Design Science

Industrial evaluation of design heuristics for additive manufacturing

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Abstract

Additive manufacturing (AM) has gained prominence over the last 15 years and become a viable manufacturing option. Since there is great industrial interest to implement serial production of products using AM, the education of engineers in design for additive manufacturing (DfAM) is important today. DfAM extends on design for manufacturing to provide knowledge about the new design opportunities enabled by AM. A set of design heuristics for additive manufacturing (DHAM) to assist designers with conceptual-level DfAM has previously been proposed. In this paper, these DHAM are evaluated through workshops with 3 engineering companies and 19 engineers, in which the participants re-design existing company products for AM using the DHAM as an aid, and then give feedback. The DHAM are well received by the workshop participants, and they find that the DHAM are good for teaching others about the capabilities of AM, provide a checklist of items to consider to help avoid oversights, and encourage the generation of new ideas. Criticisms include the number of examples provided and the lack of information about how to implement the ideas concretely. It is also found that the DHAM fulfil 16 of 18 criteria for early design phase DfAM methods, identified in academic literature.

Key words: design for additive manufacturing (DfAM), design heuristics, creativity, design card deck, design objects, opportunistic DfAM, industry

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1. Introduction

Additive manufacturing (AM), colloquially known as 3D printing, has gained prominence over the last 15 years and has moved out of the laboratory and into the industrial product stream, becoming a viable manufacturing option for end-use parts (Müller & Karevska 2016; Thompson *et al.* 2016). This advancement is significant considering the roots of AM in rapid prototyping, where the objective is to fabricate prototypes compared to the current focus on designing and producing functional parts with AM that are used directly within a product or engineering system. New knowledge in design for additive manufacturing (DfAM) is thus needed to achieve this transition successfully. Despite its viability as a new manufacturing option and growth in industry of 28% per year between 2011 and 2015 (Müller & Karevska 2016), at the time of the survey, 76% of companies have no experience with AM (Müller & Karevska 2016). Of these companies, 28% cite a lack of AM Knowledge (AMK) as their main barrier to entry (Müller & Karevska 2016). A 2016 survey found that 38% of companies worldwide wanted to implement the serial production of products using AM by 2021 (Müller & Karevska 2016), indicating that the diffusion of AMK is a pressing issue.

The diffusion of AMK into industry is a particularly difficult problem to address because of the unique capabilities afforded by AM when compared to conventional manufacturing techniques, namely shape, material, hierarchical, and functional complexity (Gibson, Rosen, & Stucker 2015). Particularly due to the shape complexity afforded by AM, many of the geometric constraints of conventional manufacturing are obsolete when designing for AM. Designers experienced with conventional manufacturing rules have difficulty breaking out of their current mind-set and require assistance to do so successfully (Seepersad 2014, Valjak *et al.* 2020, Prabhu *et al.* 2020*a*, Dordlofva & Törlind 2020).

Design for additive manufacturing (DfAM) education is a particularly pressing issue due to the large number of companies that would like to implement serial AM production. What makes this even more challenging is the fact that many future users are already in industry and may not have the time or capacity to participate in a lengthy training course, and they did not attend any courses in AM during their studies, as these courses have only started to emerge in the last 5 years. Additionally, novice designers, particularly those that are still in education, also need assistance to learn about the technology, but the education needs to be incorporated into the existing design and manufacturing curriculum, which can already be quite full (Borgianni *et al.* 2019). Subsequently, the field of DfAM has developed to address the needs of both experienced and novice designers (Thompson *et al.* 2016). Both industry and academia are active in this area.

As part of this movement, in 2009, the United States National Science Foundation and the United States Office of Naval Research developed a Roadmap for AM with specific goals for AM research over the subsequent 10 years. These goals included developing DfAM methods to help designers. As of 2014, a review of existing work revealed that although much progress in the areas of optimisation, computational tools, and restrictive design guidelines had been made, there was still a distinct lack of methods to assist designers in exploring the AM design space during the conceptual design phase (Bourell, Rosen, & Leu 2014). With the goal of addressing this lack of methods to assist designers during the early phases of the design process, several researchers have proposed design aids.

The authors have previously proposed a set of 25 design heuristics for additive manufacturing (DHAM) in a card-based format (Blösch-Paidosh, Ahmed-Kristensen, & Shea 2019) and with accompanying AM objects (Blösch-Paidosh & Shea 2021). The DHAM, DHAM cards, and DHAM objects have already been found to increase creativity and the inclusion of AM concepts in controlled novice user studies (Blösch-Paidosh *et al.* 2019; Blösch-Paidosh & Shea 2021). However, the DHAM have not been evaluated in industry-based design scenarios (i.e., in a nonfabricated design scenario) or with expert designers, and neither has open-ended feedback about the DHAM been gathered. These gaps are now addressed by conducting a series of workshops and gathering industry feedback on the DHAM, DHAM cards and DHAM objects.

It is hypothesised that similar increases in creativity and the inclusion of AM concepts will be seen in industry and workshop environments (H1). This is based on the assumption that the DHAM should perform similarly when compared to the controlled experiments. This was found by Yilmaz *et al.* (2013*a*), when comparing the use of their general design heuristics by novices and professionals.

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It is also hypothesised that the combination of the cards and objects will be positively received by the participants, as the combination was found to be more effective in the controlled experiments (H2; Blösch-Paidosh & Shea 2021). Finally, it is hypothesised that the industry participants will find that the DHAM fulfil all of the identified criteria for early-phase DfAM methods, except providing restrictive DfAM information (see Section 2) as they were not originally developed to provide such information (H3; Blösch-Paidosh & Shea 2017).

This paper first provides background information on relevant topics. Then, the workshop procedure and evaluation method are described in Section 3. Additionally, this section quickly reviews the DHAM cards and objects. Next, the results of the workshops are presented followed by a discussion, including a discussion of future work. Finally, the paper concludes with a summary. The contributions of this work are the evaluation of the DHAM in an industrial setting and a questionnaire to help evaluate and compare early design phase DfAM methods. By evaluating this early-phase DfAM method in an industry setting, it makes it one of the few methods that has been evaluated with both novices and experts, and in both workshops and randomised controlled studies.

2. Background

One approach to providing early-phase AM Knowledge, and the approach chosen by the authors, is through design heuristics or design principles. A *heuristic* is defined as 'a context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution (Fu, Yang, & Wood 2016)', whereas a *principle* is defined as 'a fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution (Fu *et al.* 2016)'. Design heuristics and design principles are similar to each other, but heuristics typically use less empirical evidence for derivation, are more general (i.e., higher-level), are less formal, and are usually more prescriptive as opposed to descriptive (Fu *et al.* 2016). Design heuristics and principles are a popular way of communicating design guidance because they are easy to use and quickly communicate the necessary information (Yilmaz & Seifert 2010; Fu *et al.* 2016; Roy & Warren 2019) and are prevalent across a variety of design domains (Roy & Warren 2019). One of the most well-known sets of design heuristics are the 77 design heuristics developed by Yilmaz *et al.* (2016). They have been validated extensively with novice and expert designers (Yilmaz, Seifert, & Gonzalez 2010; Christian *et al.* 2012; Daly *et al.* 2012; Yilmaz *et al.* 2013*a*, *b*; Kramer *et al.* 2014). Design heuristics and principles are also a popular way to communicate the design possibilities surrounding AM (Perez *et al.* 2015; Perez 2018; Yang, Page, & Zhao 2018; Schumacher *et al.* 2019; Valjak & Bojčetić 2019; Watschke *et al.* 2019).

