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Additive Manufacturing Conformity – A Practical View

G.-J. Tüzün ✉, D. Roth and M. Kreimeyer

University of Stuttgart, Germany

✉ gregory-jamie.tuezuen@iktd.uni-stuttgart.de

Abstract

With the dissemination of additive manufacturing (AM), numerous methods have emerged to support the design process. One possibility is to improve functional solutions through AM-conformal design. Literature-based criteria for the assessment of AM-conformity already exist. Within our study, we address the gap in criteria between a theoretical perspective and a practitioner's perspective. To this end, we first explain the application of the criteria through a use case and conduct an evaluation in an industrial environment adding practitioner's criteria to enable the assessment of AM-conformity.

Keywords: additive manufacturing, conceptual design, design practice, solution principles, design principles

1. Introduction

Through additive manufacturing (AM), manufacturers have the option to produce complex and functional parts by adding material layer by layer. In terms of functional parts, which realize a product solution, new possibilities are emerging for developing additively manufactured solutions (AM solutions). For example, topology optimization can be used to achieve lightweight structures that could not be manufactured conventionally. Compared to conventional solutions (e.g. manufactured by injection molding or milling), AM solutions become competitive when exploiting the high complexity of a part and geometric design freedom. According to Rosen's (2014) definition, an AM specific design (Design for Additive Manufacturing, DfAM) is necessary in order to consider the given possibilities and restrictions of AM processes. By utilizing AM potentials, such as the high degree of design freedom, the focus shifts to function-oriented design of AM solutions (Yang and Zhao, 2016). As with conventional solutions, AM solutions implement a greater function (Pahl et al., 2007). Therefore, not only individual functional parts, but also the underlying functional solution should be designed specifically for AM, i.e. AM-conformal (synonymous to "AM-compliant" from Weiss et al., (2016)) to minimize costs and counteract manufacturing problems early on.

2. Problem clarification and goal

A DfAM can be achieved with an AM-conformal design, although the former includes additional aspects. Manufacturing restrictions have to be taken into account early in the development process, which is why it is necessary to look at possible design solutions and solution principles when designing functional parts (Weiss et al. 2016). AM-conformal solution principles can therefore be the initial step of a function-oriented design specific to AM. To systematically develop such solution principles, it is necessary to know and assess whether an AM-conformal design has been achieved.

To assess AM-conformity, sets of criteria that either focus solely on the literature (theoretical) perspective or the practitioner's (practical) perspective have been used: Zhang et al. (2014) assess designs from the perspective of combined process planning and part design. Different criteria (indicators) are calculated, e.g. the adaptation indicator (suitability for additive manufacturing) and the geometry indicator (utilization of AM potential) (Zhang et al., 2014). Booth et al. (2017) developed a DfAM worksheet that includes eight weighted criteria (e.g. complexity and functionality) for assessing manufacturability and avoiding manufacturing failures. The criteria were derived from their own experience and practical knowledge (Booth et al., 2017). Weiss (2019) established a set of ten criteria for evaluating AM-conformal design based on literature and his own experience, without providing a practical example. Similarly, a comprehensive set of 17 literature-based criteria is given in Tüzün et al. (2021) covering technical and economic aspects. However, the application of their criteria and their practical relevance have not been researched yet (Tüzün et al., 2021).

In conclusion, there is no set of criteria for assessing AM-conformity that considers both the practical and theoretical perspective. Moreover, it is not certain whether criteria exist that are included in practice but are not reflected in the literature. Thus, a broadening of the existing set of criteria is necessary.

The objective of this paper is to validate the literature-based criteria through an empirical study and to determine whether they are relevant in assessing the AM-conformity from a practical view. Therefore, the criteria shall first be specified according to their application based on a use case. Furthermore, the literature-based set of criteria for assessing AM-conformity shall be expanded from a practical perspective to discuss the following research questions: How big is the gap in criteria sets that assess AM-conformity between a theoretical perspective and a practitioner's perspective? And what criteria from a practitioner's perspective can be added to the literature-based criteria?

