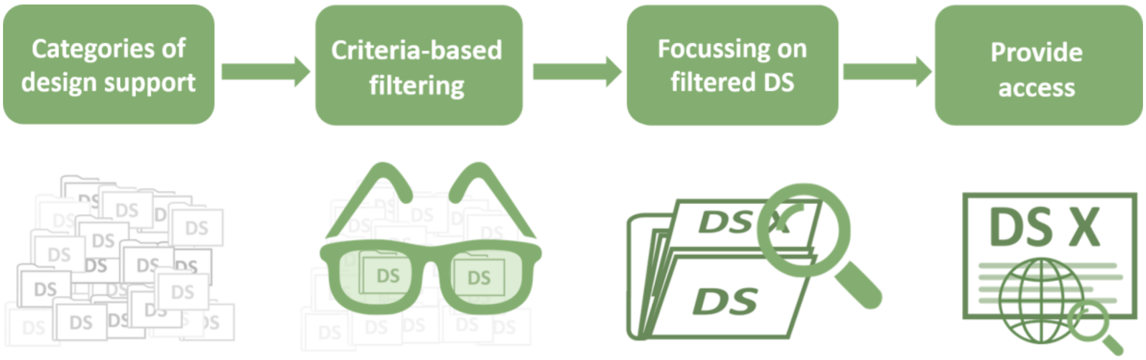

Figure 3. Design Support Repository scheme

5.3. Output validation

The AM capabilities mentioned above can add value to the product development project and the respective product. The proposed framework establishes a connection between the impact AM can have on the product in theory with the experience a designer gets by reviewing the outcome of an applied design support. Considering potential effects of AM before choosing a suitable design support allows designers to familiarise themselves with the topic. While an increasing complexity of components can have several disadvantages, AM opens up new possibilities such as weight reduction due to an increased degree of lightweight design. This is only one example out of a long list of positive effects AM can have which are used in the mentioned framework as review criteria that enable designers so assess their outputs. The criteria presented in the following two bullet point lists do not claim to be exhaustive, but cover a large part of the positive effects of using AM and represent a variety claims and examples of existing design supports. The following points are derived from established references in the field of AM.

- **Part consolidation** // (Blösch-Paidosh and Shea, 2022; Gibson et al., 2021)
- **Multi-functional products** // (Gibson et al., 2021)
- **Lightweight design** // (Gibson et al., 2021)
- **Simplified supply chain** // (Gibson et al., 2021)
- **Personalisation/Customisation** // (Blösch-Paidosh and Shea, 2022; Gibson et al., 2021)
- **Lot size of one** // (Gibson et al., 2021)
- **Short time-to-market** // (Gibson et al., 2021)
- **High performance products** // (Gibson et al., 2021)
- **Embedded components** (e.g. sensors, electronics) // (Gibson et al., 2021; Renjith et al., 2020)
- **Surface textures** // (Blösch-Paidosh and Shea, 2022; Renjith et al., 2020)
- **Internal channels and hollow structures** // (Blösch-Paidosh and Shea, 2022; Gibson et al., 2021; Renjith et al., 2020)

- **Multi-material / graded material** // (Gibson et al., 2021; Renjith et al., 2020)
- **Thin and small features** // (Renjith et al., 2020)
- **Compliant-mechanism** // (Gibson et al., 2021)

It must be mentioned, that the review criteria described here represent only one step in the cause-and-effect chain. Reduced waste production or a reduced ecological footprint are aspects mentioned in literature that could also serve as review criteria, but are not listed here because an assessment would require further elaboration. As part of the process, an individual weighting must be applied to the proposed review criteria, because this is not predefined by the authors.
The product-related review criteria (above) are complemented by a set of possible different claims given by different design supports (according the repository). By assessing the applicability to one's own use case, the method can be reviewed. Examples of design supports are referenced that address the mentioned claim.