Early design phase DfAM often has a strong opportunistic DfAM component (information about the unique capabilities of AM; Gibson *et al.* 2015) as opportunistic design support assists designers in expanding their AM design horizons, something that is key in the early design phases (Ulrich & Eppinger 2008). However, some early-phase DfAM methods also include restrictive DfAM information (information about the restrictions of the AM process; e.g., Laverne *et al.*

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2015; Weiss, Binz, & Roth 2015; Kumke *et al.* 2017; Watschke *et al.* 2017; Perez 2018) to help users make the transition from the early design phases into the later phases of the design process (e.g., detailed design) without having to use or learn an additional method. The usefulness of these different types of design support in the early phases has not been studied in detail, and there are varying opinions on the inclusion of restrictive DfAM in early-phase DfAM methods (see Table 1). DfAM methods targeted specifically at detailed design also exist (e.g., *The DfAM Worksheet*; Booth *et al.* 2017), but are not included in this literature review as they are not focussed on a design phase under investigation in this work.

The evaluation of early design phase DfAM methods in an industry setting (Kumke *et al.* 2017; Dordlofva & Törlind 2020; Prabhu *et al.* 2020a) or using expert designers (Laverne *et al.* 2015; Lauff *et al.* 2019; Fillingim *et al.* 2020; Prabhu *et al.* 2020a) are few, and the descriptions of the results and feedback are usually vague and often only involve a short survey about the method following the workshop or user study. When a post-survey is used, the questions asked are also variable between studies. Sometimes they focus on helpfulness (Kumke *et al.* 2017), amount of information provided (Kumke *et al.* 2017), or ability of the participants to understand (Fillingim *et al.* 2020), and sometimes they ask how well a method fulfils early-phase DfAM method needs (Lauff *et al.* 2019). Additionally, one study has also looked at designers' self-efficacy following the workshop (Prabhu *et al.* 2020*a*). The myriad of ways in which the methods are evaluated makes it difficult to compare the results and abilities of one method to another. A standard set of criteria should be set to ease this comparison in the future.

What exact qualities early design phase DfAM methods should embody are not clearly stated in literature. To determine what qualities are preferable, 19 academic works published between 2011 and 2019 (see Table 1) are examined for information to determine what are generally considered important characteristics in early-phase DfAM methods. Thirty-two different characteristics are found to be considered important in the literature examined; however, only 18 characteristics are consistently identified by researchers from multiple research groups. Table 1 lists these 18 characteristics and provides references to the supporting literature. Although much additional research in this area has been published since the survey was conducted in 2019 (e.g., Perez *et al.* 2019; Prabhu *et al.* 2019; Schumacher *et al.* 2019; Valjak & Bojčetić 2019; Watschke *et al.* 2019; Wiberg, Persson, & Ölvander 2019; Dordlofva & Törlind 2020; Prabhu *et al.* 2020*b*; Valjak *et al.* 2020), it was conciously decided not to update Table 1, because of the results' direct connection to the development of the questionnaire used to evaluate the method (see Sections 3–3.3).

Of the 18 characteristics identified in Table 1, some have very similar wording, which may be confusing. In order to clarify the meaning of some of the similar-sounding characteristics, we include a brief description for selected characteristics:

- *Is easy to learn how to use*: learning how to use the method is easy.
- *Is easy to use*: once one knows how to use the method, it is easy to apply.
- *Structured in an easy to understand way*: the information supplied via the method is structured in a way that is easy to understand.
- *Offers a comprehensive view of the capabilities of AM*: a comprehensive view of the capabilities of AM is offered, that is, it does not focus on just one area.

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Table 1. Literature survey of important characteristics of early-phase DfAM methods

Characteristic of Early-Phase DfAM	Supporting Literature
Increases number of AM ideas generated	Yang *et al.* (2018) Blösch-Paidosh & Shea (2019) Perez (2018)
Increases quality of AM ideas generated	Yang *et al.* (2018) Perez (2018)
Increases variety of AM ideas generated	Abdelall, Frank, & Stone (2018) Blösch-Paidosh & Shea (2019) Perez (2018)
Increases novelty of AM ideas generated	Abdelall *et al.* (2018) Kumke, Watschke, & Vietor (2016) Barclift *et al.* (2017) Perez (2018)
Is easy to learn how to use	Yang *et al.* (2018) Gross, Park, & Okudan Kremer (2018) Kumke *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019) Watschke *et al.* (2017)
Is easy to use	Yang *et al.* (2018) Gross *et al.* (2018) Kumke *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019) Watschke *et al.* (2017)
Is useful early in the design process	Yang *et al.* (2018) Kumke *et al.* (2017) Salonitis (2016) Weiss *et al.* (2015) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019) Prabhu *et al.* (2018)
Provides the information necessary early in the design process	Yang *et al.* (2018) Kumke *et al.* (2017) Laverne *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019) Prabhu *et al.* (2018)
Structured in an useful way	Yang *et al.* (2018) Kumke *et al.* (2017) Bin Maidin (2011) Weiss *et al.* (2015) Blösch-Paidosh & Shea (2019) Watschke *et al.* (2017)
Structured in an easy to understand way	Yang *et al.* (2018) Gross *et al.* (2018) Kumke *et al.* (2017)

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Table 1. Continued

Characteristic of Early-Phase DfAM	Supporting Literature
Offers a comprehensive view of the capabilities of AM	Yang *et al.* (2018) Pradel *et al.* (2018) Kumke *et al.* (2017) Salonitis (2016) Laverne *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019)
Offers opportunistic AM information	Abdelall *et al.* (2018) Kumke *et al.* (2017) Laverne *et al.* (2015) Laverne *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019) Watschke *et al.* (2017) Prabhu *et al.* (2018) Perez (2018)
Offers restrictive AM information	Abdelall *et al.* (2018) Kumke *et al.* (2017) Salonitis (2016) Laverne *et al.* (2015) Weiss *et al.* (2015) Watschke *et al.* (2017) Perez (2018)
Provides information in a variety of formats	Pradel *et al.* (2018) Kumke *et al.* (2017) Laverne *et al.* (2016) Bin Maidin (2011) Watschke *et al.* (2017) Perez (2018)
Is applicable to both parts and assemblies	Jung & Simpson (2018) Kumke *et al.* (2017) Laverne *et al.* (2016) Laverne *et al.* (2015) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019)
Is AM-process and material independent	Pradel *et al.* (2018) Kumke *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019)
Is useful for AM-novices	Kumke *et al.* (2017) Kumke *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019)
Is useful for AM-experts	Kumke *et al.* (2017) Kumke *et al.* (2016) Blösch-Paidosh & Shea (2017) Blösch-Paidosh & Shea (2019)

Abbreviations: AM, additive manufacturing; DfAM, design for additive manufacturing.