3. Terminology

First, a uniform understanding of solution principles is essential. According to the VDI standard (VDI 2221:1993), a solution principle is the combination of a *geometry* with *material properties* and a *physical, chemical, biological, or similar effect* to implement a function. In this context, design catalogs are used in the early concept phase (e.g. Weiss et al., 2016; Watschke et al., 2019; Garrelts et al., 2021) to search for solution principles that fulfill functional characteristics of a part design. Thus, combining multiple solution principles realizes the overall function of a product (Pahl et al., 2007).

Solution principles for individual functions in additively manufactured parts can be parametrically predefined (Weiss et al., 2017a). Figure 1 illustrates the integration of a predefined solution principle in an additively manufactured part. Its function is to channel energy (e.g. force) between two geometric boundaries. Two cross-axis bending beams connect these boundaries (Jensen and Howell, 2002). The bending beams apply Hooke's law as they are made of a flexible material with high elasticity. With the addition of product-specific requirements, the solution principle could be used as crossed flexible joints in an adaptive control element to channel manual force and enable/reverse a shape transformation.

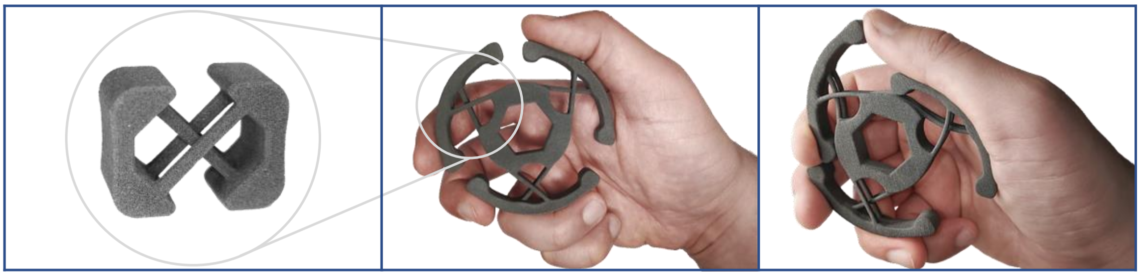


Figure 1. Solution principle "flexible hinge" designed for AM (left) and an adaptive control element using the latter (center and right) (Weiss et al. 2017b)

The depiction of a solution principle reflects the understanding of Valjak et al. (2018), who use the term "design principle" and follow the definition of Fu et al. (2016), whereby their understanding of a design principle is linked to a technical function. Therefore, design principles are established either as specific solution ideas for a given function or to leverage AM potential by identifying design opportunities such as the use of a lattice structure (Lauff et al., 2019). To avoid terminological inconsistencies, the authors refer to design principles as solution principles in this paper.

4. Method

With the synthesis of literature-based criteria, a comprehensive set of criteria was developed to describe AM-conformity (Tüzün et al., 2021). The criteria were applied in several use cases specific to solution principles to further specify them and evaluate their practicality. One of these use cases is based on Figure 1 and presented in Chapter 4.1.

Subsequently, a study with industrial participants was conducted to answer the research questions (see Chapter 4.2). We focused on the essence of each criterion described to maintain an appropriate scope of the study (see *italic description* in Chapter 4.1). The survey was structured according to Figure 2. Finally, a statistical evaluation was carried out in order to examine the collected data for significance and to draw conclusions about the research questions.

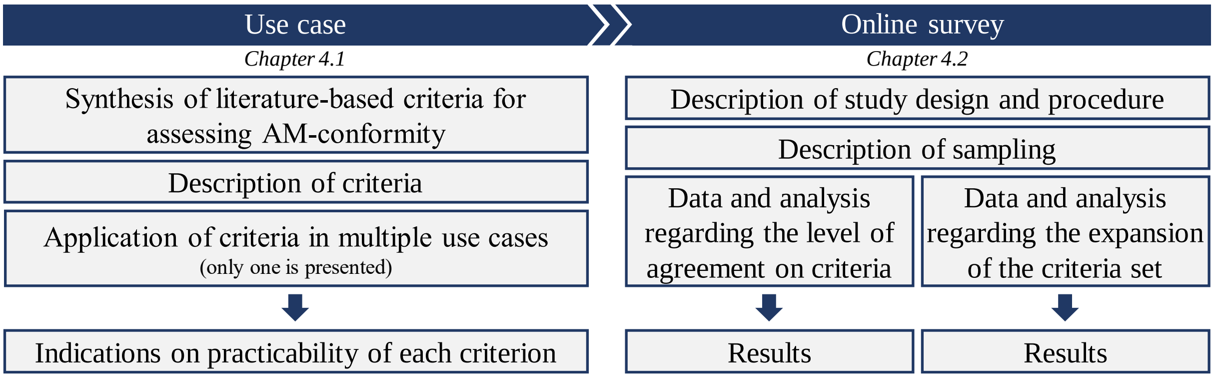


Figure 2. Methodology for the evaluation of literature-based criteria in practice

