Design Science

Characteristics of effective design support: insights from evaluating additive manufacturing design artefacts

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Abstract

Evaluation approaches are needed to ensure the development of effective design support. These approaches help developers ensure that their design support possesses the general design support characteristics necessary to enable designers to achieve their desired outcomes. Consequently, evaluating design support based on these characteristics ensures that the design support fulfils its intended purpose.

This work reviews design support definitions and identifies and describes 11 design support characteristics. The characteristics are applied to evaluate a proposed design support that uses additive manufacturing (AM) design artefacts (AMDAs) to explore design uncertainties. Product-specific design artefacts were designed and tested to investigate buildability limits and the relationship between surface roughness and fatigue performance of a design feature in a space industry component. The AMDA approach aided the investigation of design uncertainties, identified design solution constraints, and uncovered previously unknown uncertainties. However, the results provided by product-specific artefacts depend on how well the user frames their problem and understands their AM process and product. Hence, iterations can be required. Based on the evaluation of the AMDA process, setting test evaluation criteria is recommended, and the AMDA method is proposed.

Keywords: additive manufacturing, characteristics, design artefact, design support, surface roughness

Received 07 March 2023
Revised 19 September 2024
Accepted 20 September 2024

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Des. Sci., vol. 10, e38
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2024.43

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CAMBRIDGE UNIVERSITY PRESS

1. Introduction

Additive manufacturing (AM) refers to the joining of materials to create parts through a layer-by-layer process (International Organization for Standardization 2021). Using metal AM technologies like laser powder bed fusion (LPBF), which uses a laser beam to melt powdered metal to form parts, designers can manufacture innovative and customised near-net-shape part designs. As the layer-by-layer process of AM technologies provides unique capabilities for shape, hierarchical, functional, and material complexities (Gibson, Rose, & Stucker 2015), over time, traditional subtractive design methods have become unsuitable for the capabilities offered by AM technologies, and designers require new design support for thinking additively (Yang & Zhao 2015; Prabhu et al. 2020; Valjak et al. 2020). As designers have spent many years working with conventional manufacturing techniques, it may be challenging to break out of their conceptual barriers and conceive designs compatible with AM (Seepersad 2014). Hence, the design for AM (DfAM) field has emerged to support designers as they try to exploit the design potentials of AM (Laverne et al. 2015).

DfAM support has been developed in several formats. Adam and Zimmer (2014) developed geometry-focused process-independent design rules for AM by printing test specimens using three AM technologies (LPBF, laser sintering, and fused deposition modelling). However, they stipulate that their design rules are only valid within the set boundary conditions from which they were derived (e.g., the material, machine, and parameters). Becker et al. (2005) summarised some of the AM design opportunities and provided a set of design principles to direct designers to adapt their design thinking to the possibilities of AM. Diegel, Nordin, and Motte (2019) created a practical guide for DfAM that provides considerations for designing a part with minimal print time, reduced post-processing requirements, and reduced anisotropy. However, the rules and principles listed by Becker, Grzesiak, and Henning (2005) and Diegel, Nordin, and Motte (2019) are quite general, focusing on aiding designers in considering the best utilisation of AM and its capabilities in their products. Diegel, Nordin, and Motte (2019) also stated that the number-one rule of DfAM is '*it depends*', which means that design rules are variable and dependent on the geometry, part, materials, and AM technology. Thus, few design rules are universally applicable to AM, and emphasis should be placed on using process-specific design supports and test prints to balance design innovation and product realisation feasibility.

Design support is an overarching term that covers many ways to improve design, such as methods, rules, and guidelines (Blessing & Chakrabarti 2009). This article uses 'design support' as an umbrella term for these concepts. The results or knowledge obtained from design support depends on how the support was developed, and several factors contribute to the effectiveness of design support in aiding the designer and providing design understanding (Cash, Daalhuizen, & Hekkert 2023). Developers of design support need to ensure that their design support can achieve its intended outcomes correctly. To provide this assurance, evaluating the design support to validate it by demonstrating its usefulness concerning a purpose is required (Pedersen et al. 2000). Blessing and Chakrabarti (2009) and Jagtap et al. (2014) highlight that many tools, methods, and guidelines have weak foundations due to being poorly evaluated. Lack of evaluation has been noted as one of the issues concerning the transfer of methods from academia to industry (López-Mesa & Bylund 2011; Gericke, Eckert, & Stacey 2022). Despite design supports being significant and standard in design practice, little information is available to understand how and why design methods work (Daalhuizen 2014; Dalsgaard 2017).

Appropriate evaluation approaches are needed to evaluate DfAM supports for their effectiveness to confirm the development of helpful design support. Design support developers need to evaluate their support to determine if its application has led to the achievement of their intended goals and improved the design situation had the support not been used (Blessing & Chakrabarti 2009). To evaluate design support appropriately, one must understand how design supports work, the content of the support, and what makes the design support '*good*', i.e., how one can say design support has performed well.

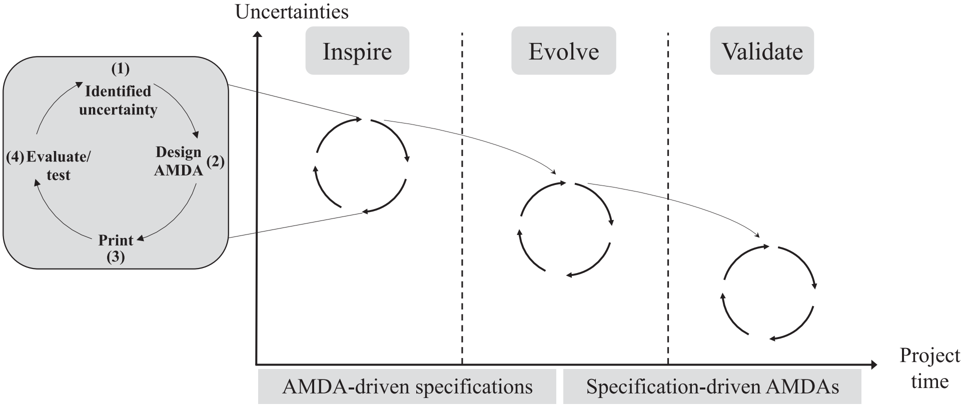


Figure 1. The design process with AMDAs as support (adapted from Dordlofva & Törlind (2020, p. 5), with permission).

1.1. The AM design artefact process

A proposed DfAM support for addressing the variability of design issues specific to AM is utilising AM design artefacts (AMDAs). As illustrated in Figure 1, the AMDA process proposed by Dordlofva and Törlind (2020) describes a systematic means of creating artefacts that investigate specific AM design uncertainties relating to the AM process and part geometry.

The AMDA process was proposed through interactive research between researchers and engineers at companies in the European space industry to develop an understanding of AM process capabilities (Svensson, Brulin, & Ellström 2015). The engineers identified AM-related design uncertainties within their products and then purposely designed test artefacts to explore these uncertainties.

The AMDA process encourages a designer to constrain the prototype design to test a critical assumption using the prototype. The AMDA process is a prototype-driven design approach in which the designer identifies design uncertainties and designs and prints product-specific design artefacts. These artefacts are subsequently evaluated to help reduce uncertainties and increase knowledge, thereby supporting DfAM through iterative testing. As indicated in Figure 1, the artefacts serve different purposes in each phase of the three-phase model: inspiration, evolution, and validation. During the inspiration phase, multiple AMDAs are constructed to explore feasible design opportunities through AM and investigate the uncertainties associated with achieving these opportunities. During the evolution phase, the design features acquire detail through further testing and evaluation of evolved solutions. In this manner, the AMDAs drive the design specifications (AMDA-driven specifications). Finally, more comprehensive prototypes can be used for validation as the design specification is set (specification-driven AMDAs) (Dordlofva & Törlin 2020).

In contrast, other DfAM supports are often set within the boundary conditions of their development and focus solely on ensuring the buildability of an AM design (Adam & Zimmer 2014). Metal AM guidelines predominantly focus on guiding to ensure the manufacturability of parts (Kokkonen et al. 2016; Schnabel, Oettel, & Mueller 2017; Diegel, Nordin, & Motte 2019). However, they often lack detailed guidance on the specific adverse effects of a particular design choice. For example, although Kokkonen et al. (2016) provide a guide for minimum wall thickness, stating that it should be 2/3 times the laser focus diameter to reduce heat accumulation and subsequent thermal stresses and distortion, they do not guide the magnitude of distortion at thickness variations. As a DfAM support, the AMDA process can provide targeted design support by investigating the specific AM process's capability and design implications. Design artefacts can be designed to investigate both buildability and the impact of specific design choices on other factors, such as performance, thereby allowing a holistic and comprehensive approach to design support. Through the prototype-driven approach, the AMDA process acknowledges the context-dependent nature of DfAM problems, encouraging the creation of context-specific design knowledge rather than adhering to pre-established general design rules and guidelines.

1.2. Purpose of the study

The purpose of this study is to evaluate the AMDA process and identify areas for improvement. This paper begins with a background on design support evaluation, followed by an analysis of design support literature to formulate and propose an evaluation approach. Subsequently, the AMDA process is evaluated based on its use in an industrial case study. The evaluation is conducted using the formulated evaluation approach, and the AMDA process is compared against alternative design support. The evaluation and comparison leads to a proposal for further developing the AMDA process. The study closes with conclusions, limitations, and future research directions.

2. Design support evaluation

The research outline of the AMDA process is illustrated in Figure 2. The observations of Dordlofva and Törlind (2020) were formulated into the AMDA process and proposed as a process that engineers employ to aid them in AM design. However, an evaluation of the AMDA process and its usefulness in supporting engineers in achieving their desired outcomes has not been thoroughly done. Additionally, such an evaluation can identify areas for further development of the AMDA process as a design support.

2.1. Design support effectiveness, efficiency and efficacy

Blessing and Chakrabarti (2009) state that a difficulty in developing design support is that the characteristics that make support effective depend on the user, the

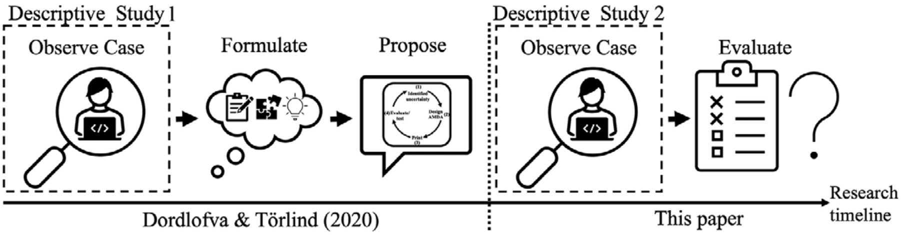


Figure 2. Illustration of the AMDA research development.

support itself, and their interaction. They review the two types of measurement suggested by Rossi, Lipsey, and Freeman (1982) regarding efficiency in a design support context: cost–benefit and cost-effectiveness. Understanding the financial implications of design choices is crucial. Cost–benefit assessment, for instance, is a measure of the monetary investment in using a support, such as a cost calculation for achieving a particular result. On the other hand, cost-effectiveness is a measure of the outcomes of the support, such as the cost spent to reduce development time by x%, which may not always be easily translated into a monetary value. Hence, creating metrics for design support effectiveness can be difficult and is relative to the user's needs. For example, CAD software that takes 1 h to analyse several variables accurately to process a design solution could be seen as good in a multinational industrial project with a 5-year development timeline. In comparison, 1 h for analysing a component design as part of an undergraduate student project with a 2-week deadline could be considered an inefficient use of project resources. In both scenarios, the solution outputted has high fidelity, but in the second scenario, the fidelity is not required.

Daalhuizen and Cash (2021) proposed that a method's efficacy and effectiveness should be evaluated to understand the relationship between its content and performance. They conceptualise and define method content as the internal elements of a method and their inter-relationships. They describe efficacy as how well a method supports the transfer of knowledge to a user and the effectiveness of a method as how well it supports designers in achieving the desired effect in context. They further state that the efficacy is typically tested under controlled conditions, whereas the effectiveness is typically tested in real-life conditions. Similarly, Gericke, Eckert, & Stacey (2022) suggest that during an evaluation, the performance or quality of a design support is assessed by measuring its effectiveness, efficiency, and overall impact. The validation square proposed by Pedersen et al. (2000) suggests that assessing the effectiveness and efficiency of design support is required for method validity. Pedersen et al. (2000) define design method efficiency as the provision of design solutions '*correctly*' and efficiency as a method's competent use of resources, i.e., costs and time. Further, Pedersen et al. (2000) suggest that one reviews the design solutions' performance to measure a design method's effectiveness. However, it should be noted that a poor-performing design solution does not necessarily imply that the design method used was poor. As Roozenburg and Eekels (1996) argue, design methods aid in searching for design solutions, but they do not guarantee that the desired solution will be found. Seepersad et al. (2010) build on the work of Pedersen et al. (2000), stating that a method is effective implies that the individual constructs of the method are acceptable, the internal consistency (how the constructs are assembled) is acceptable and that the method is being used in an appropriate problem that allows for the verification of the performance of the method. Seepersad et al. (2010) additionally consider that method efficiency implies that the outcome of a design method is useful with respect to its purpose, that this usefulness is linked to the application of the method and that the usefulness of the method is beyond some limited instances, i.e., in a more general sense. In examining design supports within the works of Daalhuizen and Cash (2021), Gericke, Eckert, and Stacey (2022), Pedersen et al. (2000), Seepersad et al. (2010), and Blessing and Chakrabarti (2009), no author employs all three terms: effectiveness, efficiency and efficacy. For comparison, Table 1 presents definitions of effectiveness, efficiency and efficacy from design research literature and dictionaries.