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- *Offers opportunistic AM information*: opportunistic information about AM is supplied (i.e., information about the capabilities specific to early phase DfAM, e.g., incorporation of metamaterials).
- *Offers restrictive AM information*: restrictive information about AM processes is supplied (e.g., design guideline for wall thickness or overhang angle).

3. Method

The method chosen to evaluate the DHAM in industrial design scenarios and with expert designers is a series of workshops with three engineering companies. This evaluation method and results reporting is based specifically on the work of Hamraz & Clarkson (2015), but workshops as a method for evaluation of design methods in industry are commonly reported (Laverne *et al.* 2015; Kumke *et al.* 2017; Rigger *et al.* 2019; Dordlofva & Törlind 2020; Prabhu *et al.* 2020*a*). This evaluation method is chosen because it focusses on evaluation of the method and not of the individual results generated by each company. It is also flexible with regard to the number of participants and the artefacts chosen.

In contrast to Hamraz & Clarkson (2015), who carried out the evaluation of an engineering design method with 1 engineering company and 10 engineers, we report the evaluation of the DHAM with 3 companies and 19 engineers in total. It is not the goal of this research to make quantitative statements about the use of DHAM in industrial situations, but rather to take more of a case-study approach (Yin 2014), which is typical for assessments of design methods in industry (Albers *et al.* 2019; Bertoni & Bertoni 2019; Sjögren *et al.* 2019; Stenholm, Catic, & Bergsjö 2019; Dordlofva & Törlind 2020). In this section, the DHAM are first briefly reviewed. Then, the workshop agenda is described. Finally, the feedback evaluation method is detailed.

3.1. Design Heuristics for Additive Manufacturing

Twenty-five DHAM were derived through the analysis and synthesis of 275 AM artefacts stemming from literature, industry sources, the popular media and hobby websites (Blösch-Paidosh & Shea 2019; Blösch-Paidosh & Shea 2021). These 25 DHAM can be broken-up into eight different categories: *part consolidation*, *customisation*, *convey information*, *material*, *material distribution*, *embed-enclose*, *lightweight* and *reconfiguration.* They are listed in Table 2.

Later, a set of cards was developed to communicate each heuristic (Blösch-Paidosh *et al.* 2019; Blösch-Paidosh & Shea 2021). The cards are multimodal and each contains seven different pieces of information. An example card with each of these pieces of information labelled is available in Figure 1. Additionally, a physical object was created to accompany each of the 25 DHAM cards (Blösch-Paidosh & Shea 2021). An example object corresponding to the card in Figure 1 can be seen in Figure 2 and a selection of the accompanying 25 DHAM objects can be seen in Figure 3. The full set of the 25 DHAM cards and objects are available to view and download at https://edac.ethz.ch/Research/Design-Heuristics-AM.html and their derivation is described in more detail in Blösch-Paidosh & Shea (2021).

The DHAM cards were inspired by the design heuristics cards of Leahy *et al.* (2018). They differ mainly from their closest AM-specific relative, the design principles for AM cards of Perez (2018), in that they focus solely on opportunistic

Table 2. The 25 DHAM organised by category

Part Consolidation		Material Distribution	
1	Consolidate parts for better functional performance	15	Absorb energy with small interconnected parts
2	Consolidate parts to reduce assembly time	16	Allow movement with small interconnected parts
3	Consolidate parts to increase robustness	17	Use material distribution to achieve desired behaviour
4	Consolidate parts to achieve multiple functions	18	Remove material to provide function
		19	Optimise structural topology or geometry
Customization		Embed-Enclose	
5	Customize geometry to use case	20	Embed functional material
6	Customize user interface to use case	21	Embed functional component
7	Customize artefact with decoration	22	Use enclosed, functional parts
Convey Information		Lightweight	
8	Convey information with color	23	Replace internal structure with lightweight lattice structure
9	Convey information with geometry	24	Hollow out artefact to reduce weight
10	Convey information with haptics		
11	Convey information with light		
Material		Reconfiguration	
12	Use single material to achieve recyclability	25	Create multi-functional artefact with reconfigurable structures
13	Use metamaterial to achieve unique and graded material properties		
14	Use multiple materials to achieve unique and graded material properties		

DfAM and that the DHAM draw from a wider derivation pool including examples from industry, academia, and the media. Additionally, the combination of the cards and objects offered by the DHAM allow the designer to not just read an instructional text and look at images, but to also interact with a physical representation of the heuristic (Blösch-Paidosh & Shea 2021).

3.2. Workshop Description

Three workshops are performed with three different industrial partners over a period of 6 months, between March and August 2019. The companies are active in

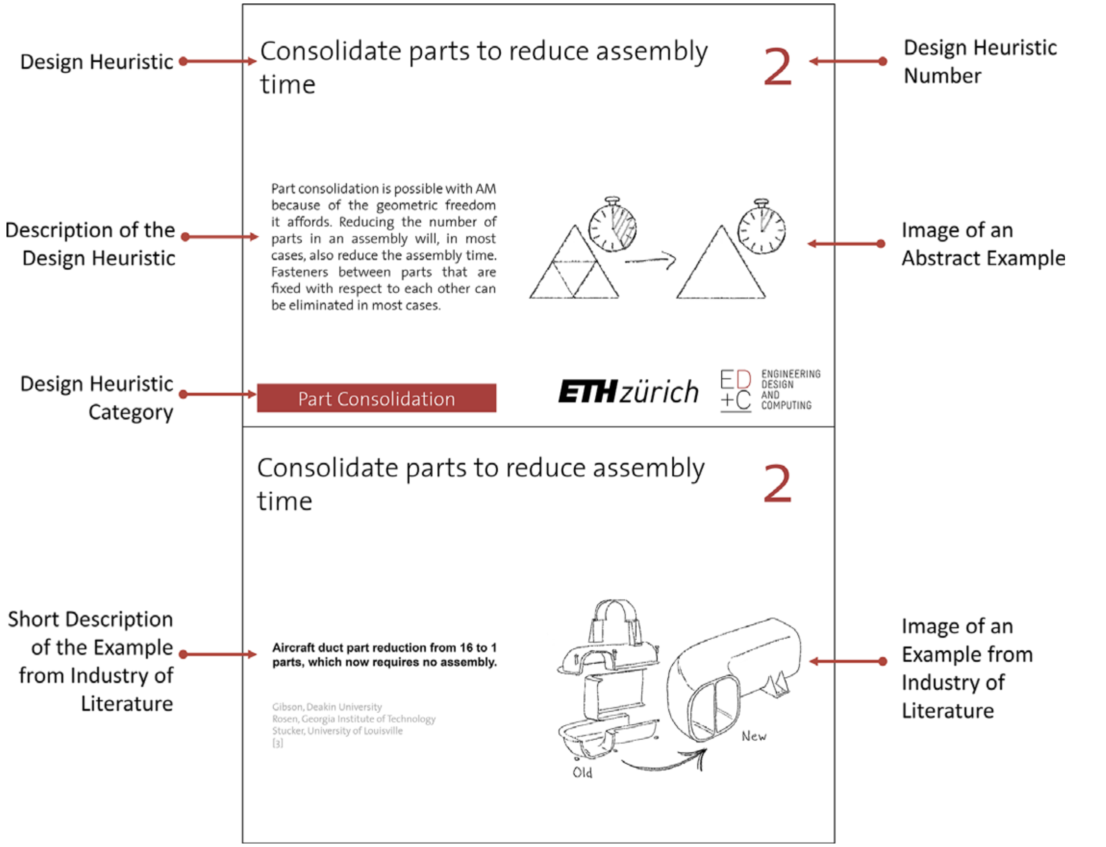

Figure 1. Example of a Design Heuristic for Additive Manufacturing (DHAM) card. The front of the card is at the top and the back of the card is on the bottom.