4.1. Use case

Figure 1 already depicts an AM design for a solution principle as well as a final part (AM solution). But are they AM-conformal? In the following, the criteria for the assessment of AM-conformity will be explained. First, a general explanation of each criterion is provided, and then specified in the form of a use case for the given solution principle in Figure 1. A distinction is made between two groups: design-defining criteria (criteria C1 to C14) and criteria independent from the design (criteria C15 to C17). The first group shall be assessed based on a printed part, while the second group shall be assessed based on rough estimates only.

Process-dependency (C1)

An AM solution shall be designed for a defined AM process and consider the process constraints and capabilities (see Figure 3). The selection of an appropriate manufacturing process is crucial. Therefore, the suitability of the chosen AM process to manufacture the solution principle should be evaluated.

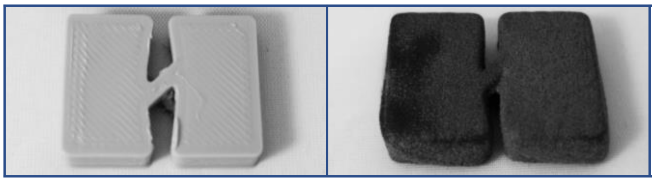
Figure 3. Solution principles to channel energy manufactured by fused deposition modeling with polylactide (left) and laser sintering with PA12 (center)

Adaptability to process parameters (C2)

An AM solution shall be designed to be adaptable to different process parameters, ensuring manufacturability and functional feasibility. The process parameters change depending on the AM process (e.g. layer thickness). This inevitably leads to differences in the geometric integrity of the printed solution principle. Therefore, the solution principle should be printed on different 3D printers with varying process parameters and tested for its performance.

Main dimensions (C3)

An AM solution shall fit into the available build volume and comply with the manufacturable minimum dimensions (see Figure 4). Usually, a single solution principle does not exceed the build volume. A varied configuration of the functional elements would still be possible. In addition to the design rules, it is important that the minimal size of the functional elements is guaranteed before the function is compromised. For verification, it is sufficient to print out the solution principle and test its functionality.

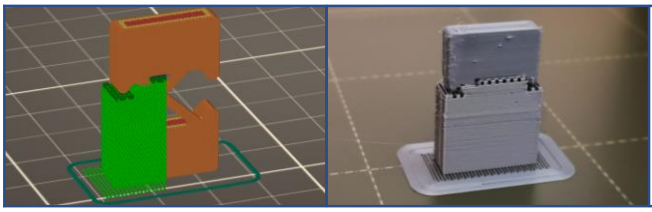


Bending beams were designed too short and prevent bending before failure; minimum functional dimensions must be specified

Figure 4. Solution principle with dimensions too small (manufactured by fused deposition modeling (left) and laser sintering (center))

Part orientation (C4)

An AM solution shall be designed according to a given part orientation (see Figure 5). The part orientation should match the orientation of the functional surfaces, while reducing overhangs and support structure (e.g. self-supporting geometry). Hence, the best possible part orientation should be determined by printing the solution principle in different orientations and evaluating its performance and the quality of its functional surfaces.



In this orientation, the part does not bend well, and the support structure is unnecessary

Figure 5. Negative example for part orientation of a solution principle (manufactured by fused deposition modeling)

Critical design guidelines and design rules (C5)

An AM solution shall comply with design guidelines and design rules. Regarding the geometry of a solution principle, the manufacturable minimum and maximum dimensions should be verified with regard to its functionality, notably the wall thicknesses, clearance/tolerances, and radii. A final comparison of the geometry with the design guidelines and design rules is sufficient. For the use case, the design guidelines (e.g. the minimum width of the bending beams) were applied during design and verified after manufacturing (see Figure 3). Further reflection would be redundant.

