Design for Additive Manufacturing – Application System based on Design Methodology in Industrial Standards

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Abstract

Over the past few decades, additive manufacturing (AM) evolved from rapid prototyping (RP) into mature manufacturing technologies for complex high-performance end use products. The transition in the industrial application of these technologies necessitates a design methodology tailored to the potentials and restrictions of AM. This contribution presents a new application system for opportunistic and restrictive component design, which can be integrated into design for additive manufacturing (DfAM) methodologies. For the first time, methods for AM part design are being drawn from standards and integrated into an application system, supporting professionals in the practical implementation of design for additive manufacturing methods.

Keywords: Design for Additive Manufacturing; DfAM; Product Development; Standards

DOI: 10.25368/2024.EEE.012

1 Motivation and Problem Definition

Products that are generally suitable for additive manufacturing (AM) tend to be characterized by complex or highly customized geometries, low production volumes, special combinations of properties or a combination of the above (DIN e. V., 2020a). To design such products, design methods and methodologies that enable designers to realize the potential of AM are needed. New ways of thinking in AM component design gave rise to the research field design for additive manufacturing (DfAM). This field of research is becoming increasingly broad, since not only design methods tailored to AM are needed as a differentiation from conventional design for manufacturing (DfM), but the paradigm shift from rapid prototyping to direct manufacturing also places new demands on the product development for AM. For this reason, a new design methodology which integrates and organizes DfAM methods is needed. However, most of the DfAM methodologies offered in the literature focus on detail design and thus support the optimization of individual aspects of existing (conventional) designs rather than whole product design processes (Taborda et al., 2021). In addition, existing DfAM methods have mainly been developed in isolation from each other and have not been implemented in a common design methodology (Kumke, 2018). This has led to a fragmented research landscape (Pradel et al., 2018) in which there is no uniform understanding of what methods and methodologies dedicated to DfAM are and how they are applied in the context of technical product development. This contradicts the primary intention of DfAM as a foundation for the professional design of AM components (Pradel et al., 2018). The development and application of suitable DfAM methods requires a common understanding of the development and design principles as well as the characteristics, potentials and limitations of AM. Standardization can be regarded as a possible basis to foster a general understanding of DfAM. For this reason, the aim of this work is to contribute to the general understanding and application of DfAM in the form of an application system for opportunistic and restrictive AM component design based on industrial standards as a generally recognized knowledge base. To the best of the authors' knowledge, this is the first contribution to the topic of DfAM that takes the approach of developing a DfAM application system based on standards.

2 State of the Art

2.1 Additive Manufacturing

Additive manufacturing is a manufacturing technology that produces physical components directly from digital 3D models in a layer-based process (Gibson et al., 2021a). The layer-wise placing, bonding and transforming of volumetric elements (voxels) to final parts enables the geometric arrangement of the material to be cellular, topologically controlled and optimized for specific functions, properties or applications (Thompson. et al., 2016; Gromat T. et al., 2023). While the industrial application of additive manufacturing was initially limited to prototyping, today 30.5% of all AM applications are aimed at producing functional end products (Wohlers Associates, 2023).

2.2 Current DfAM Standards

AM standards form the basis for a common understanding of the functionality and potential of these manufacturing technologies and thus significantly influence the industrial acceptance and application of AM (Thompson, M. et al., 2016). The main motivation for standardizing AM manufacturing processes, materials, test methods and component design stems from key stakeholder industries such as aerospace and medical engineering, which rely on the certification of their end products (Moroni et al., 2020). A unique aspect of standardization in the field of AM is the cooperation between ISO and ASTM, with the aim of giving the joint work an almost worldwide validity (Gebhardt et al., 2019). The ISO/TC 261 committee and the ASTM F42 committee have been consolidating national and international standards since 2011 and assigning them the ISO/ASTM designation. Within the scope of this collaboration, six ISO/ASTM standards have been developed addressing DfAM (Table 1).