Table 1. Design literature textbooks and dictionary definitions of effectiveness, efficiency and efficacy

Ref.	Effectiveness	Efficiency	Efficacy
Pedersen et al. (2000, p. 4)	*'We associate usefulness of a design method with whether the method provides design solutions 'correctly (effectiveness) … Correct in this context are design solutions with acceptable operational performance…'*	*'We associate usefulness of a design method with … whether it provides 'correct' design solutions (efficiency). Correct in this context are design solutions…, that are designed and realized with less cost and/or in less time.'*	No definition.
Daalhuizen and Cash, (2021, p. 6)	*'Effectiveness relates to how well a method allows designers to achieve the desired effect in context, typically tested in real-life conditions.'*	No definition.	*'Efficacy relates to how well a method supports the transfer of knowledge to the user and its effect on the designer's behaviour, that is the direct effect of the content on a designer, typically tested under controlled conditions.'*
Blessing and Chakrabarti (2009, p. 204)	No definition.	*'Efficiency of the support, that is the cost against the benefits.'*	No definition.
Cambridge Dictionary (2023)	*'The quality of being successful in achieving what is wanted.'*	*'The quality of achieving the largest amount of useful work using as little energy, fuel, effort, and so forth as possible.'*	*'The ability of something to produce the intended result.'*

The AMDA process supports designers in understanding how to design a product for AM, utilising AM's potential benefits, ensuring buildability, and fulfilling performance requirements. Therefore, this paper focuses on evaluating the *effectiveness* of the AMDA process and defines *design support effectiveness* as how well it allows designers to achieve their desired outcomes.

2.2. Approaches for design support evaluation

Approaches to the evaluation of methods have focused on the effect of the method on the design output/outcome (Frey & Dym 2006; Daalhuizen 2014). However, it is important also to understand the relationship between the method and its user and its final impact when evaluating its effectiveness (Cash, Daalhuizen, & Hekkert 2023). The design research methodology (DRM) of Blessing and Chakrabarti (2009) recommends conducting a descriptive study to validate developed design support. Validation involves the evaluation of a support's impact and the extent to which it improves the previous design situation. The DRM provides an approach to support evaluation, but that evaluation method requires specific steps to be followed during support development. Hence, assessing support against the metrics stipulated in the DRM will be complex if the support has not been developed following the DRM steps exactly. AM design support evaluation approaches have included user workshops (Kumke et al. 2018; Lindwall & Törlind 2018; Blösch-Paidosh & Shea 2022) and user surveys (Kumke et al. 2018; Lauff et al. 2019). The use and review of design support with designers in practice reveal the capabilities of the design support; however, little information is provided regarding the elements of the support that enable it to be successful (Gericke, Eckert, & Stacey 2022; Gray 2022), and no established procedure for design support assessment exists (Gray 2022). Gray (2022) described the characteristics of design methods through different vocabularies to help identify and describe the components of methods that are key to their performance potential. Gray (2022) built three vocabularies for describing the characteristic qualities of methods: a codification-oriented vocabulary, a performative vocabulary, and a presentation-focused vocabulary. First, a codification-oriented vocabulary involves the shape and purpose of the method. Second, a performative vocabulary involves the explicit inputs, potential outputs, and mechanism of the method. Third, a presentation-focused vocabulary includes the type of guidance, format, and medium of the method. Kumke et al. (2018) used a workshop and post-workshop user feedback to evaluate opportunistic DfAM support, focusing on understanding how design supports can optimally support the user. They derived a set of evaluation criteria from research on design methods and DfAM requirements to formulate their basis for evaluation. Several researchers have conducted evaluations of DfAM support for early-phase design in an industrial setting (Kumke et al. 2018; Dordlofva 2020; Prabhu et al. 2020; Blösch-Paidosh & Shea 2022). Early-phase DfAM support helps designers understand AM design capabilities (Blösch-Paidosh & Shea 2018; Lindwall & Törlind 2018). There are a few industrial examples of evaluating DfAM support for more detailed design stages. At the detail design stage, the designer's decisions are related to the design optimisation of their product and addressing specific DfAM challenges like feature size, feature shape, eliminating features requiring support, and adding material for post-processing operations (Pradel et al. 2018).

Evaluation of design supports against their characteristics has previously been used to assess and compare the effectiveness of design support (Self 2011; McAtee et al. 2009; Zhang et al. 2019; Blösch-Paidosh & Shea 2022). A characteristic is defined as a typical or noticeable feature of someone or something (Cambridge Dictionary 2022). Blösch-Paidosh and Shea (2022) conducted a literature survey to identify 18 early design phase DfAM methods characteristics from 19 academic works published between 2011 and 2019. Using these characteristics, they evaluated AM design heuristics and objects used in the industry with design experts. Blösch-Paidosh and Shea (2022) focused on the characteristics of early-phase DfAM support alone, and their work did not provide an in-depth description. Through a review of literature in different fields of design practice, Self et al. (2016) developed a framework called the Five Universal Tool Characteristics (UTC) to describe and evaluate the abilities of design tools for supporting designers. Their five characteristics were '*mode of communication*' (the extent to which the support communicates design ideas to others), '*level of ambiguity*' (how ambiguous an idea can be represented), *'transformational ability'* (the extent the tool can aid the movement between design ideas), *'level of detail'* (how detailed a design can be communicated), and *'commitment'* (how the tool communicates the level of commitment to a design idea). Zhang et al. (2019) expanded the list of UTCs by analysing literature on design tool performance. Subsequently, they used characteristics as an evaluation tool through a case study to evaluate the use of digital sketching tools in practice.

The characteristics produced by Self et al. (2016) were developed based on designer behaviour and interaction with design tools. The UTCs were further developed by Zhang et al. (2019) by exploring literature regarding the capabilities designers gain from using design tools and designers' physical and mental input.

Considering that '*good*' design supports have characteristics that allow them to effectively support the user (Self 2011; McAtee et al. 2009), this study proposes to formulate a set of general design support characteristics derived from literature definitions and descriptions of various design support types. Definitions and descriptions of design support in the literature provide explicit or implicit explanations of what makes design support effective. By comparing definitions and descriptions and grouping their themes, general characteristics of different types of design support can be identified, thereby forming a basis for evaluating the effectiveness of design support grounded in their constructs. Additionally, design support developed within a specific industry may have contextual relevance, emphasising specific characteristics unique to their needs. Understanding these contextual differences can help distinguish general characteristics from context-dependent ones.

2.3. Design support definitions

A literature review of design support terms, definitions, and descriptions was conducted to identify design support characteristics and provide a method to evaluate and improve design support. Two approaches were used to identify the definitions. First, a structured, systematic literature review was conducted using four PRISMA review phases: identification, screening, eligibility checks, and inclusion of articles (Moher et al. 2009). The systematic review comprised five stages: database searches, de-duplication, an eligibility assessment, a full-text review, and qualitative synthesis. The search term (*"design support"AND definition*) was used for the systematic review, thereby enabling the identification of definitions and descriptions of design support in product and engineering design across multiple industries. The objective of the literature review was to identify articles relating to the research or development of design support that included clear definitions of support terms or design support requirements.

The search was conducted on titles, abstracts, and keywords using the SCOPUS and Web of Science web databases. These databases were selected based on the breadth of subject areas and the literature types covered (Aghaei Chadegani et al. 2013). Once both databases had been searched, 161 articles were acquired, compiled into a spreadsheet, and screened for duplicates using conditional formatting, following which duplicates were manually deleted. Following de-duplication, 125 articles remained, and their titles and abstracts were read to assess their eligibility for a full-text review. The articles reviewed were published in the 10 previous years at the time of writing (2012 to 2022) and were required to focus on product or engineering design and design support development to be eligible for the full-text review. Following the first round of eligibility evaluation, 16 articles remained for the full-text review, and nine provided a precise definition or description of the design support type under development. The search was repeated 1 year later, and seven more papers were identified. However, none met the eligibility criteria, and they were all excluded. A more targeted literature review was conducted using canonical and seminal design engineering and product development textbooks to complement the systematic review. This approach identified design literature textbook definitions and descriptions, allowing for a more informative analysis (Huelin et al. 2015). The scope of the definitions searched within the targeted literature was determined by the terms identified from the articles in the qualitative synthesis of the systematic review. The sources were constrained to design literature textbooks and selected according to their credibility and contribution based on their scholarly impact in the design field. The books can be described as classics owing to their longevity; that is, the first edition was published over 20 years ago, and the book had high citation rates; that is, they have been cited more than 500 times (according to Google Scholar at the time of writing). A flow diagram of the systematic literature review and the details of the six targeted review sources are listed in the Appendix.

The definitions of design support terminology have previously been reviewed; for example, in the work of Fu, Yang, and Wood (2016), who conducted a targeted review to identify definitions of the terms *'design guideline*', *'design heuristics'*, and *'design principles'* to propose more formalised definitions. Various definitions of design support exist, and multiple disciplines conduct design work. Therefore, it is beneficial to consider the different types of design support, how they operate, and the general characteristics that make them effective in supporting design. Owing to the substantial diversity of design support types, reviewing design support terms allows for the differentiation and detailing of their positive support characteristics. Moreover, studying definitions from researchers who have developed design support can enable an understanding of suggested considerations within design support.

The systematic review of design support revealed definitions and descriptions for the following design support terms: *design support*, *design support system*, *design tool*, *design method*, *design methodology*, *design guidelines*, *design heuristics*, *design principles, and design guidelines.* These terms were identified as the types of design support developed or researched within the acquired articles. Once the terms were identified, the corresponding definitions for each design support term from the systematic review were searched in the targeted literature. Upon reviewing the definitions, it was noted that the terms *rule* and *procedure* were commonly used in the definitions of the design support terms. Hence, the targeted literature search was extended to include the definitions of *design rules* and *design procedures.*

The definitions and descriptions of the design support terms obtained from the systematic and targeted reviews are presented in Table A2 of the Appendix. Eight terms to describe design support were identified from 16 sources. In total, the review identified 39 descriptions and definitions of design support. The definitions obtained were not evenly distributed in the literature; most were found in the books of the targeted review, with 27 definitions from the books and 12 from the literature search. The term *design methodology* was found the most, with nine definitions from six sources. Then, the term *design method*, *design support*, and variations of both terms were identified within five sources each. *Design tool* was defined within four sources, *Heuristic* and *guidelines* in three, and *procedure*, *rules* and *principles* in two. There was also variation in the naming of some of the support terms. The review identified three variations of *design support* and *heuristic* and two variations of the terms *methodology*, *tool* and *procedure.*

2.3.1. Design support/support system

Three variations of the term design support were found in the review: design support, support system, and process support system. Blessing and Chakrabarti (2009) defined design support as: “*all possible means, aids and measures that can be used to improve design. These are prescriptions – suggesting ways by which design tasks should be carried out – and include strategies, methodologies, procedures, methods, techniques, software tools, guidelines, knowledge bases, workbooks, etc.*’ The definition by Blessing and Chakrabarti (2009) of design support covers everything a designer can use to aid design. Scurati et al. (2022) surveyed academic and industrial stakeholders to create design support for sustainability considerations during the early design phase. They defined eight success criteria from their interviews and ranked them as high/medium/low according to the priority level of the criteria for successful design support. The three high-priority success criteria were ‘*communicate complexity*’ to avoid oversimplifying the problem, ‘*enable quick what-if assessment loops*’, and ‘*support tacit knowledge sharing*’. Design support was described as a system by Zanic, Andric, and Prebeg (2013) and Zanic (2013), whereas Pikas et al. (2019) defined the term *design process support system.* Zanic, Andric, and Prebeg (2013) and Zanic (2013) defined a design support system as something that supports stakeholders in their decision-making during design. In contrast, Pikas et al. (2019) described its purpose as a means of aiding error, performance, and knowledge management. Pikas et al. (2019) and Scurati et al. (2022) noted the need for design support owing to the complexity of design activities.

2.3.2. Design tool

Blessing and Chakrabarti (2009) described a design tool as something that is used in design support; that is, a design tool supports the use of a design method or design guidelines. Other authors have defined design tools more generally. Akturk (2017) described design tools as things that aim to aid a designer by simplifying and connecting the theory of a product to its practical design; a design tool should provide guidance and approachable goals to users. Yang, Ong, and Nee (2016) defined design tools and methods as entities that help address and relieve problems. Moreover, Pahl et al. (2007) equated design tools and procedures, noting that they support a designer in analysing their design and improving the design by, for example, reducing the cost or improving the quality.

2.3.3. Design method

Cross (2000) defined a design method as any identifiable means of conducting design. This definition suggests that the term *design method* could be used as an umbrella term for all design support terms, such as design *aids*, *tools*, and *procedures.* Design methods have also been defined as a composite of design activities (Cross 2000; Blessing & Chakrabarti 2009) and sets of rules to be followed (Hubka & Eder 1982; Roozenburg & Eekels 1996). Design methods support design by providing a path for designers to follow, which leads them towards a design solution (Hubka & Eder 1982; Roozenburg & Eekels 1996). As suggested by the word '*intended*' in the definition of Hubka and Eder (1982) and the phrase '*no guarantee*' in that of Roozenburg & Eekels (1996), while a method provides a path in the hope of moving a designer towards a design solution, design methods lack an assurance that it will lead where the designer hopes. A design method can be viewed as an activity that aids in moving forward within the design process but not necessarily in the desired direction of the designer. A design method provides all users with the same logical pathway; however, their interpretation of the method dictates their destination. Different users of the same method that addresses the same problem may produce different results.