Functional optimization (C6)

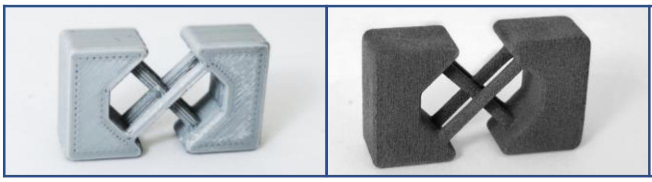
The design of an AM solution shall be optimized for performance (see Figure 6). The geometry of a solution principle is subject to its function. Despite the high degree of design freedom, the solution principle should be limited to its functionally relevant elements and structure. Once these elements and structures have been identified, all other geometric elements should be reduced if possible. The aim is to achieve a functional design.

Designed bending beams break across in the direction of stress;
counteracting unnecessary degrees of freedom to stabilize bending

Figure 6. Solution principle with double bending beams (manufactured by laser sintering)

Structural optimization (C7)

An AM solution shall be structurally optimized in terms of its topology (see Figure 7). The aim is to optimize functionality, durability, and weight of a solution principle. Lattice structures and free-formed surfaces should be used when designing a solution principle, optimized to fulfil a function. Finally, it should be tested whether additional changes to the structure benefit the functionality.



Improved bending achieved by adding a self-supporting recess at the joints

Figure 7. Solution principle with less material and improved bending (manufactured by fused deposition modeling (left) and laser sintering (center))

Structural robustness (C8)

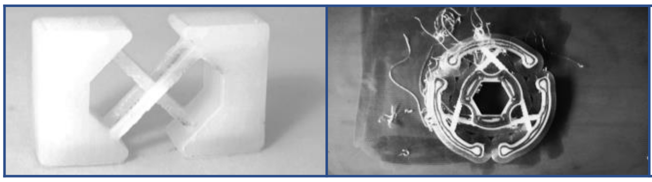
An AM solution shall be stable even under unfavorable conditions (e.g. external load), i.e. it should reliably maintain its form and function (see Figures 6 and 7). A design of a solution principle based on simplified loads indicates the structural stability (shape retention). Even during printing, the solution principle should not collapse. If it is manufacturable and performs, further verification is not necessary.

Number of components (C9)

The required number of components in the AM solution shall be minimized (e.g. through function integration). The components necessary to implement a solution principle are merged and the number of components is minimized. Ideally, the solution principle consists of only one component (see Figure 6). This can be achieved not only by part integration, but also by function integration. Components that implement non-required functions should be removed.

Material conditions and properties (C10)

An AM solution shall exploit and consider the material and its properties efficiently (see Figure 8). The material should be selected according to the physical effect of a solution principle. Furthermore, the material usage influences the durability. For testing this criterion, the solution principle should be printed with the specified material and tested to ensure functionality.



Change of material to nylon and nylon+carbon fiber for higher elasticity, but with difficulties in production

Figure 8. Solution principles with more flexible bending beams (manufactured by fused deposition modeling)

Material distribution and reduction (C11)

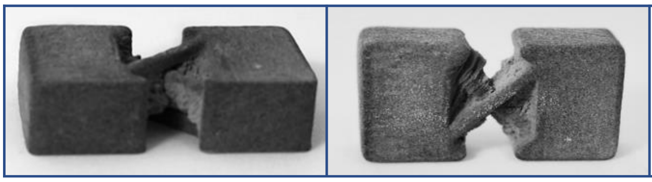
In an AM solution, unnecessary variation in wall thickness, material accumulation and warping shall be avoided. The effect of potential warpage on geometric accuracy within the solution principle should be minimized. Ideally, the geometry should consist of small or no flat surfaces and unnecessary volume should be removed. After printing, potential dents and warpage should be examined.

Approximation errors (C12)

The staircase effect shall be taken into account in the design and its impact shall be reduced within the AM solution. The layer and path approximation only allow discrete values of geometrical dimensions. Considering this criterion while designing a solution principle is sufficient.