Table 1: ISO/ASTM Standards addressing DfAM

Standard	Description	Reference
DIN EN ISO/ASTM 52910	General design strategy and methods of component design for AM.	(DIN e. V., 2020a)
DIN EN ISO/ASTM 52911-1	Design for Laser Powder Bed Fusion of metals (PBF-LB/M). VDI 3405 B 3 is integrated into this standard.	(DIN e. V., 2020b)
DIN EN ISO/ASTM 52911-2	Design for Laser Powder Bed Fusion of polymers (PBF-LB/P). VDI 3405 B 3 is integrated into this standard.	(DIN e. V., 2020c)
DIN EN ISO/ASTM 52911-3	Design for Electron Beam Powder Bed Fusion of metals (PBF-EB/M).	(DIN e. V., 2023)
DIN EN ISO/ASTM 52915	Specification of the file format for additive manufacturing (AMF)	(DIN e. V., 2020d)
DIN EN ISO/ASTM 52950	Fundamentals of data processing for AM	(DIN e. V., 2021)

Note: Matching ISO/ASTM standards under the jurisdiction of the ASTM committee F42.04 on Design

2.3 Design for Additive Manufacturing

The term design for additive manufacturing (DfAM) became a topic of discussion in the scientific literature around the same time as the use of AM was shifting away from prototyping and towards the production of functional end products (Gibson et al., 2021b). In 2007, more than two decades after the initial commercialization of industrial AM processes, the first definition for DfAM was published by (Rosen, 2007). The proposed definition reflected the need for a differentiated approach to classical DfM approaches, as the focus now began to change from cost optimization to the realization of previously unavailable potentials through AM. For this purpose, DfAM was defined as the *"Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives"* (Rosen, 2007). More recent interpretations of this definition, like the one proposed by (Kuschmitz et al., 2022) include the designer's need for assistance to exploit the potential of AM while at the same time observing manufacturing restrictions. DfAM is intended to support designers in realizing the potential of AM, which, according to (Gibson et al., 2021c), manifests itself in the shape, material, functional and hierarchical complexity of AM components.

2.4 Methods and Methodologies in DfAM

Methods are used within product development to achieve defined goals through a sequence of plannable and rule-based activities (Lindemann, 2009; VDI e. V., 2019a). The definition of a standalone method is sometimes ambiguous, as even methods with low complexity may necessitate the application of further methods within them (Lindemann, 2009). Methods have an operational character, i.e. they specify how something is to be done, while methodologies have a procedural character and help to understand what is to be done and which methods can be employed for this purpose (Lindemann, 2009; Atzberger et al., 2020). In the DfAM literature, (Laverne et al., 2015) established a distinction between opportunistic and restrictive DfAM methods while the combination of these two is referred to as dual DfAM methods. *Opportunistic* DfAM methods aim to generate new concepts, geometric shapes or designs that are conventionally impossible or very difficult to realize (ibid.). The use of these methods is intended to support the designer's creativity in finding solutions by specifically exploiting the potential of AM (ibid.). This is achieved through the methodical use of bionic structures or topology optimizations, for example (ibid.). *Restrictive* DfAM methods are intended to ensure the manufacturability of products designed for AM by considering general and process-specific limitations of the technology (ibid.). Examples for *opportunistic* DfAM Methods in the literature include design heuristics (Blösch-Paidosh, A. & Shea, K., 2017), design remixing (Friesike et al., 2018) and part consolidation (Auyeskhan et al., 2022). The design in accordance with the design rules for Laser Sintering (LS), Laser Melting (LM) and Fused Deposition Modeling (FDM) proposed by (Adam & Zimmer, 2015) are amongst the most cited examples for *restrictive* DfAM. While methods are used to support individual development activities, methodologies help to achieve overarching goals for which a variety of methods can be used along the process (Atzberger et al., 2020). A process model can therefore be utilized as the process-describing element of a methodology (ibid.). Many of the methodologies proposed in the literature on DfAM are based on organizing and incorporating various findings from research contributions into generic, sometimes simplified process models. Laverne et al. (2015) reviewed existing DfAM methods and integrated them into a design process model according to Pahl and Beitz (Gericke et al., 2021). Pradel et al. (2018) used a 'simple design process model' based on Pahl and Beitz, among others, to map DfAM methods and influencing factors onto individual design phases from conceptual to detail design and manufacturing. A similar approach was utilized by (Jemghili et al., 2023), to organize DfAM heuristics, design principles and design rules along a design thinking process to derive a user centered DfAM methodology. Kumke et al. (2016) integrates DfAM methods into a development methodology based on the process model standardized in VDI 2221 (VDI e. V., 2019a). There are also DfAM methodologies in the literature that use new process models developed for specific applications or objectives. An example of this would be the process model proposed by (Auyeskhan et al., 2022) for the purpose of parts consolidation of existing designs, within a selection of opportunistic and restrictive DfAM methods is organized. A methodology for component optimization using topology optimization was proposed by (Dalpadulo et al., 2020) and illustrated using a two-stage process model. In addition to the DfAM methodologies and associated process models published in the academic literature, proposals can also be found in industrial standards. As part of the EU project "Standardization in Additive Manufacturing" (SASAM), an AM design methodology was developed, which has since been incorporated into the DIN EN ISO/ASTM 52910 standard (DIN e. V., 2020a). The associated process model is shown in Figure 1.