2.3.4. Design methodology

The design methodology was revealed to have multiple definitions. Design methodology refers to the study of methods (Roozenburg & Eekels 1996). It has been used to describe the use of a group of design supports, such as methods, rules, and procedures, together (Hubka & Eder 1982; Roozenburg & Eekels 1996). Furthermore, the term generally describes the overall design activity (Hubka & Eder 1982; Blessing & Chakrabarti 2009; Delponte et al. 2015). Wollschlaeger & Kabitzsch (2020) defined four requirements for a design methodology to support the design of personalised assistance systems for patients. According to their requirements, a design methodology should be efficient, customisable, and automatable and provide the designer with multiple solutions. Roozenburg and Eekels (1996) further stated that a design methodology should encourage creativity. According to Cross (2000), a design methodology should ensure that the design problem is fully understood to guarantee that an excellent solution to the correct problem is obtained. Pahl et al. (2007) stated that design methodology must emphasise the need for an objective evaluation of the design results. Hence, a methodology should not only guide a design solution but also encourage the assessment that the solution is good. Furthermore, Pahl et al. (2007) defined a '*general working methodology*' as something that should be widely applicable, independent of discipline, and not require specific technical knowledge for its use. Pahl et al. (2007) described a general working procedure as a systematic procedure consisting of heuristic principles that must satisfy a set of conditions. These conditions are as follows: '*define goals*' to provide insight into the design problem and ensure motivation to find a solution, '*clarify conditions*' by defining constraints, '*dispel prejudice*' to allow consideration of all possible solutions, '*search for variants*' to enable the identification of multiple solutions, '*evaluate*' using the goals and constraints that are set, and '*make decisions*' according to the evaluation.

2.3.5. Design heuristics and design principles

Valjak and Lindwall (2021) reviewed design heuristics and principles in the context of AM. They stated that heuristics help designers perceive the unique capabilities of AM and can be used as creative inspiration during concept generation. Valjak and Lindwall (2021) also noted that design principles support the early design phase and help designers realise their designs in a suitable form for AM. Hubka and Eder (1982) described design principles as a fundamental truth on which other laws are dependent or from which they are derived, and as idealised methodical rules that guide the design process implementation. Pahl et al. (2007) used the term *heuristic principles* to describe the constituents of a general design methodology and defined a heuristic as a creativity technique or method for idea generation and solution finding. Hubka and Eder (1982) described the term *heuristic procedures* in their discussion of design engineering as a mental activity that can be considered through the psychology of thought processes. Hubka and Eder (1982) further defined the following principles for heuristic procedures: '*ensure motivation*', '*show limiting conditions*' (identify constraints), '*dissolve prejudice*' to allow for objectivity, '*search for variants*', and '*reach decisions based on evaluations of maximum objectivity*'. The principles for heuristic procedures listed by Hubka and Eder (1982) are almost identical to the conditions of a general working procedure outlined by Pahl et al. (2007).

A notable work on design heuristics, guidelines and principles definition that was not accounted for within the parameters of the literature review but is discussed in the creation of the definitions by Valjak and Lindwall (2021) is that of Fu, Yang, and Wood (2016). Fu, Yang, and Wood (2016) characterise design heuristics as the context-dependent provision of design direction that increases the chance of reaching a satisfactory, but not necessarily optimal, solution. They emphasise that heuristics are based on intuition and/or experimental understanding, focusing on reducing solution search time in a '*quick and dirty*' manner. Hence, they provide generally reliable results but are fallible depending on the circumstances in which they are being applied (Fu, Yang, and Wood 2016). Conversely, design principles, like the definition provided by Hubka and Eder (1982), are fundamental rules that provide design guidance towards reaching a successful solution, which has been derived from extensive experience and evidence.

2.3.6. Design guideline

Using design guidelines in the earlier product design phase aids decision-making when detailed information is unavailable (Ulrich & Eppinger 2012). The description of a design guideline provided by Yang, Ong, and Nee (2016) implies that design guidelines efficiently address the barriers and challenges with the specific conditions of a product design. Blessing and Chakrabarti (2009) defined guidelines as useful for designers to follow to achieve their design objectives. Furthermore, Blessing and Chakrabarti (2009) combined the terms rules, principles, and heuristics under the label of design guidelines. Notably, for a clearer differentiation between design guidelines principles and heuristics, Fu, Yang, and Wood (2016) describe design guidelines as a characteristic blend of design principles and heuristics. They assert that while guidelines are based on extensive experience, they are not fundamental; instead, they are context-dependent means of directing the design process to reach a successful solution.

2.3.7. Design procedure and design rule

Through a review of the obtained definitions, the words *procedure* and *rule* were observed to be common in the definitions. Hence, the targeted literature search was expanded to include definitions of the terms *design rule* and *design procedure* for a deeper analysis of design support. The term *procedure* was found in the definitions of design support, design method, design methodology, and design tool. Pahl et al.

(2007) stressed that it is important to define a design procedure to identify good design solutions, but that a design procedure should also be flexible, plannable, optimisable, and verifiable. They also highlighted that a designer must work systematically and already have knowledge of their field to realise a design procedure.

The word *rule* was found in the definitions of design method, design methodology, design principle, and design guideline. Design rules can be used to communicate constraints to a designer (Ulrich & Eppinger 2012). According to Roozenburg and Eekels (1996), design rules can be of two types: algorithmic and heuristic. Algorithmic rules are unambiguous and set in order, leading to a precise result. In comparison, a heuristic design rule promotes the determination of a result but leaves room for creativity and serendipitous results (Roozenburg & Eekels 1996).

2.4. Design support characteristics

Through analysis and summarisation of the design support definitions obtained, 11 characteristics were identified and are presented in Table 2.

The effectiveness of design support relates to how well the design support allows designers to achieve the desired outcomes, that is **finding a design solution** with an acceptable operational performance. Additionally, effective design support can find a solution even with minimal detail and in a short time, often defined intuitively as a certain percentage of the project time. Though the time saving from using the design support is relative, a characteristic of design support is to prevent time wastage by enabling **quick and iterative** provision of solutions and analyses as required (Scurati et al. 2022). The solutions should be *'correct'* enough to **aid decision-making** towards the next step in the design process (Zanic 2013). In doing so, the design support outlines the steps needed to advance in the design process. It **provides a path** to either the correct solution or a functional solution or

Table 2. Design support characteristics

Characteristic	Description	Supporting literature
1. Aids decision-making	Design support should aid designers in making well-informed design-related decisions	Ulrich and Eppinger (2012); Zanic (2013); Zanic, Andric, and Prebeg (2013)
2. Emphasises the need for evaluation	Evaluation is a high-priority criterion for design support. A designer should be able to assess the likely outcome of their decisions based on the design support results. Hence, an objective evaluation of the design support results should receive particular focus within the design support structure, and design support should ensure that the evaluation and assessment of results are clearly defined activities.	Hubka and Eder (1982); Pahl et al. (2007); Scurati et al. (2022)

Continued

Table 2. Continued

Characteristic	Description	Supporting literature
3. Communicates constraints	Design support should assist the designer in identifying the constraints and clarifying the feasible solution space.	Hubka and Eder (1982); Pahl et al. (2007); Ulrich and Eppinger (2012); Yang, Ong, and Nee (2016)
4. Aids creativity	Design support should encourage creativity during the process of idea exploration when generating design solutions.	Roozenburg and Eekels (1996); Pahl et al. (2007); Valjak and Lindwall (2021)
5. Provides a path	Design support should aid designers in moving forward during the design process and lead them towards a design solution.	Hubka and Eder (1982); Roozenburg and Eekels (1996); Cross (2000); Pahl et al. (2007); Blessing and Chakrabarti (2009); Delponte et al. (2015)
6. Communicates complexity	Design support should be capable of informing designers of all relevant factors that affect and are affected by their design decisions, thereby capturing the reality of the design situation without oversimplification.	Pikas et al. (2019); Valjak and Lindwall (2021); Scurati et al. (2022)
7. Supports knowledge management	Design support should facilitate knowledge management to prevent errors during the design process. Additionally, the sharing and communication of all available knowledge that can be used to solve design problems should be encouraged through design support.	Blessing and Chakrabarti (2009); Pikas et al. (2019); Scurati et al. (2022)
8. Is quick and iterative	Design support should enable designers to predict outcomes for the most informed decisions, preventing designers from wasting time through quick decisions and allowing rapid progress.	Scurati et al. (2022)
9. Defines goals (ensures motivation)	Design support should assist a designer in describing their design's goals and assessing whether they are achievable. The designer then becomes assured of their motivation to use the design support to find design problem solutions.	Hubka and Eder (1982); Pahl et al. (2007); Blessing and Chakrabarti (2009); Akturk (2017)
10. Is objective	An unbiased evaluation of the results must be possible for the design support to be effective.	Hubka and Eder (1982); Pahl et al. (2007)
11. Finds a solution and allow for multiple solutions	Design support should not internally pre-specify a solution but facilitate the identification of all possible solutions within the frame of the design problem that is presented. The quality of the solutions depends on the quality of the problem description; however, even with little detail, the design support should provide workable solutions.	Hubka and Eder (1982); Roozenburg and Eekels (1996); Cross (2000); Pahl et al. (2007); Wollschlaeger and Kabitzsch (2020)

helps eliminate poor solutions, thereby narrowing the scope of solutions. However, in narrowing the solution scope, design support should not have an internal construct that leads to a pre-specified solution. The inputs should affect the output and **allow multiple solutions** to be found when feasible. An example of exhibiting this characteristic would be CAD software, which allows for many solutions depending on how much input a designer gives. Conversely, a website design template with limited customisation options would not.

Internal evaluation constructed within the design support was found to be a high-priority characteristic of the design support description (Hubka & Eder 1982; Pahl et al. 2007; Scurati et al. 2022). Therefore, there should be an **emphasis on the need to evaluate solutions** within the support (Pahl et al. 2007). For example, design supports that present data on design considerations like structural integrity exhibit this characteristic well, as the supports enable a designer to evaluate if the solution will meet their design requirements. The design support and solution evaluation should also be **objective** (Hubka & Eder 1982; Blessing & Chakrabarti 2009). A designer should be able to assess the design support solutions without any influences or preferences not set by the designer. Design supports developed by a specific organisation may have a bias for design styles or a specific design approach within their design support. If not aware of these internal preferences when presented with the results through the support, they may be influenced to evaluate a solution that meets those preferences more highly.

Design support should allow for a clear and concise understanding of feasible designs within the design problem (Pahl et al. 2007; Ulrich & Eppinger 2012). AM nesting tools enable users to prepare their builds within models of their AM machine. These tools make the user aware of constraints impacting their print, such as build volume and allow them to evaluate these constraints, thus exhibiting the characteristic of **communicating the constraints** of a design to the user. Further, design supports should **communicate the complexity** of design solutions to reduce errors (Pikas et al. 2019). AM build preparation tools have features that highlight recommended zones for support structures, showing a designer where a design feature may be unfeasible to build through the software's understanding of build complexity. Some AM design supports simplify these complex decisions automatically by inserting support structures or adjusting the design orientation. Design support should communicate the complexity to a designer but also allow them to make their own decision on if, for example, support structure is required for a section. Further, effective design support **aids the creativity** of the designer by keeping their design options open (Roozenburg & Eekels 1996). Oversimplification of the complexities of the design can take away some of the creative freedom of a designer and prevent serendipitous design solutions.

In using design support, the designer should be able to articulate and communicate the objectives of their design clearly, that is the support should help **define the goals** of the design (Pahl et al. 2007; Akturk 2017). When designing a product, a goal could be reducing manufacturing time by x%. Effective design support for this goal in AM would provide information on factors like print time or required post-machining area (Ahn, Kim, & Lee 2007), enabling a designer to evaluate the feasibility of their x% goal and ensure the designer is motivated to achieve it. Design support is further effective when the knowledge of the feasibility of solutions, the constraints of design spaces and the complexities impacting a solution is shared and managed through it. By **supporting knowledge**

management, design support reduces the chances of users making errors (Pikas et al. 2019). Design teams have tools such as collaborative platforms that can be integrated into design software to share learnings. Similarly, open-source design guideline libraries can be integrated within design supports to help communicate an up-to-date understanding of design knowledge and solutions.

Reviewing the definitions in section 2.3 led to identifying characteristics of effective design support; that is, characteristics that make design support *'good'*. These characteristics differ from those identified by Blösch-Paidosh and Shea (2022), who focused on characteristics for early-phase DfAM evaluation. Some of their characteristics are general and are applicable for evaluating the AMDA process, such as *'is easy to use'*, *'is easy to learn how to use'*, and *'structured in an easy to understand way' [sic]*. Other characteristics, such as *'Provides information in a variety of formats'* and *'Provides the information necessary early in the design process*', are more specific to early-phase DfAM support evaluation. There are also similarities in the characteristics identified by Blösch-Paidosh and Shea (2022) and this work, such as *'structured in a useful way'* [sic] and the design support characteristic of *provides a path*. Both characteristic descriptions refer to the ease at which a user navigates and is guided towards design knowledge through design support. Similarly, their characteristics related to AM ideas generation, such as the support increases the *'number'*, *'quality'*, *'variety'* or *'novelty'* of AM ideas generated, are similar to the *aids creativity* and *finds a solution and allows for multiple solutions* design support characteristics. These characteristics are related to design support encouraging variations in design solutions.