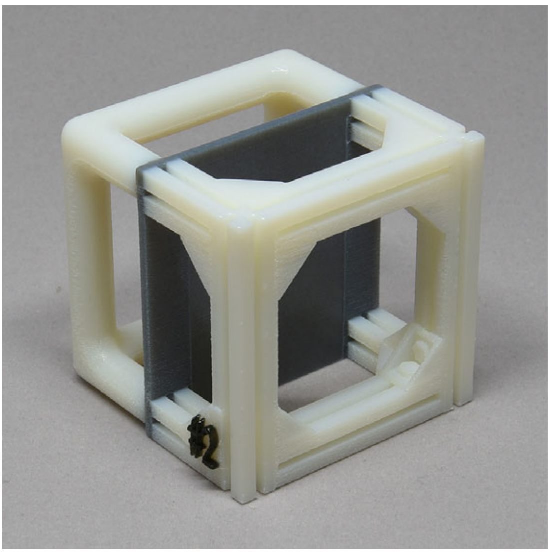

Figure 2. Corresponding Design Heuristic for Additive Manufacturing (DHAM) object for the DHAM card shown in Figure 1.

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Figure 3. A selection of the 25 Design Heuristics for Additive Manufacturing (DHAM) objects.

Table 3. Company participants in industry workshops

Company identifier	Industry	Short description of artefact(s)	Number of participants
Company A	Automotive	Component used in the distribution of windshield washer fluid	6
Company B[a]	Manufacturing Machinery	Extrusion die and injection mould	5
Company C	Construction Machinery	Drill bit	8

[a]No Brainwriting 6-3-5 performed due to each subgroup working on different artefacts.

the automotive, manufacturing machinery, and construction machinery industries. At each company between 5 and 8 employees with technical backgrounds take part in the workshops, for a total of 19 participants. The participating companies and employees are described in Tables 3 and 4, respectively. The self-reported DfAM experience is taken from a DfAM knowledge survey filled-out by each participant. It is based on the survey developed by Prabhu *et al.* (2018). Neither the workshop facilitators (researchers), the companies, nor the participants are compensated monetarily for their time or participation, and each of the workshops takes place at the participating company during normal working hours. In exchange for conducting the workshops, the workshop facilitators receive

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Table 4. Participants in the industry workshops

Participant Identifier	Job Function	Time at Company	Years in Industry	Self-Reported AM Design Experience
A.1	Development Engineer	6.5 years	12.5 years	Intermediate
A.2	Development Engineer	7 months	not indicated	Novice
A.3	Development Engineer	3 years	5 years	Intermediate
A.4	Development Engineer	5 months	3 years	Intermediate
A.5	Leadership in R&D	14 years	20 years	Intermediate
A.6	Scientific Project Manager - Simulation Expert	2.5 years	20 years	Intermediate
B.1	Mechatronic Project Manager & Head of Maker Space	22 years	26 years	Fundamental Awareness
B.2	Maker Space Project Manager	6 years	7 years	Intermediate
B.3	Design Team Manager	17 years	17 years	Intermediate
B.4	Vocational Teacher for Designers	19 years	19 years	Intermediate
B.5	Development Engineer	2.5 years	2.5 years	Intermediate
C.1	Project Manager	1 year	1 year	Novice
C.2	Project Manager/Systems Expert	22 years	22 years	None
C.3	Technical Project Manager	4 years	4 years	Fundamental Awareness
C.4	Materials Expert	23 years	29 years	None
C.5	Development Project Manager	4 years	4 years	Intermediate
C.6	Development Engineer	12 years	16 years	Intermediate
C.7	Materials Expert	12 years	21 years	None
C.8	Design Engineer and AM Project Leader	19 years	19 years	Advanced

feedback on the method and the allowance to publish it as compensation for their time.

The artefacts used during the workshops as a design task are actual company products that are defined by each company prior to the workshop, and details about the chosen artefacts and the changes made to them are confidential and cannot be reported here, as per agreements with the participating companies. However, a short description of the artefacts worked-on by each company is available in Table 3. They were all part of Research and Development projects. The advantage of carrying out the study this way, rather than giving the same academic example to all three companies, is that the method can be tested in the context of each company, across different industry sectors, and on a product that the company and participants have direct interest and motivation to improve.

Each workshop lasts approximately 3 hours and follows the outline shown in Figure 4. The workshop begins with an introduction of the facilitator(s) and the participants to each other, followed by an overview of the agenda. Then, the workshop participants are asked to describe the current state of the product(s)

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I. Introduction & Ice Breaker (10 min)

II. Definition of Current Product Concept/State (10 min)

III. Collection of Data – Current Design Process at Company (10 min)

IV. Explanation of Design Heuristics and Design Heuristics for Additive Manufacturing with Examples (10 min)

V. Ideation using Design Heuristics for Additive Manufacturing in Two Sub-Groups (60 min)

  a. Brainstorming in Two Groups (45 - 60 min)

  b. Brainwriting 6-3-5 (15 min) (optional)

VI. Discussion of Generated Results in Full-Group (30 min)

VII. Collection of Data & Conclusion (30 min)

  a. Feedback on Proposed Ideation Method in the context of Company's Design Process

  b. Feedback on Design Heuristics for Additive Manufacturing

  c. Fill-out Numerical Evaluation Survey about Design Heuristics for Additive Manufacturing (5 min)

Figure 4. Industry workshop agenda outline.

or concept(s) that they would like to work on during the workshop. This is an important step, as it was found during previous failed user studies, that it is difficult to apply the DHAM without a well-defined artefact as a starting point. Then, a discussion of the current design practices at the company is led by the facilitator(s), including their general design process and how they currently incorporate DfAM into their design process. The goal of these workshops is not to gather data on DfAM or development practices in industry, but to obtain industrial feedback on the DHAM cards and objects. This discussion is included so that the facilitator knows the context of the statements made by the participants while giving feedback on the DHAM. Next, the benefits of using design heuristics (not just the DHAM) are explained to the participants along with an example DHAM card and object. The participants are also provided with some example applications of the DHAM. Following this, the participants are split into two equal subgroups and the ideation session begins, during which the participants use the DHAM as an aid to help redesign their chosen product(s) for AM. The results of the DfAM knowledge survey are not used to divide the participants into groups based on their experience during the workshop. Instead, the participants are allowed to self-divide. Group instead of individual ideation is used to keep the workshop/group brainstorming feeling. The users are split into subgroups to keep the teams small and allow each of the participants to fully participate.