- **Assess the cost-effectiveness of a component in relation to the manufacturing process** (Kampker et al., 2019; Kazmer et al., 2023)
- **Identify the potential of AM** (Blosch-Paidosh and Shea, 2021; Brennan et al., 2021; Lachmayer and Lippert, 2020)
- **Identifying & specifying problems related to AM** (Renjith et al., 2020; Toguem et al., 2020)
- **Provide inspiration through existing components** (Bender and Gericke, 2021)
- **Create system architecture/product architecture to identify potentials and contradictions** (Ganter et al., 2021; Valjak and Bojčetić, 2023)
- **Adopting functions and shapes from nature** (Lachmayer and Lippert, 2020)
- **Create ideas and solve problems with the Contradiction Matrix** (Gross et al., 2018; Mazlan et al., 2022)
- **Optimising design for AM-processes** (e.g. fused filament fabrication (Djokikj and Kandikjan, 2022), laser powder bed fusion (Herzog et al., 2022), laser metal deposition (Ewald and Schlattmann, 2018))
- **Numerical generation of multiple solutions for defined constraints** (Ntintakis et al., 2022)
- **Facilitate the selection of suitable software for the application** (Nieto and Sánchez, 2021)
- **Support selection of print material** (Lachmayer and Lippert, 2020)
- **Support selection of printing process** (Lachmayer and Lippert, 2020)
- **Provide checklists adapted to the design phases** (Kumke, 2018).

A selection of intended effects through the use of AM and claims given by the design support must be assessed in terms of application and outcome. It is proposed to assess this either binary (applies / does not apply) or in comparison with other variants (better/worse) or with introduced scaling. This cannot be considered an evaluation because no measurement is provided to quantify the degree of fulfilment of the criterion (consequence) and claims.

6. Discussion & conclusion

Additive manufacturing has become crucial in contemporary production due to its distinctive capabilities. To fully harness these abilities offered by additive manufacturing technologies, Design for Additive Manufacturing (DfAM) has gained prominence, offering tools and guidelines for product design. Yet, existing DfAM approaches lack comprehensive design frameworks necessary for effectively integrating additive manufacturing capabilities into the initial phases of product design.
To address this issue, this paper presents a framework that intends to guide designers in considering and implementing additive manufacturing into their development process. The framework covers the required steps, which are the following: consideration of AM with the help of project criteria, choosing a suitable design support, applying the respective support strategy and generation of an output, validating the output against predefined review criteria and using the results to adjust the process or the product.
The framework, which is based on the Scrum framework, aims at adressing at different needs of designers in dealing with knowledge gaps and the methodical access to the field of AM. On the one

hand designers are often overstrained by the growing field of AM. DfAM serves as the basis for the main need of gaining access to relevant AM knowledge. There are continuously appearing new design supports, that are in some cases still in the development phase which results in a lack of trustworthiness among designers. This is why it is important to improve the knowledge transfer from research to industry. The framework addresses this problem in presenting designers a list of available design supports suitable for specific design phases that can be chosen guided by a selection process.

Other problems are that designers tend to consider AM too late in the process, even though AM has its greatest effect when implemented early and that designers are unsure about how to successfully integrate AM into the design process. The proposed framework provides project criteria that advocate AM and can help assessing whether AM can be useful, especially when unexperienced with the field.

Another aspect addressed by the proposed framework is the wish of designers for fast-track development and rapid feedback. The review as a core element of the framework forces designers to critically question the chosen design support and the generated output. The output has to be validated against predefined criteria in order to estimate its effect on the product. The feedback loop prevents the result or output from being implemented into the design process without further scrutiny. This does not just add value to a single development project but enables designers to gain experience and to reuse the findings for future projects.

The approach proposed here is a step towards designers benefiting not only from the experience of a few case studies (internal and external) but from a larger number of designers who have used the design support. The review process improves the exchange of experience and knowledge between industry and academia. Additionally the development of design support can be driven forward and even tailored more closely to the needs of designers. Regarding the dynamic development of DfAM, a constant integration of upcoming design supports and update of the design support repository would be a necessary course of action. There is also great potential in extending case studies not just to validate the different design supports but also to test and evaluate the proposed framework.

As a limitation of the framework it has to be mentioned, that there are currently no rigorous restrictions regarding the actors, the development stage or the field of application and the type of outcome could be very wide-ranging. The proposed criteria are therefore very broad and certainly need to be adapted. There is currently no setting for a review that provides benefits to other users and at the same time does not pose a risk in terms of intellectual property. Besides that, currently there is no infrastructure for storage and processing of the generated/shared results.

The next step would be to evaluate the individual elements of the framework and to further develop the framework based on the findings. In an initial internal study, the design support repository was tested with groups of students. The results are currently still being analysed. However, a study in real-life applications, i.e. in industry, is required to determine the effectiveness of integrating the framework into the workflow.

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