Assessing the general applicability is essential in defining and proposing general design support characteristics. This assessment ensures that the characteristics are not dependent on the application area or specific type of design support. A review of the sources of the literature was conducted to evaluate this and examine the distribution of the characteristics across the different types of design support and their development contexts. The review revealed that of the 39 definitions and descriptions of design support terms, 27 came from design literature textbooks, providing definitions in a general context. The remaining 12 definitions were sourced from discipline-specific literature on design support development in AM, healthcare, architecture, sustainability, ship manufacturing and construction. Thus, the identified characteristics could have been influenced by the design support development research context, potentially making them specific to particular contexts. Upon reviewing for potential contextual biases, it was found that the characteristics were distributed across the various design support types and development contexts, signifying their general applicability. However, some characteristics were notably associated with specific design support types. The characteristic '**provides a path**' was noted most frequently, identified from 12 definitions. It was especially prominent in design method and methodology, with five and four instances respectively. The next most general characteristic for design support was **'Finds a solution and allows for multiple solutions'**, noted seven times, with three instances for design methodology and two for design procedure. Other characteristics were each identified in no more than two definitions across various types of design support, with the characteristic **'define goals'** noted twice in the definitions of design tools and **'aids creativity'** noted twice for design heuristics. The generalisability of the 11 characteristics means that they can be used to evaluate a wide range of design supports across different contexts and applications. However, the findings indicate that the specific type of design support being developed influences which characteristics are particularly important or expected by users. Therefore, when using general design support characteristics for evaluation, it is important to recognise that not all characteristics will hold equal importance in every situation. Thus, consideration should be taken of the kind of design support being developed and its objectives when evaluating the various characteristics, as some may conflict. If, for example, a design support prioritises offering a distinct, clear, and detailed path towards finding a design solution, this might inhibit the designer's creativity, potentially reducing the support's ability to **aid creativity**. Similarly, if design support is intended for use within a limited time, the characteristic of **quick and iterative** becomes more relevant for its evaluation. However, design support that is quick to use and easy to repeat may not fully **communicate the complexity** of a design problem due to the limited time available to process or define the problem in detail.

The review of the definitions provided valuable insight into characteristics for consideration when developing design support. Further, the review highlighted the variety of available design support types and the complexity of their content and structures, providing details on the distinctive features that differentiate the design support types. The 11 characteristics listed in Table 2 are initial proposals. Further research will be necessary to validate them. However, understanding these differentiating features of design support can aid in evaluating and developing design support with appropriate structure and naming, depending on the goal of said support.

3. AMDA case study

A detailed description of the implementation of the AMDA process is required to evaluate its effectiveness as a design support using the 11 identified design support characteristics. The following section presents the background of the design issue, which is the context for the AMDA evaluation. First, the description of a unique AM design uncertainty related to a design feature in a rocket engine turbine manifold with a consolidated design, illustrated in Figure 3, is presented.

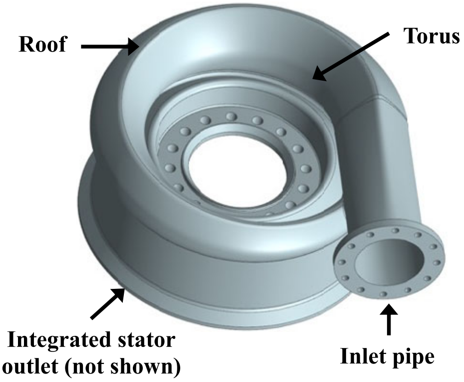


Figure 3. A rocket turbine manifold with an integrated stator.

3.1. LPBF surface roughness design considerations

Although AM technologies such as LPBF provide design engineers with new geometric freedoms, there are still limitations to this freedom. Complex geometries may require support structures to ensure a successful build when taking advantage of the geometric complexity that LPBF offers. In many cases, the support structure is impossible or impractical to remove or adds unnecessary post-processing that diminishes the advantages of AM (Zink et al. 2020). An example of accessibility issues of support structure removal is LPBF part designs with enclosed inner volumes, making reaching the internal areas challenging (Obilanade, Törlind, & Dordlofva 2022). When using LPBF for manufacturing parts with unsupported areas, the newly printed material in the unsupported area overhangs the powder, and the melt pool may sink into the powder bed below, mixing with unsolidified powder and cooling, causing rough surfaces and dross formation (Charles et al. 2022). Dross is an LPBF phenomenon that mainly occurs on the down-facing unsupported and overhanging surfaces of LPBF parts owing to insufficient heat transfer and, as illustrated in Figure 4, may result in a reduction in the dimensional accuracy (Kokkonen et al. 2016). Furthermore, when two separately built part islands meet, the residual stresses at their junction layer pull the material islands together, disrupting the underlying part and powder, thereby increasing roughness. This phenomenon is known as transversal shrinkage, and as with dross formation, it causes rough surfaces and geometric deviations from the part design, as illustrated in Figure 4. Hence, the roughness of surfaces is intrinsically linked to design choices.

Down-facing overhang areas, such as the inner roof of the manifold depicted in Figure 3, may be critical for a part, as the surface roughness is high in these regions, which can negatively impact the part's mechanical properties (Dhansay, Tait, & Becker 2014). Post-processing methods are often used to improve the surface and performance (Sagbas 2020). For example, Kahlin et al. (2020) found that using centrifugal finishing, shot peening, and linishing increased the fatigue strength of rough as-built LPBF Ti-6Al-4 V test specimens by 125%, 70% and 25%, respectively. However, consolidated parts can make post-processing difficult due to the challenge of accessing enclosed areas. The surface roughness complicates the use of

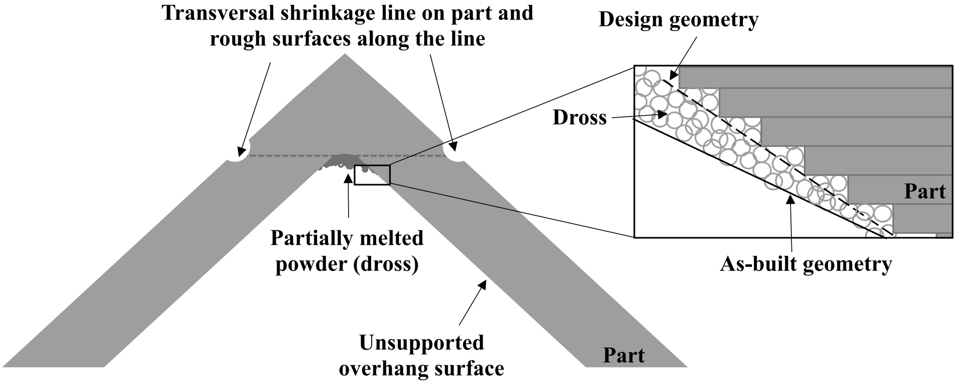


Figure 4. Illustration of an unsupported roof section with geometric inaccuracy owing to partially melted powder, inspired by Gumbleton et al. (2021).

LPBF as it presents challenges for characterisation and analysis; hence, there is a need for more standardised data on the effect of the surface finish on the mechanical performance of the parts (Diaz 2019).

Research and development of DfAM support for addressing LPBF surface roughness is ongoing. For example, Zhou et al. (2021) have developed design guidelines and a friction factor prediction model for calculating the pressure loss in LPBF-fabricated fluid channels. Other DfAM support for surface roughness focuses on aiding the designer in selecting the optimal build orientation to minimise surface roughness (Ahn, Kim, & Lee 2007; Azar et al. 2021). However, such supports are ineffective when, for example, size limitations or other factors restrict the orientation. Furthermore, few standards are available regarding understanding the surface finish requirements of LPBF parts (Lee, Nagalingam, & Yeo 2021). Moreover, the variation in the thermal history of AM parts causes concerns regarding the mechanical properties generated from standard test specimens when designing and evaluating load-bearing AM components (Pegues et al. 2018). Therefore, it is necessary to develop design procedures and standards to better understand the relationship between the AM test specimens and part performance (Yadollahi & Shamsaei 2017).

3.2. AMDA industrial case study

Dordlofva and Törlind (2020) studied the use of the AMDA process as engineers at a space industry company used it to investigate uncertainties related to designing the rocket engine turbine manifold depicted in Figure 3. The consolidated design with an integrated stator outlet implied an unsupported inner design due to concerns about support removal. The designers identified the unsupported roof of the enclosed internal volume as a critical design feature and used the AMDA process to investigate LPBF design limits regarding unsupported roofs. The purpose of the investigation was to obtain an additional understanding of LPBF unsupported roof design limits and the impact of surface roughness on fatigue and investigate alternative testing methods for verification/validation. Dordlofva & Törlind (2020) conducted an analysis of the engineers' use of artefacts to investigate the relationship between LPBF process limits, design choices, surface roughness and fatigue. The engineers began by evolving the roof design by designing a series of artefacts to explore the buildability limits of unsupported roof geometries (RG), as shown in Figure 5.

The build results of printing the RG artefacts showed the machine's capability to manufacture unsupported geometries and enabled the identification of an appropriate unsupported roof geometry for the product. Once an appropriate roof geometry was identified, the design uncertainty of the impact of the roof surface roughness on the mechanical properties was investigated through artefact A, shown in Figure 6 (left), and its geometry is detailed in Table 3. Artefact A was printed and fatigue tested at two radii, R1 and R2. R1 represented the unsupported roof radius, and R2 represented a radius printed parallel to the build direction, that is, supported from the build plate. The fatigue testing results on the two different radii indicated a negative impact of surface roughness on fatigue life (Dordlofva & Törlind 2020).

As explained by Dordlofva and Törlind (2020), artefact A was designed to evaluate an alternative test method for investigating the roof radius (R1) surface

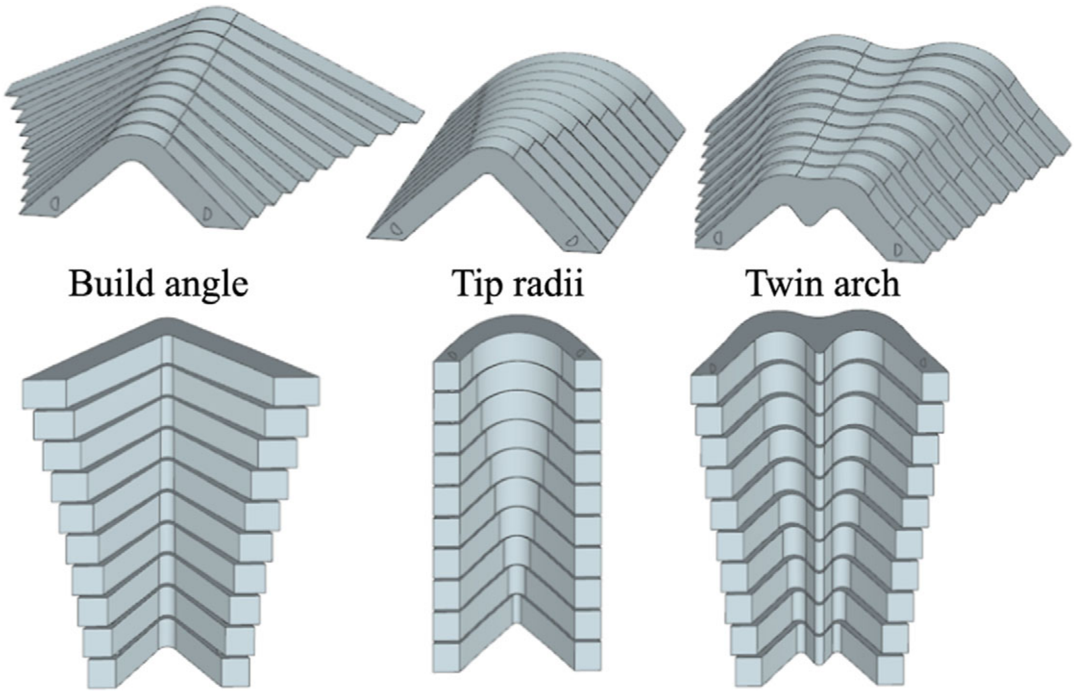


Figure 5. Roof geometry artefacts designed to test the machine's capability for manufacturing potential roof geometries, revised from Dordlofva and Törlind (2020).

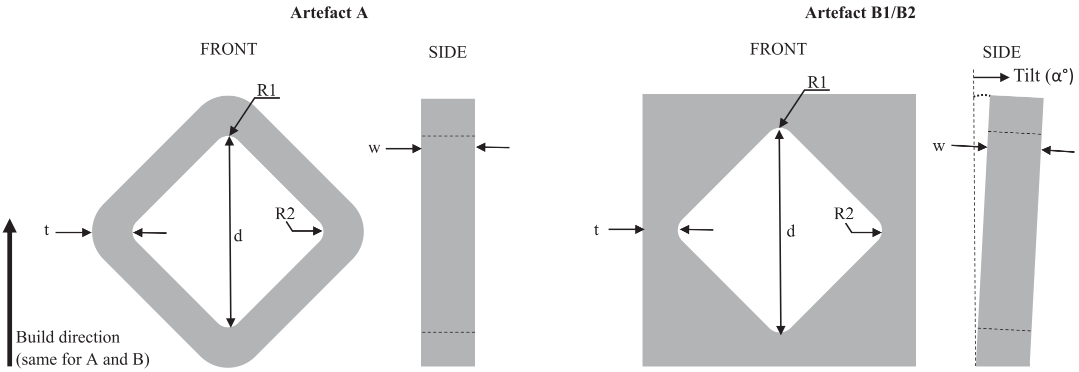


Figure 6. Diagram of artefact iterations A (left) and B1/B2 (right) (Obilanade, Törlind, & Dordlofva 2022).