During the ideation session, each subgroup has access to one complete set of the DHAM cards and objects. The cards are laid out in numeric order in a 5×5 grid on a table with the object on top of the corresponding card. The ideation session lasts about 1 hour and is done in a group. If both subgroups are working on the same

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product or concept, each subgroup freely brainstorms for 45 minutes. Then, the ideas generated by one subgroup, in the form of annotated sketches, are passed to the other and each subgroup uses the other subgroup's ideas as the basis for a Brainwriting 6-3-5 session (Rhorbach 1969), adjusted to the number of ideas and participants. This second portion of the ideation session lasts no more than 15 minutes. However, if each subgroup is working on a different product or concept, the second portion of the ideation session is eliminated and the first portion is extended to 1 hour. The companies, which do not complete a 6-3-5 session are indicated in Table 3.

There are many different creative ideation methods aside from Brainstorming including SCAMPER (Eberle 1996), the Gallery method (Vangundy 1988), Synectics (Gordon 1961), Six Thinking Hats (de Bono 1985), and Brainwriting 6-3-5 that each have their own strengths. In order to keep the focus on the DHAM, it is not desired to introduce another method, which would require lengthy explanation. Additionally, due to the limited time available for the second ideation method, some of the aforementioned methods are not suitable. This leads to the selection of Brainwriting 6-3-5, because it is simple, quickly explained, and highly flexible depending on the number of participants and ideas generated during the initial Brainstorming session.

Following the ideation session, the subgroups come back together to discuss the generated ideas as a group. Once the participants are finished discussing the ideas they generated, the participants are asked to evaluate the DHAM in various ways. In a focus group-style session (Morgan, Krueger, & King 1998), the participants are asked to give feedback on the method. They are asked about if they could see themselves using this method in conjunction with future development projects and how it would or could fit into their existing development process. Additionally, they are encouraged to give direct feedback on the DHAM cards and objects, such as, what they liked and disliked about them, what was possibly confusing and what they would change about them if given the chance. They are also encouraged to provide any open-ended feedback about the DHAM. Throughout this data collection session and the session about the company's design process, notes on the responses are taken by the workshop facilitators. None of the companies agrees to the sessions being recorded for later analysis, so no transcript analysis is possible. Finally, each participant is asked to fill out a questionnaire in which they rate the suitability of the DHAM as an early-phase DfAM method. This questionnaire and its derivation are described in the next section.

3.3. Evaluation Method

The evaluation of the workshop data consists of two main parts: analysis of the oral feedback and analysis of the early-phase DfAM questionnaire. The analysis of the oral feedback is quite simple. Immediately following each workshop, the notes taken by the workshop facilitator(s) are transferred to a spreadsheet, where each comment, its provider, and any necessary context are recorded. Observations made by the facilitator(s) are also recorded. Then, the comments are clustered based on their content and relevance to certain topics. As more workshops are conducted, the comments are combined together in categories, and patterns in the responses are examined to draw conclusions (Yin 2014).

Statement	Rating				
	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
DH for AM help me to generate more ideas.					
DH for AM help me to generate higher quality ideas (quality = fulfils design requirements, technically feasible).					
DH for AM help me to generate a wider variety of ideas.					
DH for AM help me to generate more novel ideas.					
Learning to use DH for AM is easy.					
DH for AM are easy to use.					
DH for AM are useful early in the design process.					
DH for AM provide the information I want/need early in the design process.					
The information provided by DH for AM is structured in a useful way.					
The information provided by DH for AM is structured in an easy to understand way.					
DH for AM offer a comprehensive view of the capabilities of AM.					
DH for AM provide me with information about the opportunities provided by AM.					
DH for AM provide me with information about the restrictions of AM.					
DH for AM provide information in a variety of formats.					
DH for AM are applicable to both single parts and assemblies.					
DH for AM are AM-process and material independent.					
DH for AM is useful for AM-Novices.					
DH for AM is useful for AM-Experts.					

Figure 5. Early-phase design for additive manufacturing (DfAM) questionnaire based on the criteria of literature. Statements follow the same order as the characteristics listed in Table 1.

A questionnaire to determine if the DHAM fulfil the qualities desirable in early design phase DfAM methods is derived based on the 18 characteristics designated as important for early-phase DfAM methods based on the literature survey in the background section (see Table 1). A statement is created for each of the 18 characteristic deemed important by literature in which the DHAM are stated as fulfilling that characteristic (18 total statements). The questionnaire asks each participant to rate their agreement with the statement on a 5-point Likert scale (*Strongly Disagree* to *Strongly Agree*). Although the questionnaire is designed with the DHAM in focus, the text can be easily edited to accommodate any other early-phase DfAM method by replacing 'DH for AM' with the name of the chosen method and is thus suitable for the general evaluation of early-phase DfAM methods. The designed questionnaire is available in Figure 5. For analysis

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purposes, the Likert scale is transformed into a numeric scale (−2 to 2, with −2 = *Strongly Disagree* and 2 = *Strongly Agree*) to help visualise tendencies in the responses. A −2 to 2 conversion scale is chosen so that a neutral response by the participant (*Neither Agree nor Disagree*) corresponds with a neutral value (0) on the scale.

4. Results

The results of the oral feedback analysis are presented in the following tables. The analysis is split-up into multiple tables that each focus on a different aspect of the responses: the praised advantages (Table 5), suggested improvements (Table 6), and suggestions for use (Table 7). Each statement is labelled with the participant that stated it as indicated in Table 4. Some statements, however, were generally agreed on by all of the participants at a particular company. In these cases, the company is indicated instead of a specific participant.

The results of the questionnaire are available in Figure 6. The participants generally agree with all but two statements: *DHAM provide me with information about the restrictions of AM* and *DHAM are AM-process and material independent.* For the former of these statements, they do give a mean negative rating, but for the latter, they are slightly positive. However, the mode responses are *neither agree nor disagree.* Additionally, the maximum rating for all but the aforementioned statements is *strongly agree* and the lowest rating for 10 of the 18 statements is *neither agree nor disagree.* The mode responses for 15 of the 18 statements are either *agree* or *strongly agree.* For the other three statements, it is *neither agree nor disagree.* None of the mode responses is negative.

5. Discussion

The discussion is organised into five sections: praised advantages, suggested improvements, suggestions for use, fulfilment of early-phase DfAM characteristics, and comparison to novice designer studies.