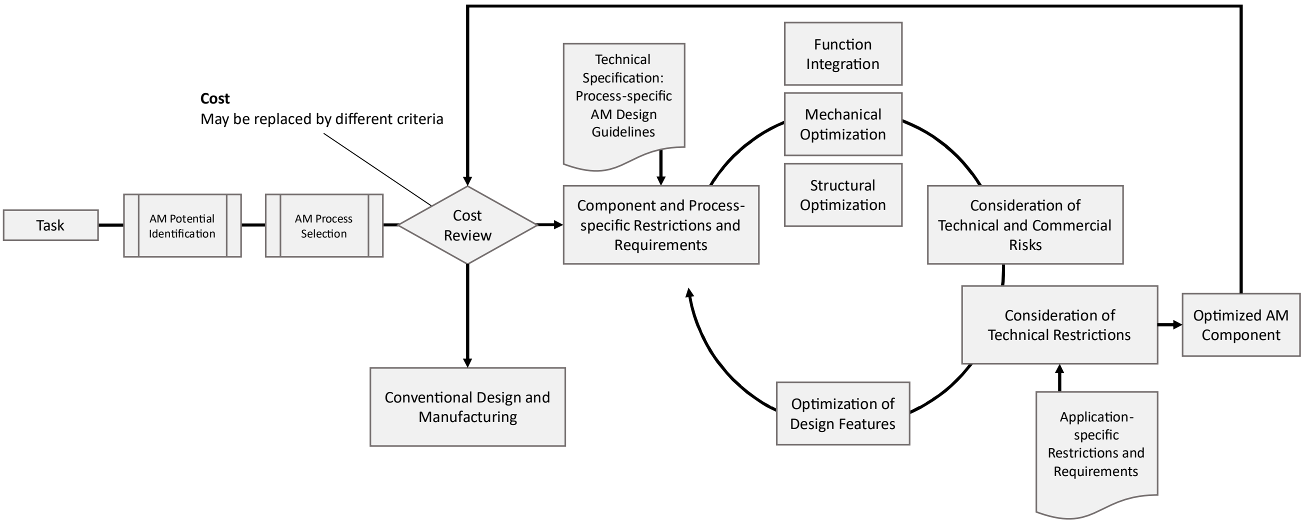

Figure 1: AM Design Process Model based on DIN EN ISO/ASTM 52910 (DIN e. V., 2020a)