Table 3. AMDA artefact geometries (all internal angles = 90°) (Obilanade, Törlind, & Dordlofva 2022)

Artefact	Diagonal width, *d* (mm)	Artefact width, *w* (mm)	Thickness, *t* (mm)	Inner radius, *R* (mm)
A	45	12	8	4
B1 (as-built)	45	12	8	4
B2 (to be machined)	44	12	8.5	4

condition and to compare it to a smoother radius, the reference radius (R2). The investigation aimed to understand the fatigue behaviour and predictability of R1/2. Hence, a similar, but not identical, radius value to the selected design was deemed sufficient for this investigation. On visual inspection of the A artefacts, the R1 radii had a substantially rougher surface than that of R2, as observed in Figure 7(a) and (c).

R1 and R2 of artefact A were measured. The average radius for the printed artefacts was 2.7 mm and 3.9 mm for R1 and R2, respectively (Obilanade, Törlind, & Dordlofva 2022). Figure 7(a) shows that R1 had a high level of dross formation, thereby creating a much rougher surface than R2. In R1, transversal shrinkage occurred, as indicated by the distortion line at the roof junction layer in Figure 7(b), leading to the geometric deviation from the design. The fatigue testing results suggested that the geometry and surface roughness affected the artefact mechanical properties. However, a transition line from a smooth to a rough surface was observed where the artefact arm design changed from the R2 radius to an unsupported 45° overhang surface, as seen in Figure 7(c). The abrupt change in the surface condition at the transition line is believed to have caused the point of fatigue failure of R2 to occur off-axis, as can be observed from Figure 7(d). Due to the off-axis fatigue failure, the engineers concluded that the artefact fatigue results, although informative, lacked a comparison between the roof radius and the reference radius. Consequently, these results did not accurately represent the design uncertainty under investigation. Thus, they designed and printed artefact B, as described in Figure 6 (right) and Table 3, to better focus the artefact

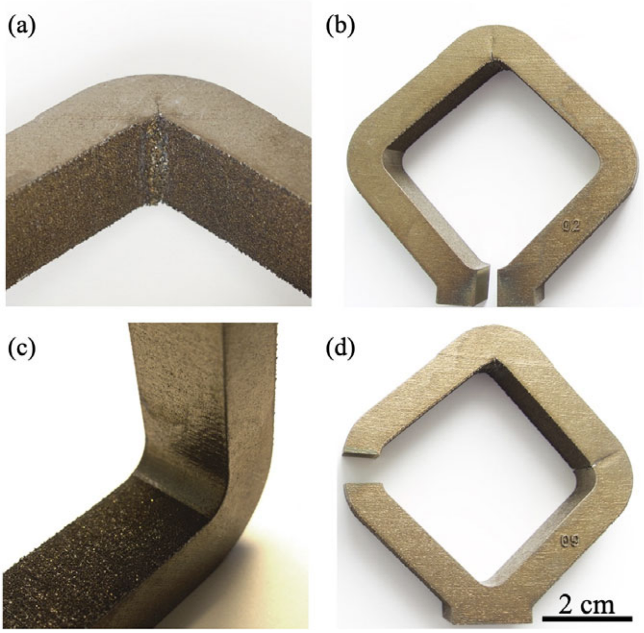


Figure 7. (a) Artefact A's surface condition post-test roof radius R1, (b) roof radius after fatigue testing, (c) surface condition of reference radius R2 (oriented bottom-up), and (d) reference radius after fatigue testing (Obilanade, Törlind, & Dordlofva 2022), [Courtesy of P. Åkerfeldt, Luleå University of Technology].

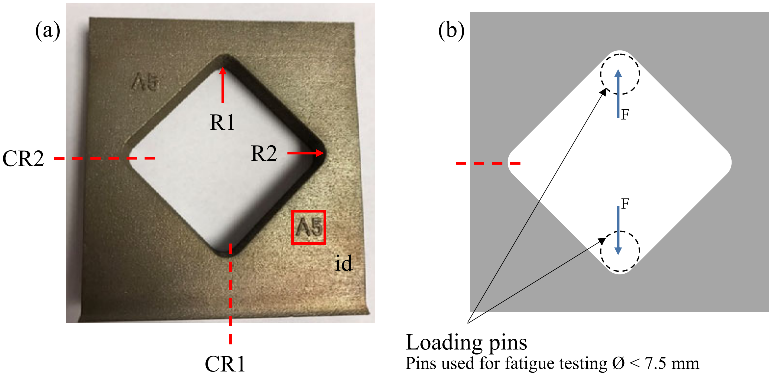


Figure 8. (a) Image of the B artefact indicating the radius notations R1 (roof) and R2 (reference) and the cut locations for radius investigation, namely CR1 (cut to investigate R1) and CR2 (cut to investigate R2). (b) Diagram of the applied cyclic load for examining the artefact radius.

design on the studied uncertainty, i.e., the comparison of the impact of surface roughness in the roof radius and reference radius.

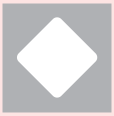
Artefact B was designed with two significant changes: a tilt and a square geometry. The tilt was introduced to counteract the impact of transverse shrinkage and reduce dross formation at R1. With a tilt, the R1 junction plane gradually connects over several layers, thereby reducing the impact of thermal stresses as these layers cool (Kokkonen et al. 2016). The square geometry of artefact B was designed to prevent R2 off-radius failure at the roughness transition line by causing the failure to occur at the weakest point on the artefact, the radius. Furthermore, the scope of investigation for artefact B was expanded to include a verification study of the obtained results. Thus, artefact B had two designs, as shown in Table 3. The B1 design was fatigue tested in the as-built condition, whereas the B2 design was machined using milling to obtain the same dimensions as B1 before fatigue testing. An indication of the material properties of the design geometry could be obtained by testing and comparing results from the two conditions. This would help determine whether the performance of the feature could be better understood with these artefacts.

The B artefacts were cut at two locations in preparation for fatigue testing: opposite the R1 roof radius and opposite the R2 reference radius. The positions of the cuts are denoted as CR1 and CR2, which correspond to their related radii, as illustrated in Figure 8(a). A cyclic tensile load could be applied to the radius opposite the cut by applying the load perpendicular to the location of the cuts, as depicted in Figure 8(b). The printing and fatigue testing for both artefacts A and B was conducted using the same LPBF machine and fatigue test settings.

4. Evaluation of the AMDA process

The identified design support characteristics are used in this section to evaluate the effectiveness of implementing the AMDA process. This article defines design support effectiveness as its ability to help designers achieve their desired outcomes. Therefore, the AMDA process results are also evaluated against alternative design

Table 4. AMDA process overview

Artefact	Roof geometry (RG)	Artefact A	Artefact B
Identified uncertainty	Design limits of self-supporting overhangs	Internal surface roughness and its impact on mechanical properties	
Artefact Design			

support approaches, i.e., what would have happened during the case study if only existing DfAM methods and guidelines had been used. Blessing and Chakrabarti (2009) suggest that to evaluate the state of improving the effectiveness of design support, one needs to either compare a design situation before and after using support or compare the situation with and without the support. By comparing the case study results (supported by the AMDA process) with alternative designs (using existing methods), one can better deliberate on the added value of the design support (Daalhuizen 2014). Suggestions for developing the AMDA process are then proposed based on the evaluation of its use in the case study. An overview of the AMDA process case study is provided in Table 4.

4.1. Aids decision-making

The designers in this study used the RG artefacts to evaluate unsupported roof designs. The results obtained from the RG artefacts gave the designers a clearer understanding of the unsupported design limits; hence, the RG artefacts aided decision-making by providing the designers with an initial proof of concept for the roof geometry during the embodiment phase.

The designers could have found a solution from the self-supporting hole designs of Thomas, Computer, and Product (2010) or Diegel, Nordin, and Motte (2019), although both suggest a maximum unsupported wall angle of 45°. Alternatively, Kranz, Herzog, and Emmelmann (2015) and Diegel, Nordin, and Motte (2019) suggest 12 mm and 8 mm as a limit for unsupported channel diameters, respectively. Diegel, Nordin, and Motte (2019) also offers a picture series on the impact of unsupported angles on an LPBF part and a guide to maximum overhang angle for various materials. Standards such as ISO/ASTM 52910 (2017) and ISO/ASTM 52911-1-19 (2019) describe the issue of self-supporting features but direct to the use of support structure or orienting the part. ISO/ASTM 52911-1-19 (2019) states a self-supporting limit range from 30° to 45°. While these design guidelines, standards and 45° limit provide valuable design support information, they are limited in their application by factors like material, machine and specific product requirements.

The results obtained from the RG artefacts overcome this issue. They indicated to the designers the feasibility of designing wall angles less than 45° and provided insights on the condition of the down-skin surfaces at various roof designs. These insights enabled the designers to make informed decisions on a feasible design, considering both product-specific geometry and process-specific capability. The AMDA process in this case study strongly aided decision-making as the RG artefacts enabled the selection of a feasible solution with more context than had the alternative guidelines or standards been followed. To better aid decision-making, the AMDA process could include a more detailed and structured approach to the recording and presenting of artefact results, directing the user to conduct detailed documentation.

4.2. Emphasises the need for evaluation

The AMDA process is based on an iterative design-build-test loop where evaluation is explicitly part of the DfAM process. The direction for evaluation comes at the end of the process, in the fourth stage. However, the case study highlighted that consideration for evaluation should begin earlier in the process.

Artefacts A and B were used to investigate internal surface roughness and its impact on design adherence and performance of the design feature. To investigate the design adherence, the engineers measured the R1 and R2 radii of the B1 artefacts and found the average deviation to be less than 10% and less than 5%, respectively, improving the adherence of the radii of artefact A. Additionally, transversal shrinkage was less pronounced at the R1 roof radius of artefact B. Thus, the design changes between the iterations of the AMDA process produced a design artefact more representative of a 4 mm unsupported roof radius than artefact A, as shown in Figure 9(a).

The resultant surface condition was mainly attributed to the expected dross formation in this area. As observed in the case study, further iterations of design artefacts are required if the results of an artefact investigation are still not considered representative. Of the 10 printed as-built B1 artefacts, six were cyclically fatigue tested. Additionally, three machined B2 artefacts were built and cyclically fatigue tested. After fatigue testing, failure was observed to have occurred along the radial axis, as shown in Figure 9(b), leading to the artefact results being deemed representative of the uncertainty investigation (roof radius vs reference radius).

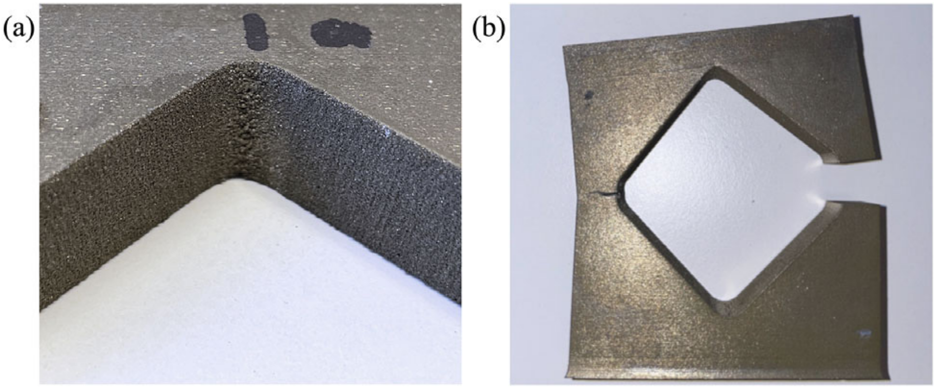


Figure 9. B1 artefacts: (a) B1-R1 (as-built roof) and (b) B1-R2 (as-built reference) post-fatigue testing, indicating on-axis failure.

Table 5. Test evaluation criteria and pass/fail table for the performance uncertainty case study

Criteria		Artefact A		Artefact B	
Requirement	Value	Result	Pass/Fail	Result	Pass/fail
Average radius	X +/− 0.5 mm	$R1 - \bar{X} = X - 1$ mm $R2 - \bar{X} = X - 0.1$ mm	Fail Pass	$R1 - \bar{X} = X - 0.2$ mm $R2 - \bar{X} = X - 0.1$ mm	Pass Pass
On-axis failure?	Yes	No	Fail	Yes	Pass

The case study underscored the importance of evaluating design artefacts to ensure that the artefact represents the investigated uncertainty, providing feedback that reduces uncertainty. This necessity was demonstrated in the case study where artefact A failed to represent the uncertainty correctly. Although the AMDA process already includes an '*evaluate and test*' stage, the review and case study highlighted the value of elaborating on the evaluation further. Given that the evaluation of whether the artefact results adequately represented the uncertainty was based on the subjective judgement of the designers rather than objective measurement, it is difficult to definitively determine that the evaluation goal had been achieved. For the AMDA process to emphasise evaluation, the '*Design AMDA*' stage could be detailed by adding the requirement for the designer to express the design rationale for the artefact (what the designer wishes to learn) through the setting of test evaluation criteria. These criteria should be constructed to tell the designer whether their evaluation is sufficient or whether another AMDA iteration is required during the '*Evaluate/test*' stage. The evaluation criteria and assessment table for the performance investigation of this study could have resembled Table 5, with a pass/fail assessment of the degree to which the artefact represented the design uncertainty. The uncertainty could have been described as the degree of tolerable geometric deviation from the radius value X. The addition of setting the evaluation criteria during the artefact design stage aids the designer's decision-making by simplifying the act of evaluating and identifying unknown uncertainties.