5.1. Praised Advantages

Overall, the reception of the DHAM by the industry participants is overwhelmingly positive. In fact, at one of the companies, one of the participants is quite sceptical of the DHAM at the beginning of the ideation session, and implies he could only apply the DHAM in a trivial manner, but by the end of the ideation session and during the discussion, he is one of the biggest supporters of the method at the workshop (A.6). The advantages of the DHAM as described by the participants are four-fold: they are good for teaching others about the capabilities of AM, they provide a checklist of things to consider to help avoid oversights, the inclusion of the DHAM objects helps to improve their understanding of the DHAM, and they encourage the generation of new ideas. The generation of new and a wider variety of ideas is something that is empirically mirrored in the previous novice user studies (Blösch-Paidosh & Shea 2021), so it is beneficial to have confirmation of this from an industrial perspective. Therefore, H1 is confirmed. A limitation on these results is that they could only be qualitatively confirmed in industry, and not also quantitatively as in previous research with

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Table 5. Praised advantages of the DHAM with supporting comments (continued on the following page)

Praised Advantage	Supporting Comments
Good for teaching others about the capabilities of AM	They are good as a promotion for new AM parts [with our partners, production managers]. (A.6)
	I see these as a good didactic support method. For example, when I'm explaining an AM concept, like multi-material, to someone, they can directly see what I mean when I have the object. They may not otherwise understand the concept if I'd just explained it verbally. (A.6)
	We need to train our people (e.g., local R&D managers, local production managers) and these could really help us to do that. We're doing a big training push in a few months, and we might want to use these. (A.5)
	This method would be good for teaching our apprentices or others who do not know at all or only very little about AM. (B.4)
	There's a gap in understanding about what's possible for most people, that this can help fill. (C.1)
	The objects are helpful for people who do not know AM well. (C.4)
Provides a checklist of things to consider and helps avoid oversight	It would help me not to forget certain AM possibilities (A.5)
	It makes a good checklist for the possibilities of AM, so that I do not forget certain things. (A.6)
	It's good to go over the part at the end of the process with the cards and see if one missed anything that could be useful. (B.3)
	Do a double check to see if I've gotten everything out of AM that I can. (B.1)
Having the DHAM objects together with the cards is preferable	50% of my understanding of the DH came from the cube, and 50% came from the card. I think you need to use them together for full understanding. They complement each other. (A.4)
	The objects were super useful. (Company A)
	Some may prefer the cards to read (as I typically would), but I really liked the objects. (A.6)
	A 'proactive' engineering mind likes to play with the object. It helps them to understand. (A.6)
	Having the real world example sometimes was needed to seal-the-deal of understanding. (Company A)
	The cards were difficult to understand by themselves. (A.6)
	I need both the cubes and the cards to see the full picture (especially with language barriers). (B.1)

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Table 5. Continued

Praised Advantage	Supporting Comments
	The cubes really get to the heart of the heuristic and make everything clear. (B.1)
	Supporting comments
	It was really helpful to hold the objects in my hand. Without them, I would not have had some of my ideas. (B.4)
	What really drove the point across were the different heuristic objects. They made the whole experience more engaging. (C.1)
	Having things to play with would be good for our designers. (C.6)
	We found the objects very helpful. (Company C)
	Well, one certainly has some favourite objects. It's a lot of fun when I can play with some of those that move. (C.7)
DHAM encourage the generation of new ideas	We're working with the old-school rules [of manufacturing] in our heads and we do not know all the possibilities of AM. These [DHAM] help open my eyes to the new possibilities of AM. (A.1)
	They [DHAM] help me to put new images in my head [about manufacturing], as references for the possibilities of AM. (A.1)
	They [DHAM] provided me with a lot of ideas. (Company A)
	I'm not sure if they [ideas] are better, but we definitely had more ideas. (A.1)
	The ideas are also over a wider range than we would have otherwise had. (A.1)
	We only had the idea to use colour from the DH! (B.4)
	Yes, the DHAM definitely helped us develop better ideas! (Company B)
	Having the 25 objects stimulated new ideas. (C.5)
	Having the tactile element and the actual different textures of the objects helped us to generate new ideas, including non-AM ones. (C.5)
	Yes, this method helped us to develop better ideas. (Company C)

Abbreviations: AM, additive manufacturing; DHAM, Design Heuristics for Additive Manufacturing.

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Table 6. Suggested improvements to the DHAM with supporting comments (continued on the following page)

Suggested Improvement	Supporting Comments
Move examples to the front of card	Maybe it was a mistake to not flip the cards over…did not really notice that they were 2-sided. (Company A)
	You should make the information on the back more accessible. (Company A)
	Maybe you can move the real-world example to the front/ combine all of the info on one side. (Company A)
	The description wasn't so helpful. I'd rather see an example than have a lot of text. I read some of them, but they really did not help me. (B.4)
	Perhaps it would be better to have the example on the top instead of underneath. (B.4)
Make objects more robust	Some of the objects seemed really fragile to me. I was afraid to touch some of them [because I thought I may break them]. (A.5)
Include objects made of other materials than plastic	Physical examples in metal are missing. (B.4)
	Printing some of the objects in metal would be useful to make it more obvious to the uninformed that the heuristics are also applicable with those types of materials. (C.4)
Reduce size of cards	The cards were a bit big. They take up a lot of the table when I lay them out. (B.4)
Include information about how to implement ideas shown on cards	How do I actually achieve some of the ideas presented here? I'd like to see a list of how to actually achieve the ideas displayed in the cards (e.g., #14). (B.4)
	We came up with some ideas that have a higher technical risk and higher cost in comparison to what we do now [conventional manufacturing]. The question for us is how we move forward with each of these ideas after this workshop? (C.2)
	We were missing data about how you would actually make it. For example, what materials would you use? (C.4)
	I would like to see some specific opportunities and restrictions for each AM process in relation to each heuristic. (C.4)
Include heuristics about hybrid manufacturing	Hybrid (AM and Traditional Manufacturing) examples would also be nice. For example, how do I physically connect the two parts? (B.4)
Include heuristics about overcoming the limits of the technology	We have a #26! A heuristic that shows you how to deal with the challenges that you meet when applying AM (e.g., printing a chain into a long tube to help remove the powder). Something that shows me what I can do when I come up against a limit of the technology. (B.1)

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Table 6. Continued

Suggested Improvement	Supporting Comments
Include more examples	I wish there were some examples that included parts of parts instead of just only whole parts/assemblies. (B.4)
	Interest could be triggered by including more actual examples. (C.4)
	Having more examples would bring more inspiration. (C.5)
	Having more examples would be good, but one should provide some specific examples in metal, either printed or on the cards. (C.4)
	I would like to see some examples that are really only possible with AM. (C.2)
	Having extra models as CAD models or physical things one can print would better than extra images on the cards. (C.4)
Make all objects printable with desktop FDM printers	Can we not buy a set of these? We'd like to use them, but we do not have all the machines to print all of them… (Company B)
Translate cards if they are to be used by the nontechnically literate	The cards themselves were well written, but the English is not suitable for someone without a technical background. (C.4)

Abbreviation: DHAM, Design Heuristics for Additive Manufacturing; FDM, fused deposition modelling.

novice users. Therefore, it would be beneficial in the future to confirm them in a controlled experiment using industry professionals. However, getting the support of enough industry professionals and developing a relevant and publishable design task with them is difficult.