3 Research Approach

This paper proposes a new application system for DfAM methods to answer the following research question: *What might a standards-based application system for DfAM methods in the context of a DfAM methodology look like?* In contrast to other works, the content of the DfAM application system, i.e. the DfAM methods, is drawn from standards instead of academic literature. In a first step, the standards developed and consolidated by ISO and ASTM (ASTM committee F42.04 on Design) are analyzed for opportunistic and restrictive DfAM methods. Since not all relevant national guidelines have been integrated into ISO/ASTM standards to date, this analysis is supplemented by the VDI 3405, e.g. component design for electron beam melting (VDI e. V., 2018) and material extrusion (VDI e. V., 2021a), as well as VDI 3405 Part 3.2 (VDI e. V., 2019b) on limiting geometries for the AM process. After identifying the methods, the DfAM application system is presented, placing the DfAM methods in a context of opportunistic and restrictive component design based on standards.

3.1 DfAM Methods in Standards

By analyzing the standards listed in Table 1, supplemented by the VDI 3405, seven different DfAM methods according to the aspects outlined in Chapter 2.4 are identified. Table 2 shows the DfAM methods together with a brief description.

Table 2: DfAM Methods in Standards

DfAM Method	Description	References
Part or product consolidation	Minimizing the number of individual parts in a product without diminishing functionality. The consolidated components are often geometrically more complex than the original.	(DIN e. V., 2020a)
Part or product decomposition	Splitting a component into individual parts due to e.g. geometric restrictions of the available building volume of an AM system.	(DIN e. V., 2020a)
Bionic design	Use of bio-inspired cellular structures to increase product performance.	(DIN e. V., 2020a)
Local property customization	Local adjustment of properties by changing the material composition or microstructure within a layer or from layer to layer with the aim of producing functionally graded components.	(DIN e. V., 2020a)
Design optimization based on functional characteristics	Realization of components with mathematically defined functions (i.e. geometries) e.g. topology optimization to optimize a component according to specific requirements.	(DIN e. V., 2020a) (VDI e. V., 2021b)
Functional mechanisms	Realization of relative movement between components without the need for downstream assembly by utilizing multi-part mechanisms or elastic mechanisms that with defined bending patterns.	(DIN e. V., 2020a)
Function integration	Integrating performance-oriented functionalities directly into the material (e.g. cooling channels).	(ISO/ASTM, 2020)

VDI 3405 Part 3.2 proposes test specimens and test characteristics for limiting geometric features and characteristics of components manufactured by AM (VDI e. V., 2019b). The limiting geometric features and characteristics defined in VDI 3405 Part 3.2 are listed in the left-hand column of Table 3 which provides an overview of the currently valid standards in which quantitative or qualitative design recommendations are given correspondingly.

Table 3: Design Information on Limiting Geometric Characteristics according to VDI 3405 in Standards

Geometric features and characteristics	Design recommendations				
	PBF-LB/M	PBF-LB/P	PBF-EB/M		ME
	ISO/ASTM 52911-1	ISO/ASTM 52911-2	ISO/ASTM 52911-3	VDI 3405 P 3.5	VDI 3405 P 3.4
Minimum hole diameter	○	●	●	●	●
Maximum horizontal hole diameter	○	○	●	●	●
Minimum and maximum thickness of vertical walls	○	●	○	●	●
Minimum angle of inclination of free-standing walls	—	○	—	●	●
Minimum free-standing cylindrical pin	—	●	—	●	●
Minimum angle of inclination of free-standing cylindrical pins	—	○	—	●	●
Thickness variations of cylindrical components	—	○	—	—	●
Thickness variations of rectangular components	—	○	—	●	—
Roundness	○	○	○	○	—
Maximum unsupported bridging	●	○	—	—	—
Maximum unsupported overhang	○	○	○	●	●
Minimum gap	○	○	●	●	●
Gaps for moving parts	—	●	—	●	●
Surface quality	●	○	○	●	●
Dimensional accuracy	●	○	○	●	●
Shrinkage	○	○	—	—	○
Susceptibility to residual stresses and distortion	○	●	○	—	●
Labeling	●	●	●	—	—

● quantitative ○ qualitative — none

3.2 Proposed DfAM Application System based on Standards

The DfAM methods presented in Section 3.1 are integrated into a DfAM application system which is embedded in a process model of a DfAM methodology as shown in Figure 2.