Post-processing (C13)

The functional surfaces of an AM solution shall receive an offset and access points for removing the support structure or the loose powder shall be integrated (see Figure 9). The post-processing of the functional surfaces is done by removing material. It should be examined whether the functional surfaces of a solution principle are within the predefined tolerances and whether functional interference occurs.



Loose powder blocks the movement of all bending beams and thus hinders the functionality

Figure 9. Solution principles with necessary post-processing after laser sintering

Exploit of complexity (C14)

An AM solution shall consist of complex free-formed surfaces. Simple geometries can be avoided, thus increasing the complexity. It should be examined whether it is a relatively complex solution principle or simply a copy of a conventionally manufactured part.

Fulfillment of design objective (C15)

An AM solution shall meet at least one of the following design objectives if it replaces an existing solution: increased performance, increased functionality, weight reduction, cost reduction and/or faster part production. No further specification exists for solution principles.

Economic value (C16)

The AM solution shall be more economical than existing or conventional solutions with the same utility. Even for a solution principle, the material costs, the manufacturing time and costs, and the effort for pre- and post-processing should be estimated. Overall, the solution principle should be more economical than another solution principle that implements the same function or the same value.

Batch size superiority (C17)

If an AM solution is designed to replace an existing or conventional solution, the recommended batch size for the selected AM process shall be adhered to. This criterion influences the redesign of a solution principle to substitute an existing (conventional) solution principle. The substitution is only appropriate if the implemented solution principle has a sufficiently high complexity within the batch size mentioned, such that conventional solutions would not be economical.

4.2. Online survey with AM experts on AM-conformity

An initial search on the web returned contacts from firms active in the field of additive manufacturing and which originate from Germany, Switzerland, or Austria. For the acquisition of further potential participants, entries from the extensive list of firms in AM by Baumann and Roller (2017) were added. The invitation to participate in the survey was issued via mail between July and August 2021.

The participants were active in firms of different sizes (Figure 10). The mailing list was compiled to survey AM practitioners involved in the product development process at various phases. After a pretest, a total of 37 respondents took part in the survey, which comprises questions concerning demographic and descriptive data about the participants. Subsequently, the study objective was specified and fundamental terms such as DfAM, solution principle, and AM-conformity were elaborated.

All participants were then asked about their level of agreement with each criterion. Each criterion was formulated as a 5-point Likert item: (1) strongly disagree; (2) disagree; (3) partly agree / partly disagree; (4) agree; (5) strongly agree. A 5-point scale has a higher accuracy and allows indecision compared to a 4-point scale, while the frustration level and response rate are higher than with a

7-point scale. Finally, the study asked the participants about criteria that they considered necessary but were not included.

4.2.1. Sampling

Out of 37 respondents, 28 participants are included in our sample. Only respondents who had at least a technological or applicational knowledge were included in the sample to be investigated (see Figure 10). The sample consists of industrial participants, including executives (46%), managers (43%), and employees (E.) (11%). Everyone had at least 1 year (yr.) of experience in AM, with the majority having over five years of experience (75%). In order to verify the sample, one aspect was the self-assessment of professional and technical experience in additive manufacturing.

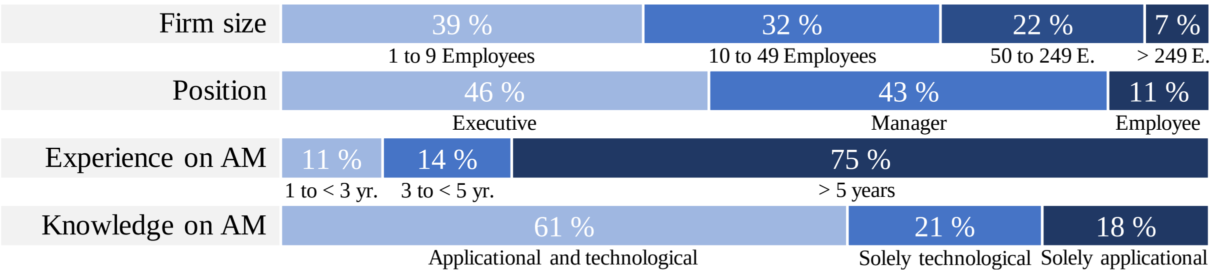


Figure 10. Sampling participants by demographic data (n = 28)