4.3. Communicates constraints

The AMDA process is intended to aid the designer in understanding the restrictions and limitations of the LPBF process. In this case, the designer wishes to understand how they could consider the design limits of the self-supporting overhangs, the internal surface roughness and its impact on mechanical properties. In this study, the RG artefacts were used to explore the limitations of the AM solution space, that is testing the buildability of different roof geometry designs. Hence, an understanding of the machine's capabilities to build self-supporting RG was communicated, and AMDA-driven specifications (constraints) were created. The results from artefact A highlighted how surface roughness can impact performance, communicating a potential material property constraint on the artefact design feature. Artefact B was designed to provide further insight into the impact on design feature performance. Together, the investigations of both artefacts communicate potential design adherence outcomes and effects on the material properties of the design feature, exploring an alternative method for feature verification. The AMDA process successfully provided insights into the buildability constraints and surface roughness implications on the performance of an unsupported design feature.

Other AM design support provides guidance on the constraints of the processes. However, in doing so, support can sometimes hinder the full exploration of AM's capabilities. For instance, in the design method proposed by Orquéra et al. (2017), it is noted that not all functional surfaces can be attained using AM. This suggestion does not communicate the real constraints, but instead, Orquéra et al. (2017) describe the limitation and suggest that a designer must identify if machining is needed on a surface during design. They advocate for using post-processing to overcome surface finish issues, a recommendation also suggested and guided by Salonitis and Zarban (2015). In this case, post-processing would be complex, so the designers have used artefacts to explore the limitations of their design. Kranz, Herzog, and Emmelmann (2015) provide a guide on the average roughness for parts through a table of surface roughness at various angles from the horizontal. However, the table was created specifically for Ti6Al4V LPBF parts. Hence, depending on the material used, the guidance may not be directly applicable. Their guide also suggests orienting the radius of a part to the y–x plane to mitigate the staircase effect, which would not have been feasible in the case study. They further highlight the roughness variability across part shapes, materials, and machines, advocating using small radii for better surface quality.

A key constraint of DfAM supports is their tendency to be highly general or applicable only within specific contexts, such as particular machines, processes, or materials. The underlying idea of the AMDA process is that it should be a relatively quick and iterative process. Consequently, the results depend on the artefact's design, the selected material, and the process. Ultimately, it will only communicate constraints within a limited scope of the solution space. The AMDA process complements both general guidelines and parameter studies, contributing to broader knowledge and a specific understanding of identified design uncertainties. To learn from others' results, designers must understand the constraints of the design knowledge. Clarifying each stage of the AMDA process with more detailed steps and a greater emphasis on documenting decisions and reasoning will enhance the communication of the design knowledge developed.

4.4. Aids creativity

The RG artefacts were built to inspire a self-supporting roof geometry design and are depicted in Figure 5. These artefacts aided the creativity of the engineers by allowing them to explore the design space and test the buildability boundaries, thereby enabling them to find a design that challenges the 45° overhang rule that can be found in many design guidelines and standards (Kokkonen et al. 2016; Diegel, Nordin, & Motte 2019; International Organization for Standardization 2019). The AMDA process mainly aids creativity in the first phase (inspiration), where the engineers used the RG artefacts to explore which designs and radii were buildable. The RG artefacts enabled an investigation into opting for a part consolidation design approach. The A and B artefacts were created in the second phase (evolve) and were designed to evaluate and inspire new (creative) ideas for verification/validation. They focused on investigating the implications of a creative design choice. Thomas, Computer, and Product (2010) outline a range of rules for achieving geometric accuracy through oversizing a part design to enable material removal in the post-processing stage. Oversizing increases costs and manufacturing time by requiring additional post-processing to achieve the desired dimensions, and such an approach would lessen the foreseen benefits of using AM in this case study.

The designers used the artefacts to explore creative solutions and investigate the capabilities of AM. The process output was design knowledge on the practical feasibility of their creative solutions. Design supports can aid creativity by being a means to learn from others, helping designers to understand the boundaries of what is achievable and what has not yet been achieved. A wealth of AM design knowledge is generated in mechanical testing and industry-specific literature that is not documented or shared in tangible ways by designers. Hence, designers can make errors and waste time when being creative due to a lack of awareness of their design's feasibility despite the available useful knowledge. Hence, to strengthen the aids creativity characteristic in the AMDA process, documentation of design knowledge should be an explicit activity through the loop, helping the designers and others explore future creative ideas.

4.5. Provides a path

The AMDA iteration loop provides a logical path for the designer to reduce design uncertainties. The RG artefacts provided a path towards a roof design solution by aiding the designer in exploring possible design solutions when using the LPBF process. The design solution would likely not have been achieved if the general DfAM guidelines were followed (owing to the 45° limit). Artefacts A and B led the designer to gain knowledge regarding the LPBF process and the specific design features. Additionally, even if the AMDA process provides a path of identifying uncertainties, the designers are responsible for developing an artefact that satisfactorily represents this uncertainty: '*Selecting the focus of a prototype is the art of identifying the most important open design questions*' according to Houde & Hill (1997, p. 368). As shown in the case study with artefacts A and B, several iterations may be required to reach the intended outcome.

4.6. Communicates complexity

The AMDA process directs a designer to break down the complexity by identifying the most important uncertainties and how to remedy them. In this manner, the problem is simplified so that it can be investigated quickly. As the artefact is printed, tested, and evaluated, designers learn whether the design uncertainty is sufficiently embodied in the artefact or reveals additional complexity (unknown unknowns). Through the case study, the designers gained an understanding of the complexity involved in manufacturing their geometry.

Regarding the communication of complexity for manufacturing LPBF geometries, other design supports recommend zones of angles for manufacturing. Wang et al. (2013) state that the overhang angle needs to be greater than or equal to 40° for a "*stable fabrication zone*". Within 40° to 35°, they designate the "*critical fabrication zone*", and anything below 35 degrees falls into the "*hard fabrication zone.*" They further communicate the complexity of the design decisions through suggestions of the various process parameters that can be optimised, such as laser energy, to reduce the powder adhesion to the surfaces. Similarly, Thomas, Computer, and Product (2010) advise that the angles should range from around 20° up-facing to 45° down-facing and state that surfaces under 45° require support structures. The design supports of Wang et al. (2013) and Thomas, Computer, and Product (2010) communicate the complexity of manufacturing AM geometry in a general manner.

DfAM support tools and methods acknowledge the complexity of machine-material-geometry relationships by stipulating the limitations of their applicability. This complexity becomes apparent through the evaluation of design artefacts, as the systematic approach allows the communication of the complexity of the machine-material-geometry relationship as the designer considers their uncertainty. The communication of complexity would be better exhibited by the process with more detailed step-by-step guidance rather than the simple logic loop in its current form. More straightforward guidance on the steps for the loop stages will help users navigate and understand the complexities associated with describing and investigating their uncertainty. Coupled with the setting of test evaluation criteria, the designer will also be better directed to identify unknown uncertainties when reviewing their results.

4.7. Supports knowledge management

The AMDA process has been used to explore possible design solutions (validating the buildability of unsupported roof sections) and to acquire knowledge regarding the impact of the surface roughness (the performance indications provided by artefacts A and B). In the case study, most of the knowledge was gained in the evaluation/test stage. Comparing the AMDA process with other more general design methods and tools reveals the absence of a step for documentation and knowledge generation. In this documentation step, knowledge synthesis and generalisation are performed to identify and understand the implications of the results. This step involves interpreting the data in the context of the experimental conditions and comparing it with existing knowledge or predictions. Based on this understanding, designers can develop generalised models or theories that predict behaviour or outcomes beyond the specific conditions of the initial experiments. Knowledge of the influence of other factors would allow for the generalisation of an AMDA study's results when applied in a similar context. However, the window for generalisability could be narrow, particularly if factors are radically changed.

Other design supports require the user to capture and input factor values of their design to utilise the design support. For example, Piscopo, Salmi, and Atzeni (2019) conducted an experimental analysis of AlSi10Mg LPBF AM parts to propose an equation that relates overhang length, the angle from the horizontal (α) and the surface curvature to calculate a surface quality index, suggesting that a surface quality index of less than 0.4 indicates a '*good*' surface. They advise that, for α lower than 37.5°, the combination of overhang lengths less than 6 mm and low curvature leads to favourable results. Their design support supports knowledge management by requiring the designer to record the different variables that impact their design decision. A designer can then refer to the record variables and the knowledge generated to modify their design appropriately. While, like Diegel, Nordin, and Motte (2019), Piscopo, Salmi, and Atzeni (2019) offer a general figure as a guide for the effect of varying the build angle on the surface roughness, the figure's applicability to the material and machine settings of the case study is uncertain, unlike design artefact results.

Boyard et al. (2014) suggest leveraging a CAD database to help define the capabilities of a part design to meet a set function by comparing it to the parts in the database. Design databases could have helped investigate the design uncertainties of the case study. However, creating an effective database requires significant effort and substantial data. Boyard et al. (2014) state that such an exhaustive database's development time and complexity are hard to quantify. Similarly, collating the research regarding process parameters, material characteristics, geometries, and roughness within a database would be of benefit. Further, linking this to a CAD program would enable real-time analysis of the geometric adherence of the part due to the build parameters. However, by using a database, the designer limits the design for AM based on the constraints in which the knowledge of the database was built. When trying to push the design barriers of AM for innovative applications, a designer may come across design uncertainties which have not yet been considered. It may be less effective if the database lacks the information required to address an uncertainty under investigation.

Currently, no specific tasks within the process loop are available to capture knowledge. The setting of evaluation criteria could be an avenue for improving the knowledge management of the AMDA process by creating a more explicit intent for the artefact. With evaluation criteria, designers would be required to clarify their understanding of the uncertainty and expectations of the design artefact through these criteria. The recorded criteria can be reviewed to demonstrate how the knowledge was obtained and the design decisions were made according to what was achieved, thereby aiding the management of knowledge regarding the AM process and the specific design features obtained from the process. If a design artefact satisfies all criteria, the designer gains greater confidence in the knowledge obtained. If an artefact fails a criterion, the designer discovers previously unrecognised uncertainties, as the failure highlights an area in which knowledge of the AM process or AM design feature is lacking. Further, there should be a direction within the AMDA process loop to *capture* (document) design knowledge to encourage any new knowledge developed from the artefact investigation and criteria to be recorded by the designers.

4.8. Is quick and iterative

One aim of design support is to prevent time from being wasted later in the design process through poor design decisions, thereby helping ensure that the correct decision is made earlier. Hence, the design support should be relatively quick to use. The inspiration for the AMDA process is rooted in the three-stage prototyping model proposed by IDEO, as described by Hartmann (2009). This model leverages prototypes for various purposes: inspiration, evolution, and validation. During the inspiration stage, the prototypes are used rapidly and iteratively to explore different design concepts, as described by Lawrence (2003), who suggested the use of '*rapid, rough and right*' principles, whereby early prototypes should be rapidly produced and refined through a series of iterative prototypes. Furthermore, Lawrence states: '*Instead of spending your time and resources speculating solutions and analysing the problem, spend your time solving it. Fail early in order to succeed sooner.*' Thus, the first stages of AMDA are quick and iterative. However, the speed of the process depends on several factors, such as print time and post-processing. The RG artefacts exemplified the concept of rapid prototyping in the case study, for which many geometries were used to assess the construction feasibility. In the subsequent stages, (artefacts A and B), prototypes are used to evaluate specific design questions. Finally, more comprehensive prototypes are employed for validation purposes, in which the artefacts must represent the product (specification-driven prototypes). At this stage, more advanced evaluation methods are used, such as material characterisation, SEM analysis, and microtomography, at which point each prototype cycle becomes slow and expensive.

Further detailing the stages of the process and providing more structure will allow for clarifying the basic steps at each stage. The added clarity will enable the designer to work quicker through the process and iterate their steps more specifically. Further, evaluation criteria will enable a quicker evaluation of the process results.

4.9. Defines goals (ensures motivation)

The AMDA process aims to help designers define their design goals by identifying the most important design issues and creating artefacts to explore and understand them. A designer defines the goal of testing an artefact: what they wish to learn about their design choice through this investigation. In this study, the goal of the RG artefacts was to assess achievable designs and inspire a self-supporting roof design. The goal of artefacts A and B was to explore alternative test methods to validate the surface roughness and its impact on fatigue life. Overall goals for a product are generally set during product development, and these goals may not be specific to Design for AM. However, design supports such as simulation tools, like topology optimisation software, enable designers to define design goals to meet specific properties while adhering to specific design features.

Integrating evaluation criteria into the AMDA process will support designers in clarifying their uncertainty investigation goals by guiding the designer in articulating the goal of the artefact design and testing. When using artefacts, the designer decides when the knowledge generated is ‘*good enough.’* However, complementing this judgement with clear, objective criteria that provide understanding of when the designer should be satisfied with the knowledge acquired, i.e., when the goal of the artefact uncertainty investigation has been achieved, will make it easier to decide on when to continue and move on to the next step of the design process.

4.10. Is objective

The AMDA process aims to be objective by focusing on unravelling specific uncertainties to provide product-specific design and performance indications. However, as the designer’s current understanding of the design and AM process determines the investigated design uncertainties, there is a possibility of bias towards a solution in the first artefact. The designer’s subjective perspective of the design uncertainty influenced their choice of geometries for the RG artefacts, using the AMDA process to inspire a suitable geometry. Moreover, when evaluating the A artefact the designers found that the design did not lead to a representation of the design uncertainty, indicating that the issue was more related to the artefact’s design rather than process-related capabilities.