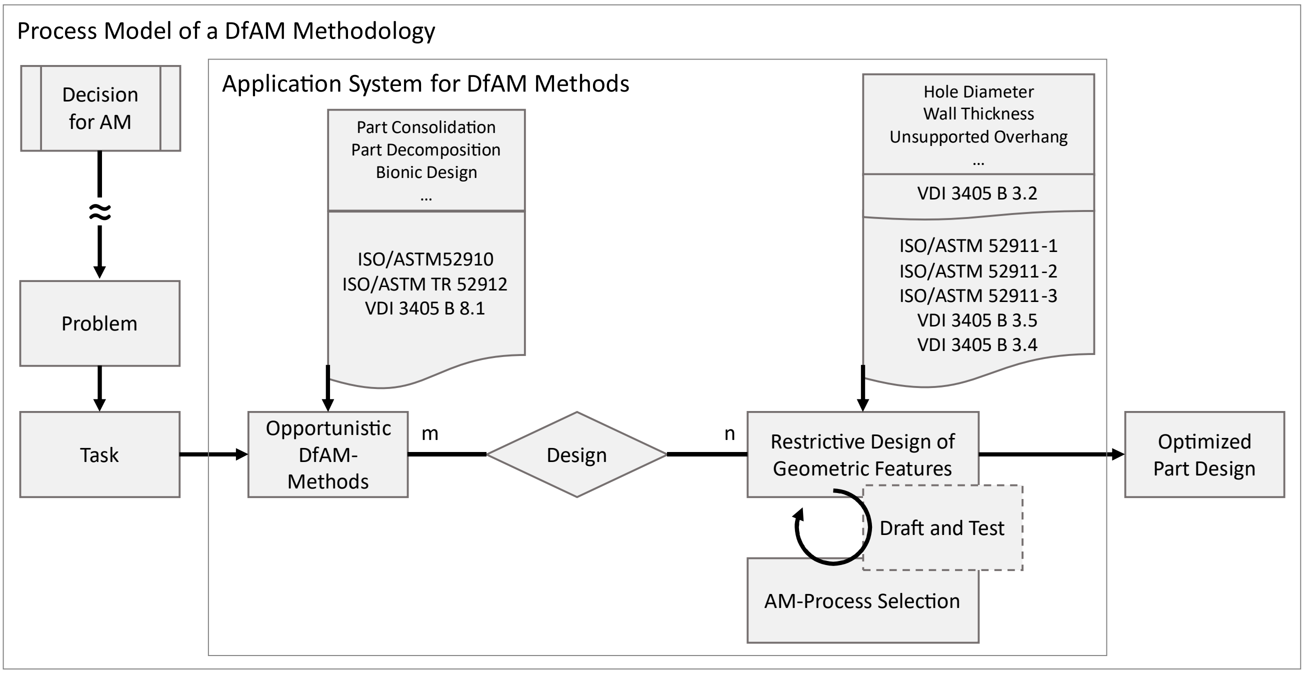

Figure 2: Proposed Application System for DfAM Methods incorporated into a Process Model of a DfAM Methodology

The DfAM application system accommodates the opportunistic methods (Table 2) as well as the restrictive design of the geometric features and characteristics (Table 3). As shown in Figure 2, the entities for the opportunistic respectively restrictive design receive their content input from the corresponding standards. The entity that contains the opportunistic DfAM methods is linked to the restrictive design of geometric features via an m to n relationship. This means that the application of an opportunistic method can require the restrictive design of several geometric features, but the design of a particular geometric feature can depend on several opportunistic methods.