The importance of having physical examples for each DHAM is repeatedly expounded on by the participants. Their praise of the DHAM objects falls mainly into two categories: quicker understanding of the DHAM and the ability to 'play' with a real example. The DHAM cards are in English, but the objects are languageless. Although all of the engineers that participate in this study speak English well, it is the native language of only one of them. This may factor into why they gravitate toward the DHAM objects: when the objects are there to supplement the information on the cards, language is less of a factor. This indicates that the DHAM may be useful in cross-cultural design situations and that significant changes to the DHAM are not needed for different cultures. Additionally, the ability to 'play' with an object may help the user of the DHAM understand the concept faster (Spallek & Krause 2017) and possibly help them retain the information longer (Golinkoff, Hirsh-Pasek, & Singer 2006). This is also supported by some of the statements in Table 7, in which the users indicate their ability to quickly recall the objects in the future through a small reminder, and in Table 5, in which some of the participants specifically mention liking to play with the objects. Therefore, H2 is considered confirmed.

The statements indicating that the DHAM are useful for teaching others, and implicitly oneself, about the unique capabilities of AM are direct support of the stated goal of the development of the DHAM, indicating that this goal is at least

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Table 7. Suggestions for use of the DHAM with supporting comments

Suggestion for Use	Supporting Comments
1 hour group ideation session	The 1 hour ideation session was a good length. (Company B)
Use during group brainstorming sessions	In my daily work? Maybe yes? But I think they would be much more useful in such group brainstorming sessions. (Company A)
Lay cards and objects out on table for session	It's nice to have everything laid out so that you can sort of take in everything at a glance. (B.1)
	It would be better to lay them out in 8 rows (one for each category), so that I can see the different categories better. (B.1)
Have more physical card sets than cubes available	Cards alone are also quite helpful when you have already seen the objects once. (B.2)
	You do not need as many physical objects as card sets. You could have one or two physical sets in a central location, and then let everyone have a set of cards at their desk. (B.1)
	We could get one set of the DHAM and set them up in our MakerSpace for the development teams to come by and use. (B.2)
	You could also visualise the cubes digitally. Then you only need to have the cards next to a digital representation that you can just scroll through on your computer. Once you have had the cubes in your hand once, all you need is the images/digital representation to remind you. (B.3)
Attach company-specific success stories to each DHAM	It would really help us in convincing people to consider AM as a manufacturing option if we would attach specific internal examples to the relevant heuristics, when we implement an AM project at the company. (B.2)
Do not use with greenfield projects	This method would be difficult to use in a greenfield development project, as you really need a part with which to start. (B.4)
More applicable for multi-component products	This method is much more applicable to multi-component tools, but it gave us some good ideas to start thinking. (Company C)
Pilot workshop may be necessary before widespread use would be accepted	I was sceptical before we tried using it on a 'real' project. Seeing that it actually helps generate developable concepts changed my mind. (C.1)

Abbreviation: DHAM, Design Heuristics for Additive Manufacturing.

qualitatively achieved. Additionally, the participants talk about using the DHAM as a comprehensive checklist about what is possible with respect to AM, something that is mirrored in the questionnaire responses, where the lowest rating given is *neither agree nor disagree*. This indicates that from the industry perspective, the DHAM are providing a comprehensive view of the possibilities of AM.

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Statement	Mean Rating (Strongly Disagree / Disagree / Neither Agree nor Disagree / Agree / Strongly Agree)	Mode	Min	Max
DH for AM help me to generate more ideas.	1.42	Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM help me to generate higher quality ideas (quality = fulfills design requirements, technically feasible).	0.63	Neither Agree nor Disagree	Neither Agree nor Disagree	Strongly Agree
DH for AM help me to generate a wider variety of ideas.	1.53	Strongly Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM help me to generate more novel ideas.	1.37	Agree	Neither Agree nor Disagree	Strongly Agree
Learning to use DH for AM is easy.	1.00	Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM are easy to use.	1.05	Agree	Disagree	Strongly Agree
DH for AM are useful early in the design process.	1.17	Agree	Disagree	Strongly Agree
DH for AM provide the information I want/need early in the design process.	0.95	Agree	Disagree	Strongly Agree
The information provided by DH for AM is structured in a useful way.	1.05	Agree	Neither Agree nor Disagree	Strongly Agree
The information provided by DH for AM is structured in an easy to understand way.	1.33	Strongly Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM offer a comprehensive view of the capabilities of AM.	1.16	Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM provide me with information about the opportunities provided by AM.	1.11	Strongly Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM provide me with information about the restrictions of AM.	-0.42	Neither Agree nor Disagree	Strongly Disagree	Agree
DH for AM provide information in a variety of formats.	0.68	Agree	Neither Agree nor Disagree	Strongly Agree
DH for AM are applicable to both single parts and assemblies.	1.22	Agree	Disagree	Strongly Agree
DH for AM are AM-process and material independent.	0.11	Neither Agree nor Disagree	Disagree	Agree
DH for AM is useful for AM-Novices.	1.17	Agree	Disagree	Strongly Agree
DH for AM is useful for AM-Experts.	0.94	Agree	Disagree	Strongly Agree

Figure 6. Summary of the questionnaire results, $n = 19$.

5.2. Suggested Improvements

In addition to the praise, there is a variety of criticisms about the DHAM as well. In contrast to the praised abilities, most of the critical points stem from one or two comments. However, there are three criticisms that repeatedly appear. The first repeated criticism is that the real-world examples are on the back of the cards instead of the front. Although the contents of the cards, both back and front, are explained before the ideation session begins, some of the participants never turn

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over the cards during the session, and some do not even realise that there is a backside, despite the explanation. This may partially stem from how the cards and objects are lain out on the table during the session; because the object sits on top of the card, the participants may be discouraged from picking-up and flipping over the card. However, as the laying-out of the cards is positively commented on by the participants, it is not suggested to change this layout method. Additionally, each of these workshops is the first experience that the participants have with using the DHAM. As they use them more often, they may grow more familiar with the DHAM, which could alleviate this problem. This familiarity may also address the feeling that participant A.5 has about accidently breaking one of the objects.

Related to the concern about breaking the objects, is the concern that the participants will not be able to produce their own copy of the objects because of a lack of the necessary AM machines. As described by Blösch-Paidosh & Shea (2021), effort was taken to make as many of the objects as possible manufacturable with a dual-extruder desktop FDM printer exactly to address this accessibility concern. However, due to the nature of some objects, for example, inclusion of multiple colours, adaption was not possible for all objects. However, any of these special objects should be manufacturable through online 3D printing services. The perceived difficulty around the procurement of a set of DHAM objects may also be overcome by reducing the number of DHAM object sets needed at one company by distributing digital copies of the cards and objects to whomever would like them, but keeping only one or two of the physical object sets in a central location such as the ideation room or MakerSpace, as per the suggestion of the participants at Company B.

The second repeated criticism relates to the number and types of examples provided. Some of the participants, particularly those at Company C, would like to see more examples directly connected to specific AM-processes and materials. This desire to see more examples is a sentiment echoed by the novice designers of the previous DHAM user studies (Blösch 2020). As this feedback is coming from both novices and experts, some more examples could be added, but maximum one or two per heuristic, because if too many examples are added it becomes a different type of design support method, e.g., a design catalogue, like Weiss *et al.* (2015), instead of heuristics. Another option would be to include access to a database similar to that of Bin Maidin (2011) that connects each of the DHAM to the AM artefacts used to derive it, so as to give the users another way to access more examples if desired, but keep the number of immediate examples low.