The objectivity of the artefact investigation is revealed during testing and result evaluation. Data is typically objective, and experimental testing is often relatively objective due to having a defined framework. Design guidelines derived from parametric studies offer objectivity through this approach. Incorporating evaluation criteria can enhance the objectivity of the AMDA process. The designer can make informed decisions based on objective artefact design assessment by establishing goals through evaluation criteria. Moreover, when one can generalise results, the objectivity of the design support increases.

4.11. Finds a solution and allows for multiple solutions

The first stage of the AMDA (inspire) focuses on exploring multiple solutions, and the later stages are more focused on improving the current solution (evolve) and finding and evaluating a final solution (validation). The RG artefacts aided the identification of a selection of buildable unsupported roof geometries, while artefacts A and B aimed to investigate an alternative test method for validating the design–roughness–fatigue relationship for an unsupported roof design feature. The AMDA process has been used to investigate the practical implications of a design choice, thereby reducing uncertainty by providing a means to assess the properties of the design feature. In general, in the final artefact iteration of an AMDA process, the designer has reduced the uncertainties and is provided with a clear understanding of the design effect. Thus, ideally, a design specification with no remaining uncertainties can be created to validate the final design solution. Furthermore, an AMDA investigation may not provide a solution; instead, it is similar to the concept of co-evolution of problem and solution (Cross 2004; Wiltschnig, Christensen, and Ball 2013). In this case study, artefact A could not be used to validate the design feature, but it identified issues with the artefact design that affected adherence.

4.12. Evaluation reflection

It is inherent that several of the AM design support and guidelines could have been helpful for the designers; however, their generality makes their solutions conservative because they are based on experience from earlier designs. To push boundaries and create innovative designs, one needs to see these supports as guidelines, not limitations. This concept is very similar to the old proverb, ‘You have to know the rules before you start breaking them’, implying that a thorough understanding of the foundational principles and conventions provides the knowledge and credibility required to push boundaries and explore new possibilities with intention and insight. In this case study, it is evident that many existing guidelines and standards highlight the problem of unsupported overhangs. However, they do not propose a solution to mitigate the problem. Here, the AMDA process is designed to help the user challenge the limits of conventions by identifying uncertainties and exploring the unknown. The knowledge generated that the AMDA facilities could then further be captured within guidelines for the process, the product or the specific design feature.

The AMDA process embodies the mental method strategy of *‘keep going’* when prototyping (Daalhuizen 2014). With each artefact iteration, the level of uncertainty gradually decreases until the designer feels they have enough information to progress with their design development. When the artefact behaves as expected, and the result provides the required knowledge, then design uncertainty is reduced. However, if the artefact does not perform as anticipated or a new uncertainty is identified, the designer must *'keep going'* in their investigation, learning from each iteration.

The AMDA process encouraged the engineer's initial creativity by enabling them to explore the initial design space as they tested the buildability boundaries. How the engineers used the AMDA process highlights a need for developing DfAM support that helps designers balance creativity with ensuring a design's feasibility. In this case study, an unsupported roof geometry was a necessity, and a feasible solution was identified through the roof geometry artefacts. However, this approach introduced conflicting constraints as the unsupported roof design resulted in rough surfaces, potentially having a negative impact on the feature performance.

When investigating the alternative test method for validating the impact on the feature performance through the artefacts, no explicit criteria for evaluating the test were set. Instead, prior knowledge was used to determine if the artefact results accurately described the design uncertainty. Hence, the suggestion to explicitly set test evaluation criteria in the process will aid the designer in outlining the goals of the evaluation/test stage. The process was found to aid the designers in addressing the unique design challenges, understanding the process limitations, and grasping machine capabilities, thus facilitating the comprehension of possible design specifications. The AMDA process enabled an exploration of the design options beyond the standard guides and rules while investigating an alternative method of validating the performance of a specific design feature more deeply than current guidelines could suggest.

4.13. The AMDA method

The systematic review found definitions and descriptions for *design support*, *support system*, *tools*, *methods*, *methodologies*, *guidelines*, *heuristics*, and *principles*. Notably, the term *design process* was not found to be a descriptor of structured design support in this review. References of the design process from the identified definitions stated how design support acts within the design process. Design support aids stakeholders of the design process in making educated decisions (Zanic 2013), improves particular stages of the design process (Blessing & Chakrabarti 2009), can be combined to form a design process (Cross 2000), and guide the execution of the design process (Hubka & Eder 1982). The design process realises a transformation (Hubka & Eder 1982), whereas design support acts within the process, and its output is not necessarily a transformation. The design process is a broad and general concept encompassing various design activities. In contrast, the AMDA process focuses on a specific activity and a more detailed design aspect. Considering the definitions of the design support types presented and the description of a design process, if the AMDA process were to become more detailed and formalised, the AMDA process may be more appropriately described as a design method. Based on the evaluation of the AMDA process, an improved version is presented in Figure 10.

In the current formulation of the AMDA process, shown in Figure 1, the first stage is titled *'Identified uncertainty'*, indicating that the process began with the

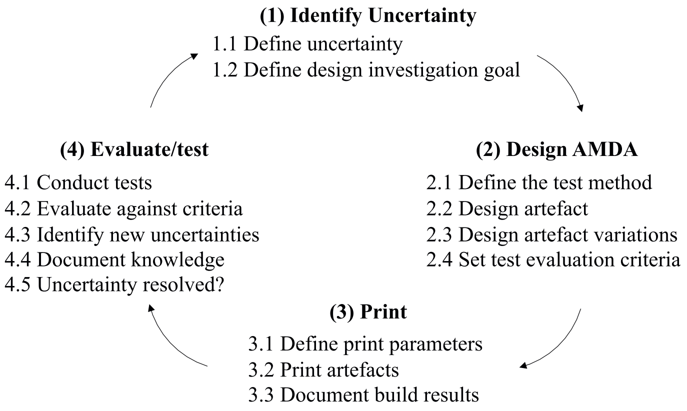


Figure 10. Proposal of the improved AMDA method.

designer already aware of the uncertainty. The proposal now highlights the steps to *identify uncertainty*. Firstly, the user must define the AM uncertainty (as shown in this case study, design limits of self-supporting overhangs). Then, the designers must define the goal of their design investigation, i.e., what they wish to learn from the investigation. For the RG artefacts, the goal was to identify a suitable choice based on three different design solutions for the roof geometry and explore the buildability of different geometries. The second stage of the AMDA method is *Design AMDA*, starting with defining the test method. With the testing method and the defined uncertainty, the designer can design the artefact according to the product's specific geometry, incorporating their understanding of the test and uncertainty. Furthermore, depending on the phase (inspire, explore, validate), the test scope and parameters to be investigated are defined by designing artefact variations, such as those for the RG artefacts. In the final step of D*esign AMDA*, the designer establishes the evaluation criteria to outline the expected behaviour of the artefact. For the RG artefacts, the evaluation criteria could have been a simple pass or fail based on whether the artefact's structure was fully built, while artefacts A and B could have been evaluated using the criteria outlined in Table 5. In the *Print* stage, stage 3, the printing parameters for the machine and material are established and recorded, and then the artefacts are printed accordingly. Once the printing process is finished, the results are documented. Finally, the test is performed in the *Evaluate/test* stage, and results are recorded. Then, the results are assessed against the evaluation criteria to determine how well they represent the uncertainty and, consequently, the correctness of the results. At this step, if the test fails to meet the evaluation criteria or exhibits unexpected behaviour, the designer is directed towards identifying potential unknown uncertainties as the artefact behaved contrary to the designer's understanding of the uncertainty. Hence, it is important to acknowledge the possibility of the test meeting the criteria while uncovering an unknown uncertainty. Finally, knowledge produced from the artefact investigation is documented, and the designer decides if they have found a resolution to the uncertainty and can move forward in their design process or if the uncertainty remains. If so, the gained knowledge is used as a base for the next iteration loop. In the case study, the off-axis failure due to the design of artefact A was fed back into the design loop and addressed in the design of artefact B.

The review of the generalisability of the characteristics suggests that certain characteristics are of more importance than others for evaluating different types of design support. While all the characteristics are considered important components of effective design support, Section 2.4 highlights that the characteristic *provides a path* that is particularly relevant to design methods. Therefore, in evaluating the newly proposed AMDA method, it is crucial to consider how well it conveys this characteristic. The added detail and direction from the formalisation provide stronger support for the user in understanding the path they can take to use the AMDA method as an effective design support.

5. Conclusions, limitations, and future research

The purpose of this study was to evaluate the AMDA process and identify areas for improvement. As the AMDA process helps designers leverage AM benefits, ensure buildability, and meet performance requirements, the evaluation focused on assessing the AMDA process's effectiveness, i.e., how well it helps designers achieve their desired outcome. A literature review of design support definitions and descriptions was conducted to identify general characteristics to be used as a framework for evaluating effectiveness. The review identified the following 11 design support characteristics:

1. Aids decision-making.
2. Emphasises the need for evaluation.
3. Communicates constraints.
4. Aids creativity.
5. Provides a path.
6. Communicates complexity.
7. Supports knowledge management.
8. Is quick and iterative.
9. Defines goals (ensures motivation).
10. Is objective.
11. Finds a solution and allows for multiple solutions.

All the identified characteristics are considered important for effective design support. However, the review revealed that certain characteristics may be significant for specific types of design support, such as the characteristic of design methods to *provide a path.* These characteristics have been used to evaluate the proposed AMDA process, as it was applied in an industrial case study with the design of a space component. The characteristics also offer potential value to researchers aiming to develop and evaluate design support. In addition to the design support characteristics, the proposed AMDA process was evaluated against alternative design supports. The case study first used a series of prototypes to explore the design space (i.e., buildability). Then, the artefact design was narrowed to create a more focused prototype for an alternative method of verification for a specific uncertainty (i.e., surface roughness impact on fatigue performance). Design artefacts were found to be useful for testing and evaluating the limitations and constraints of a design solution and uncovering previously unrecognised uncertainties, thereby providing knowledge to aid design decision-making. Design artefacts also help challenge existing guidelines and provide context-specific design support that other DfAM support cannot provide due to their generality. The results confirm that the AMDA process is an iterative procedure that requires iterations to provide satisfactory conclusions regarding the design uncertainty. With each iteration, valuable knowledge regarding the AM process and product design can be gained. When analysing the case study, it is obvious that the evaluation stage is important. However, the test evaluation relied on the designers' subjective assessment, with no metrics in place to help determine if the desired outcomes from using the design support were achieved.

Based on the evaluation, an improved AMDA method is presented. The AMDA method provides detailed recommended steps for each stage of the loop. Additionally, evaluation criteria are created during the second stage to improve the evaluation of the test results. The evaluation criteria will improve the assessment of the test result (i.e., if the artefact correctly represents the design uncertainty) and provide the designer with increased confidence in the knowledge gained from the artefact testing.

The literature search in this study was limited because it only considered articles published between 2012 and 2023 to focus on identifying current design support characteristics, using the search term (‘*design support*’ *AND definition*) to identify different design support types. A broader search is recommended to validate the results further. A more extensive search could collate the results of repeating the search term and using the identified terms, such as *guidelines*, *tool*, and *method*, instead of the general term *support*, to identify articles with definitions in which the design support type is specified. Also, adding a more extensive literature study into the evaluation and effectiveness of design support should strengthen the validity of the literature study.

This work is a continuation of the previous work of Dordlofva and Törlind (2020), and the identification of design support characteristics was conducted after their work and four iterations of the AMDA method. Future research should investigate how lessons from the exploratory phase can be used to create and evaluate verification artefacts. The knowledge generated from the AMDA method in this study can be replicated to produce information on similar geometries. While knowledge can be generated quickly through an AMDA loop, the simplicity of the artefacts limits them to offering only indicative information regarding the general understanding of the design uncertainty. Additionally, the case study centred on evaluating the AMDA method used for an AM product within the space industry. To improve understanding of DfAM supports used in practice, conducting a study on AM design supports within the space industry would provide valuable insights and help identify any existing gaps in support for addressing design challenges, such as surface roughness.

Acknowledgements

The authors would like to acknowledge GKN Aerospace Sweden AB for supporting this work and their colleagues at Luleå University of Technology Solid Mechanics for the fatigue testing during this research. Figure 7 courtesy of Dr P. Åkerfeldt.

Financial support

This research was funded by the LTU Graduate School of Space Technology and the EU Regional Growth Project RIT (Space for Innovation and Growth). This work was also supported by the Swedish National Space Research Programme (NRFP), funded by the Swedish National Space Agency (SNSA).

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Appendix.