4 Discussion and Outlook

4.1 Analysis of DfAM Methods in Industrial Standards

Since all the methods identified in the standards are basically aimed at the realization of design features that cannot be implemented using conventional methods or can only be realized with considerable effort, it is concluded that these are exclusively opportunistic DfAM methods. The opportunistic character is also evidenced by the fact that the method descriptions (Table 2) do not contain any strictly restrictive statements. Although the need to use *part or product decomposition* is partly due to the restrictions of the build volume of AM manufacturing processes, it is not a restrictive DfAM method, as the possibility of being able to separate a component before production has an opportunistic character. Conversely, this also means that currently valid standards for the design of AM components do not contain any stand-alone restrictive DfAM methods. For the restrictive DfAM, the authors suggest using the quantitative design of typical geometric features according to (VDI e. V., 2019b) as specified in Table 3. Although the design of these geometric features is mostly quantified in the standards for PBF-LB/M, PBF-LB/P, PBF-EBM and ME processes, recommendations on the methodological procedure and the overall context for the application of this restrictive design are missing. To close this gap and to facilitate the practical utilization of DfAM, the proposed application system for DfAM methods places opportunistic methods in a common context with the restrictive design of typical geometry features and characteristics of components designed for AM.

4.2 Discussion of the Application System for DfAM Methods

The proposed application system follows the idea that the employment of opportunistic DfAM methods (Table 2) determines the geometrical characteristics of the product and thus necessitates the quantitative design of certain geometric features (Table 3). The quantitative design of the geometric features defined in (VDI e. V., 2019b) is highly process-dependent, as there are many AM processes with different capabilities in terms of resolution, surface quality and the need for support structures, for example. As a result, the decision-making process and the selection of a specific AM process should ideally be based on the geometric features that have to be realized within the component. Combinations of different geometric features can require compromises in the selection of a suitable AM process, especially in connection with material selection. Determining a specific AM process before the opportunistic design of the component is executed can lead to a loss of potential or unnecessary restrictions, as it is not yet known at this point which geometric features must be realized and thus quantitatively designed regarding process-specific restrictions. The draft and test cycle is intended to foster the designing as well as the decision making for a specific AM process. According to DIN EN ISO 52911-1 (DIN e. V., 2020b) and DIN EN ISO 52911-3 (DIN e. V., 2023) draft and test cycles are intended to explore the process-specific limits, which can vary depending on the manufacturer, machine and material, through the practical testing (i.e. manufacturing) of geometric features. The purpose of such a cycle is extended in the context of the proposed application system, as quantitative design information is not available for all geometric features and not for all processes in the standards. Practical testing of component features can be helpful for both restrictive component design and the selection of a specific AM process. The process model shown in Figure 2 does not claim to represent a comprehensive DfAM methodology. However, it is intended to show that the application system has interfaces that allow for integration into process models of holistic DfAM methodologies in future work.

4.3 Closing Remarks and Further Work

The application system for DfAM methods proposed in this work is intended to contribute to the practice-oriented use of DfAM methods. For the first time, a uniform and easily accessible knowledge base in the form of industry standards was chosen as the basis for opportunistic and restrictive component design. To show how the proposed application system may be integrated into an AM development methodology, it was assumed that the decision for AM was made at the very beginning of the development process. However, the question of both the optimal timing of the decision for AM and the role of DfAM in early phases of product development has not yet been clarified and is subject of future research. Since there is a frequently reported lack of DfAM methods (Blösch-Paidosh, A. & Shea, K., 2017), (Formentini et al., 2022), (Taborda et al., 2021) dedicated to early phases of product development, the authors expect a particular need for a comparable application system as well as the associated methods for the problem and task clarification in the context of a comprehensive AM design methodology.

Acknowledgement

Parts of this research paper were funded by the European Union’s program NextGenerationEU and dtec.bw as part of the project FLAB-3Dprint.

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