Two of the companies (Companies B and C) are concerned about the lack of metal objects and metal examples, and during the ideation session, some participants sometimes seem hung-up on the material of the objects. Company B mainly manufactures products out of metal and the participants at Company C work specifically on metal products produced by the company, whereas the participants at Company A work regularly with both polymers and metal. The participants that work regularly with both materials may be better at transferring the principles indicated in the objects to different materials than those that work primarily with one material. This feeling may also be part of the reason that the statement *DHAM are AM-process and material independent* receives the second lowest rating. Although all of the DHAM are broadly applicable to different AM-processes and materials and include real-world examples utilising various materials and processes, the fact that all of the objects are fabricated using polymers may be

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biasing the responses of the participants. As one of the main goals of the DHAM is to be AM-process and material independent, this effect should be investigated in future research. This is the first indication that H3 is not fully confirmed.

The third repeated criticism is that the DHAM do not provide the user with specific next steps for implementing their AM-enabled concepts. The goal of the DHAM is to provide inspiration, not implementation instructions (Blösch-Paidosh & Shea 2019). However, if the users need assistance in taking the next steps with regard to implementing their ideas, perhaps some sort of support system for this needs to be considered. One option would be to include some suggested implementation resources such as software, complementary methods or papers as references on the back of each card. A second option would be to integrate the DHAM into a DfAM-supplemented design process framework in which methods developed by various researchers and industrialists could be recommended for use during each design phase, as an extension of the work of Pradel *et al.* (2018).

5.3. Suggestions for Use

Several recommendations for future use of the DHAM are also made by the participants. Generally, they like the 1-hour ideation session format and that the DHAM cards and objects are spread out on the table for them to have a good overview. Additionally, although they could see themselves using the DHAM as a sort of checklist for AM alone at their desk, they see their primary function in a group brainstorming session. They also intimate that they do not see these as useful for a blue-sky development project, as one needs a starting design or concept to which one can apply the DHAM, i.e. something to re-design. This statement is consistent with the idea that design heuristics are concept modifiers, not concept generators. This is a limitation on the usefulness of the DHAM. However, according to Jensen (1999), '80% of all designs are adaptive or variant, that is, a design based upon a well-known solution principle'. This is the vast majority of all design, which therefore makes them a relevant and useful design method despite the limits on their use.

Related to the types of applicable design scenarios for DHAM, Company C works on a single-part product during their workshop, but thinks that the DHAM would be more useful when developing concepts for some of their other multi-component products. In contrast to this statement, Company A, who reacts most positively to the DHAM of all of the companies involved in the workshops, also applies the DHAM to a single part product. Both of the design tasks previously employed in the controlled user studies with novice designers are multi-component products (Blösch-Paidosh *et al.* 2019; Blösch-Paidosh & Shea 2019; Blösch-Paidosh & Shea 2021). Conflicting evidence surrounding this statement means that no definitive recommendation can be made.

Statements from the participants also indicate that their companies could be hesitant to regularly implement the DHAM in design sessions and implement AM in general. Two suggestions are provided by the companies to address this. The first is to do some trial workshops using business unit projects and not only Research and Development projects to demonstrate how effective use of the DHAM can be in order to get buy-in from management and designers. The second recommendation, is to start attaching existing, company specific (i.e., internal) examples to each of the relevant heuristics so that users do not only have the general examples

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to work from, but also see how their company has applied them. Doing this could help customise the DHAM to each company that integrates it into their design process, which could increase their willingness to use it and, potentially, the effectiveness.

A final important note, is that since the conclusion of the workshops, all three companies that participated in the workshops have gone on to acquire a set of the DHAM cards and objects to use during future brainstorming sessions. Additionally, one of the companies used the objects to help instruct their employees in the capabilities of AM during a large company workshop.

Based on the feedback of the participants during the workshops, the following recommendations can be made for using the DHAM in future ideation workshops:

(i) Use an existing product that the participants already know as a starting point (i.e., no blue-sky projects).
(ii) Previous experience with the DHAM is not necessary for a successful workshop, although a basic awareness of AM is beneficial.
(iii) Laying the DHAM cards out in a gallery allows for a collaborative approach.
(iv) It is highly preferable to have a printed set of the DHAM objects available for the session.
(v) If the budget permits it, make sure some of the DHAM objects are printed in something other than polymers, for example, metal, to show the material independence.
(vi) If the company or group already has some existing examples of AM applications in their repertoire, the DHAM cards can be augmented to use these as examples.
(vii) The workshop does not need to be long; 1-hour of ideation time appears to be sufficient.

5.4. Fulfilment of Early-Phase DfAM Characteristics

According to the results of the questionnaire, the DHAM fulfil[1] 12 of the 18 characteristics identified as necessary for early-phase DfAM methods, and partially fulfil[2] 4 of the 18. That the vast majority of the mode responses are positive and many of the minimum response values are neutral indicates general agreement on the ability of the DHAM to fulfil the 18 characteristics of early-phase DfAM methods. As previously mentioned, it is concerning that it is not clear that the DHAM are process and material independent. However, the fact that the DHAM do not seem to fulfil the criteria of providing information about the restrictions of AM is not surprising, as this was never the intent of the DHAM (Blösch-Paidosh & Shea 2017; Blösch-Paidosh & Shea 2019). From the results of this questionnaire, it can be said that the DHAM cards and objects generally fulfil criteria for early design phase DfAM methods as defined by literature; however, H3 cannot be fully confirmed.

[1]Defined as a mean rating of ≥ 1.00.
[2]Defined as a mean rating of >0.50.

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5.5. Comparison to Novice Designer Studies

When compared to the previous controlled user studies with novice designers, the following is found:

(i) The DHAM are an effective tool for both novice and experienced designers.
(ii) The DHAM are effective not just in fabricated design situations, but also in industry-derived design scenarios.
(iii) Working in teams, novice and experienced designers use the DHAM cards in a similar fashion.
(iv) Evidence from industry qualitatively confirms the numeric increases in creativity metrics found in controlled studies with novices.

6. Conclusion

The goal of this paper is to evaluate the DHAM card and objects (Blösch-Paidosh & Shea 2021) in an industrial setting with expert designers. A total of 3 workshops are conducted with 19 different participants at 3 companies from 3 different engineering industries. Verbal feedback on the method is collected from the participants and analysed by clustering similar responses together to determine the praised advantages, suggested improvements and suggestions for use of the DHAM. Additionally, the participants answer a questionnaire to determine how well the DHAM fulfil the characteristics desirable in early-phase DfAM methods. The verbal response to the DHAM is overwhelmingly positive, however, some suggested improvements provided by the participants should be considered in any further development. Additionally, the DHAM are considered to embody 16 of the 18 DfAM community-defined characteristics for early-phase DfAM methods. The failure to fulfil one of these criteria (*providing restrictive DfAM information*) is expected, but one is not (*AM process and material independence*). The results confirm two of the three hypotheses, and partially confirm the third.

Glossary

AM	Additive Manufacturing
AMK	Additive Manufacturing Knowledge
DfAM	Design for Additive Manufacturing
DHAM	Design Heuristics for Additive Manufacturing
FDM	Fused Deposition Modelling

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