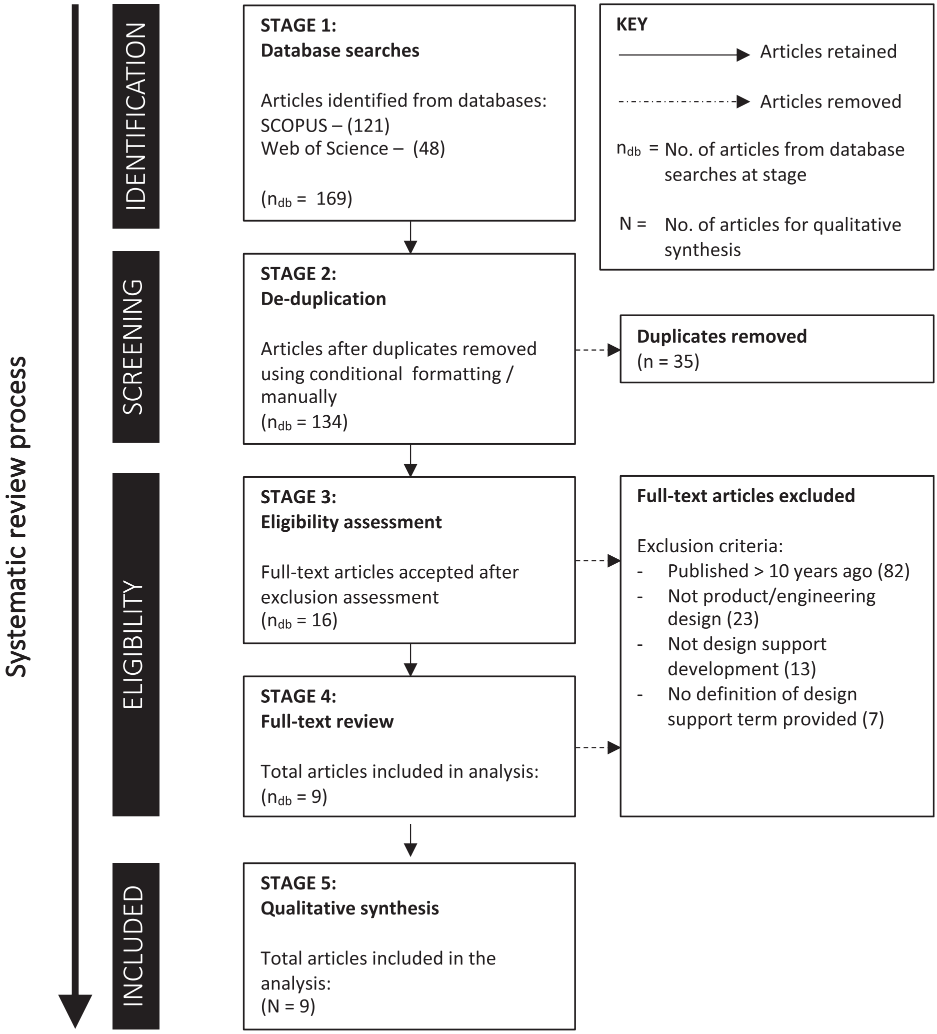

Figure A1. Flow diagram of the different phases of the systematic review (based on a generic diagram by Moher et al. (2009)).

Table A1. List of the seminal literature selected for the targeted review

Reference	Year of 1st edition	Citations*
Hubka, V., & Eder, W. E. (1982). Principles of Engineering Design.	1982	625
Blessing, L., & Chakrabarti, A. (2009). DRM, a Design Research Methodology.	1999	2402
Roozenburg, N.F., & Eekels, J. (1995). Product Design: Fundamentals and Methods.	1995	2118
Ulrich, K.T. (1995). Product Design and Development.	1995	2539
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering Design: A Systematic Approach. Engineering Design: A Systematic Approach.	1984	13622
Cross, N. (2000). Engineering design methods: strategies for product design.	1989	4514

*(citations of all editions according to Google Scholar on 02/01/2023).

Table A2. Literature review results of definitions and descriptions of design support terms and the characteristics related to them according to Table 2.

Term		Definitions and descriptions	Source [Characteristics]
Design support/ Support system	Design support	(1) Eight *‘success criteria’* for a gamified design support are defined for sustainability considerations: “communicate complexity”, “enable quick what-if assessment loops”, “support tacit knowledge sharing”, “support cross-functional negotiation”, “provide examples”, “support lateral thinking”, “stimulate acceptance of sustainability engineering’, and ‘stress that engineering is not happening yet”.	Scurati et al. (2022, p. 9) [C.6], [C.7], [C.8]
	Design support system	(2) “…to support multiple stakeholders in their design-related decision-making.”	Zanic, Andric, and Prebeg (2013), p. 383) [C.1]
	Design support system	(3) “…endow stakeholders with direct involvement in the design process and will support their educated decisions by sophisticated techniques for the subjective decision making.”	Zanic (2013, p. 226) [C.1]
	Design process support system	(4) “…to facilitate the error, performance and knowledge management; needed because design as a complex activity is prone to errors.”	Pikas et al. (2019, p. 92) [C.6]

Continued

Table A2. Continued

Term		Definitions and descriptions	Source [Characteristics]
	Design support	(5) "All possible means, aids and measures that can be used to improve design. These are prescriptions – suggesting ways by which design tasks should be carried out – and include strategies, methodologies, procedures, methods, techniques, software tools, guidelines, knowledge bases, workbooks, etc."	Blessing and Chakrabarti (2009, p. 142) [C.5]
Design tool	Design support tools	(6) "…bridge the gap between the theory and current building practice by offering indicators and frameworks." (7) "…aim to simplify the theoretical underpinnings and thinking process of [regenerative design] and to provide guidance and approachable goals for practitioners."	Akturk (2017, p. 337) [C.9]
	Design tools and methods	(8) "Design tools and methods are formulated …to address and alleviate the problems' of design for remanufacturing."	Yang et al. (2016, p. 145) [C.1]
	Design tools	(9) "…hardware and software for supporting design, based on some design approach, method or set of guidelines. The design tool supports the effective and efficient use of the approach, method or guideline. Sometimes, their use would not be possible without a computer tool."	Blessing and Chakrabarti (2009, p. 143) [C.7]
		(10) "Procedures and computer-based tools have been developed to help designers analyse and define tolerances that maximise the quality and minimise the cost of complex parts and assemblies."	Pahl et al. (2007, p. 181) [C.9]
Design method		(11) "System of methodical rules that determine (classes of) possible procedures and actions which are intended to lead via a planned path to the accomplishment of a desired aim."	Hubka and Eder (1982, p. 103) [C.5]
		(12) "Sequences of activities to be followed in order to improve particular stages of the design process (task clarification, conceptual design, detail design, etc.), and specific tasks within these stages (e.g., generation, evaluation, etc.)."	Blessing and Chakrabarti (2009, p. 142) [C.5]

Continued

Table A2. Continued

Term		Definitions and descriptions	Source [Characteristics]
		(13) "In a sense, any identifiable way of working, within the context of designing, can be considered a design method…. Design methods can, therefore, be any procedures, techniques, aids or "tools" for designing. They represent a number of distinct kind of activities that the designer might use and combine into an overall design process."	Cross (2000, p. 46) [C.5]
		(14) "A method is the consciously applied diachronous structure of an action process." (15) "A method itself can be seen as a composite of a number of rules … They aid in finding something, but there is no guarantee that it will be found always and by everyone." (16) "Design methods are heuristic methods which are based on 'weak' knowledge. They do not guarantee a result, but do increase the chance of achieving a result."	Roozenburg and Eekels (1996, pp. 40; 42; 45) [C.5], [C.5], [C.11]
Design methodology	Design methodology	(17) "…the wholeness of issues that determine how the design is done, including target setting, organisation of design tasks, use of techniques, criteria and assessment methods."	Delponte et al. (2015, p. 900) [C.5]
	Design methodology	(18) "A design methodology needs to meet the following requirements: (Req. A) Efficiency and Sustainability allows the methodology to incorporate the re-use of existing components. (Req. B) Allowing for individual Customizability states that fine-grained customization capabilities are required [(Maeder & Williams, 2017; Meyer et al. 2015)]. Since manually exploring the design space is not feasible due to a large number of potential solutions, (Req. C) Capability of Automation demands the automation of key processing steps of the design methodology. Considering the variety of possible solutions, determining the most suitable solution will involve multiple criteria (such as costs, installation, and maintenance effort). Thus, (Req. D) Multiple Solutions states that a design methodology needs to be able to offer a	Wollschlaeger and Kabitzsch (2020, p. 829) [C.11]

Continued

Table A2. Continued

Term		Definitions and descriptions	Source [Characteristics]
		"design space" containing possible alternative designs [(Estudillo-Valderrama et al. 2010)]."	
	Design methodology	(19) "Design methodology is the science of methods that are or can be applied in designing. In English the word 'methodology' has two meanings. The first meaning is: a science or study of method, i.e., the description, explanation and valuation of methods. The second meaning of 'methodology' is: a body of methods, procedures working concepts and rules employed by a particular science, art or discipline."	Roozenburg and Eekels (1995, p. 29) [C.5]
	Design methodology	(20) "Design methodology, however, is a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains. It includes plans of action that link working steps and design phases according to content and organisation… (21) Design methodology should therefore foster and guide the abilities of designers, encourage creativity, and at the same time drive home the need for objective evaluation of the results."	Pahl et al. (2007, p. 9) [C.2], [C.4], [C.5]
	Design methodology	(22) "The intention is to try to ensure that the design problem is fully understood, that no important elements of it are overlooked, and that the real problem is identified. There are plenty of examples of excellent solutions to the wrong problem."	Cross (2000, p. 34) [C.2]
	Design methodology	(23) "General theory of procedures for the solving of design problems. It involves both the general design strategy and also the tactical approach to individual portions of design work." (24) "System of methods that may be used by an individual to attain a desired objective."	Hubka and Eder (1982, pp. 102; 103) [C.5], [C.11]
	Design methodology	(25) "By a design approach or methodology, we mean an overall framework for doing design."	Blessing and Chakrabarti (2009, p. 142) [C.5]

Continued

Table A2. Continued

Term		Definitions and descriptions	Source [Characteristics]
	General working methodology	(26) “A general working methodology should be widely applicable, independent of discipline and should not require specific technical knowledge from the user.” (27) “The following conditions must be satisfied by anyone using a systematic approach: • Define goals by formulating the overall goal, the individual subgoals and their importance. This ensures the motivation to solve the task and supports insight into the problem. • Clarify conditions by defining the initial and boundary constraints. Dispel prejudice to ensure the most wide-ranging search for solutions possible and to avoid logical errors. • Search for variants to find a number of possible solutions or combinations of solutions from which the best can be selected. • Evaluate based on the goals and conditions. • Make decisions. This is facilitated by objective evaluations. Without decisions and experiencing their consequences there can be no progress.”	Pahl et al. (2007, p. 53) [C.3], [C.9], [C.10], [C.11]
Design guidelines		(28) “The most commonly used and effective approach to facilitate product design for remanufacturing is through generating design guidelines to address the various barriers and challenges during the remanufacturing process.”	Yang et al. (2016, p. 145) [C.3]
		(29) “Design guidelines are rules, principles and heuristics that are useful to follow in attaining some design objectives.”	Blessing and Chakrabarti (2009 p. 143) [C.5], [C.9]
		(30) “Guidelines help product design teams to make early [design for environment] decisions without the type of detailed environmental analysis that is only possible after the design is more fully specified.”	Ulrich and Eppinger (2012, p. 240) [C.1]

Continued

Table A2. Continued

Term		Definitions and descriptions	Source [Characteristics]
Design heuristics and principles	Design heuristics	(31) "…to help designers to perceive the unique capabilities of AM and to be a source of inspiration for creative activities during concept generation."	Valjak and Lindwall (2021, p. 2577) [C.4]
	Design principles	(32) "…their main purpose is to support the early design and its realisation in a form suitable for AM."	Valjak and Lindwall (2021, p. 2577) [C.6]
	Design principle	(33) "The source, or basis, or law (e.g. of nature), or primary element, or fundamental truth (e.g. an idea), from which the other laws, elements, etc., may be derived or on which they are dependent, may also refer to idealised methodical rules to guide the execution of the design process…"	Hubka and Eder (1982, p. 108) [C.5]
	Heuristic principles	(34) "[Systematic procedures] are also known as "heuristic principles" (a heuristic is a method for generating ideas and finding solutions) or "creativity techniques"."	Pahl et al. (2007, p. 53) [C.4], [C.11]
Design rules		Two types of rules are defined: algorithmic and heuristic. (35) Algorithmic rule: "a rule that can be transferred in to an algorithm", where an algorithm is defined as "an unambiguous set of questions or commands that have to be dealt with in the dictated order, and will lead to reaching a clearly described result." (36) Heuristic rules: "behavioural rules that promote the finding of something in an – at least partially – goal-rational situation … Also with divergent (creative) thinking all kinds of behavioural rules are used more or less consciously, including methods to keep the mind open, to derive inspiration, and to promote inventions that were not intended ('serendipity')."	Roozenburg and Eekels (1995, p. 43) [C.5], [C.11]
		(37) "The constraints of a process can be concisely communicated to designers in the form of design rules."	Ulrich and Eppinger (2012, p. 264) [C.3]

Continued

Table A2. Continued

Term		Definitions and descriptions	Source [Characteristics]
Design procedure	Design procedure	(38) "…it is important to have a defined design procedure that finds good solutions. This procedure must be flexible and at the same time be capable of being planned, optimised and verified. Such a procedure, however, cannot be realised if the designers do not have the necessary domain knowledge and cannot work in a systematic way. Furthermore, the use of such a procedure should be encouraged and supported by the organisation."	Pahl et al. (2007, p. 9) [C.5], [C.11]
	Heuristic procedures	(39) Principles on which *'heuristic procedures'* are based are defined: "(a) Ensure motivation, (b) show limiting conditions (expanded, clarified problem), (c) dissolve prejudice (no fixations), (d) search for variants (possibilities of optimisation), and (e) reach decisions based on evaluations of maximum objectivity (without decisions the design process is impossible)."	Hubka and Eder (1982, p. 28) [C.3], [C.9], [C.10], [C.11]