Since the literature-based criteria were compiled based on the processes of fused deposition modeling (FDM), laser melting (LM), and laser sintering (LS) (Tüzün et al., 2021), the participants were asked which AM process they were familiar with. Synonyms for the respective AM processes were given, e.g. fused layer modeling instead of FDM. All participants stated that they apply at least one of these manufacturing processes. Overall, 43% of participants were familiar with LM, 46% with LS, and 54% with FDM.
To conclude our sampling, the specific application of the AM processes was examined (see Figure 11). This was necessary to filter out all respondents that use AM only for prototyping subsequent conventionally manufactured (CM) parts. In general, attention was paid to the fact that additive manufacturing is used for the development of additively manufactured parts. Thus, it was possible to assess the extent to which the participants were able to evaluate the criteria of AM-conformity.

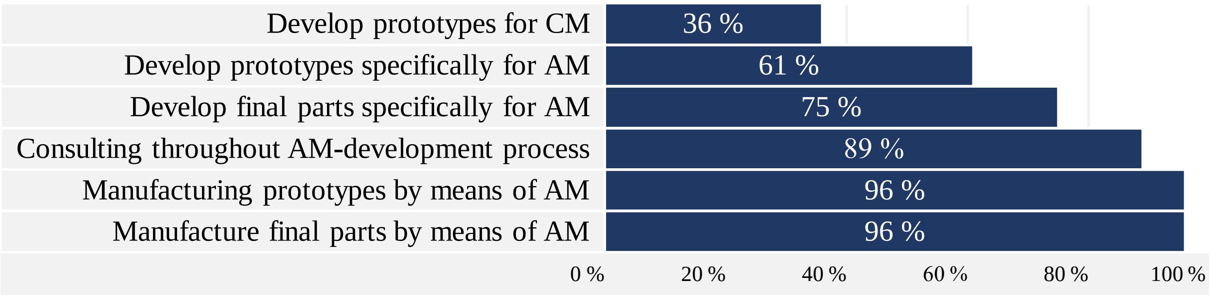


Figure 11. Sampling participants by their reasons for applying AM (n = 28)

4.2.2. Evaluation of criteria for assessing AM-conformity from a practitioner's perspective

To validate the literature-based criteria in a practical environment, the level of agreement with each criterion was measured. Due to the fact that the subjective answers did not follow a Gaussian distribution (Kolmogorov–Smirnov test; $p < .05$), all Likert items were analyzed using the sign test for dependent samples (two-tailed). The criteria are derived from an extensive literature review (Tüzün et al., 2021). Thus, it can be assumed that the theoretical perspective agrees with each criterion presented. According to the 5-point scaling of the Likert items, a median of $\tilde{x}_{ref} = 4$ can be assumed for each literature-based criterion, which corresponds to a high level of agreement (see Chapter 4.2).
If each literature-based criterion has an assumed median, we can execute the sign test in respect to the following hypotheses: The null hypothesis states that a criterion derived from the literature to assess AM-conformity *is not considered* in practice (Median $\tilde{x}_i < 4$). Therefore, the alternative hypothesis

states that a criterion derived from the literature to assess AM-conformity *is considered* in practice (Median $\tilde{x}_i \geq 4$). Figure 12 shows the result of this evaluation:

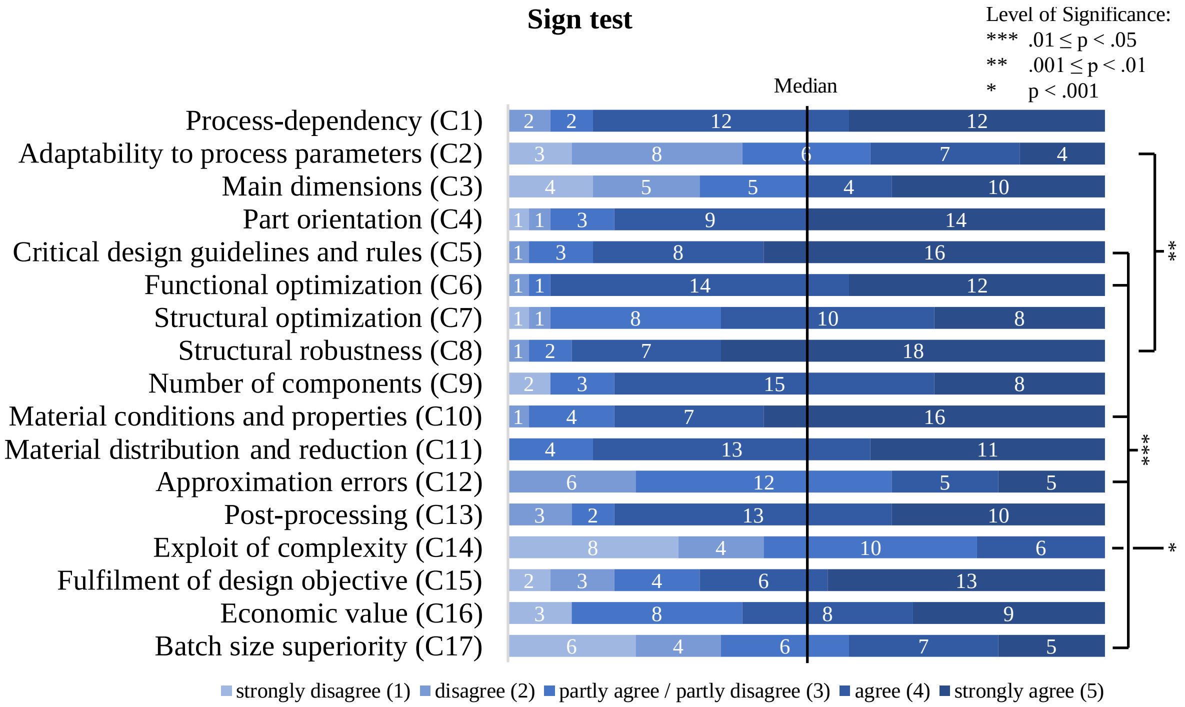


Figure 12. Level of agreement with each criterion for assessing AM-conformity (n = 28)

The sign test determines whether the central tendencies of two dependent samples are different. Accordingly, a significant result means that the practitioner's perspective differs from the theoretical perspective. As indicated in Table 1, the medians of some criteria differ significantly from the assumed median ($p < .05$, $n = 28$). Due to the two-tailed test, the medians shall be examined in detail. Specifically, for the criteria C2, C12, C14 and C17 the individual median is below the assumed median, meaning that the significant difference between the practitioner's perspective and the theoretical perspective is negative (see Table 1).

Consequently, the practitioner's perspective matches the theoretical perspective in all, but the four criteria mentioned previously. The adaptability to process parameters (C2), the consideration of approximation errors (C12), the exploit of complexity (C14), and the economic superiority (C17) play only a minor role in the assessment of AM-conformity but are nevertheless considered in some cases. In particular, the criteria concerning design guidelines (design rules) (C5), functional optimization (C6), structural optimization (C8), and material conditions and properties (C10) rated highly. Accordingly, these criteria are of great significance for the evaluation of AM-conformity.

Table 1. Differences in contrast to the assumed median from the literature perspective

Criterion i	C1	C2^{a}	C3	C4	C5^{b}	C6^{b}	C7	C8^{b}	C9
Median $\tilde{x}_i$	4.21	3.04	3.39	4.21	4.39	4.32	3.75	4.50	3.96
Exact significance p	.077	.007	.541	.064	.012	.013	.815	.001	.581
Criterion i	C10^{b}	C11	C12^{a}	C13	C14^{a}	C15	C16	C17^{a}	
Median $\tilde{x}_i$	4.36	4.25	3.32	4.07	2.50	3.89	3.71	3.04	
Exact significance p	.027	.118	.011	.302	.000	.523	.824	.027	

$^{a)}$ $\tilde{x}_i < \tilde{x}_{ref}$ and $p < .05$; $^{b)}$ $\tilde{x}_i > \tilde{x}_{ref}$ and $p < .05$

4.2.3. Addition to the existing literature-based set of criteria for assessing AM-conformity

To establish a holistic set of criteria for assessing AM-conformity, practitioners were asked about missing criteria regarding the assessment of AM-conformity. The question only allowed open field answers. While 21 participants responded with no missing criteria, seven participants provided feedback with respect to the assessment of AM-conformity. The answers had no tangible connection to solution principles. Therefore, an additional analysis was required.

After a thematic analysis, five aspects were identified to extend the existing criteria set in Chapter 4.1. The number of mentions is indicated in parentheses:

1. Criterion for the evaluation of product development time (n = 1)
2. Criteria for economic feasibility (e.g. cost comparison with conventional solutions) (n = 2)
3. Criterion for assessing the potential of adopting a new AM solution (n =1)
4. Consideration of product characteristics related to ergonomic or quality requirements (n = 2)
5. Criteria for sustainability (e.g. CO2 savings) (n = 1)

The first two aspects overlap with criterion C16, which is hereby completed by the consideration of the product development time. With the extension of C14, the third aspect can also be incorporated into the existing set of criteria: *An AM solution shall exploit design-specific AM potentials (e.g. complex geometries or customization or internal structures).* The fourth aspect requires compliance with product requirements, which resembles C15. Accordingly, C15 is extended by the *fulfillment of design objectives and requirements.* Functional integration (C6), reduction in the number of components (C9) as well as mass reduction (C11) have a positive effect on sustainable design. However, the impact of sustainability on design should be further explored to formulate a distinct criterion.

5. Discussion and conclusion

In the study design, only a brief description was presented for each criterion. On this basis, the relevance from a practitioner's perspective was examined. The criteria were tested and refined with a use case prior to the study. Hence a convergence in the relevance to AM-conformity with the practitioner's perspective was apparent. Nevertheless, every criterion derived from literature. By surveying respondents with different inclinations toward the application and technology, a broad practitioner's perspective could be covered. Ultimately, the brief descriptions were adequate to enable an evaluation.

It should be noted that the general description of the criteria applies to both final parts and solution principles. However, the detailed descriptions for final parts and solution principles can differ. For example, the economic value of a solution principle would be more difficult to estimate than for final parts, for which product requirements are known and economic estimation is more realistic. In general, all criteria should be considered. However, depending on one's design objective, it may not be possible to follow all criteria to achieve AM-conformity once the criteria are mutually exclusive.

Regarding the first research question, it can be summarized that the results show a discrepancy between theoretical and practical perspectives. Almost every literature-based criterion is at least partially agreed with, but not all criteria are approved without discrepancy. An exception is criterion C14, which is significantly worse than the other criteria in terms of its relevance in the assessment of AM-conformity. It is not clear whether the criterion is fundamentally of little relevance in practice. Finally, the practitioner's perspective does not necessarily correspond to that from the literature, as there is no clear correspondence with $\tilde{x}_i \geq 4$ for each criterion. Consequently, some literature-based criteria are disregarded in practice. There exists a gap between both perspectives, which could be addressed by answering the second research question.

To close the gap between the literature view and the practitioner's view, the participants were queried about missing criteria. Consequently, the newfound aspects and their implied relations were included in the existing literature-based set of criteria to clarify the second research question (see chapter 4.2.3). Four out of five aspects mentioned above could be adopted unconditionally in the existing set. However, as there are multiple influences on the design, sustainability as a fifth aspect could be added to various criteria, which would result in better AM-conformity as well. Further investigation on the expanded criteria and their independencies to the existing criteria set is necessary. While all criteria should be considered holistically, the general description of each criterion applies to both final parts and solution principles. Further research should differentiate them in detail. The final consolidation of all criteria, for example in the form of a checklist, could ease a manual assessment of AM-conformity.

Finally, a designer needs to reflect on manufacturing constraints and function fulfillment early in the development process to ensure concept feasibility and minimize design iterations. The presented criteria assist in evaluating the concepts as well as the implemented solution principles with regard to several aspects such as functional performance and manufacturability. Accordingly, future research should aim to develop a repository of predefined AM-conformal solution principles to provide an opportunistic approach in finding AM solutions while addressing the constraints imposed by AM-conformity early on. In conclusion, the answer to our rhetorical question at the beginning of chapter 4.1 is that both the solution principle and the final part in Figure 1 are AM-conformal. Without a predefined AM-conformal solution principle, it would have taken several iterations to finalize the part design.

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