FUNCTION INTEGRATION IN ADDITIVE MANUFACTURING: A REVIEW OF APPROACHES

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ABSTRACT

This paper provides an overview of established approaches for function integration in additive manufacturing and critically compares their capabilities. One of the decisive factors is how functions and structures are addressed. This is necessary because function integration - among many others - affects material decisions and the manufacturing process chain. It is one of many reasons to rethink the product architecture and a way to support the design of resource-efficient products. Various strategies for function integration exist. However, there are currently no approaches in additive manufacturing that provide systematic support for early function integration.

A systematic literature review identified 21 unique approaches. All approaches were categorized according to their abstraction level within a product architecture and their design type to be supported. They were then compared on the basis of their categorization, design objective and strategy for function integration to allow for a better understanding of when to use the approaches in research and practice. Key findings and considerations for adapting function integration approaches to early design stages are presented. In addition, several research gaps were identified.

Keywords: Additive Manufacturing, Product architecture, Function integration, Conceptual design, Solution principles

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1 INTRODUCTION

Resource efficiency is one of many factors for a sustainable design, as highlighted by EU Parliamentary Research Administrator Georgios Amanatidis (2021). Apart from the optimization of the product life cycle, the development of sustainable materials and design guidelines, to mention only a few, implementing strategies such as function integration to reduce material and energy consumption (Yang and Zhao, 2018) may result in higher resource efficiency (Chakrabarti, 2001; Despeisse and Ford, 2015). Unique to function integration is the ability to save weight, cost, and time simultaneously, while increasing the performance of a product. In particular, the product development defines the product architecture in a resource-efficient manner at an early stage of product design by adopting different approaches for function integration. Design objectives of function integration may include the ease for sustainable design (including ease of repair, maintenance, reuse, and recycle), ease of manufacturing, and ease of assembly as well as manufacture cost reduction, assembly cost reduction, and disassembly effort reduction (Yang and Zhao, 2015). These design objectives can lead to a reduction in material and/or energy consumption and become more feasible when combined with additive manufacturing technology (Lindemann et al., 2015) by exploiting the design freedom in terms of shape, hierarchical, functional, and material complexity. However, these design objectives lead to a decision on trade-offs in function integration and design complexities. For example, ease of assembly may be the objective, but an appropriate design may result in higher part count or more demanding maintenance of a product, which negatively affects resource efficiency.

Different approaches for function integration exist but are limited by several restrictions (e.g. functional links between components or disassembly constraints) (Wagner, 2018), which restrict the design freedom in product design and thus the achievable resource efficiency. Additive manufacturing allows designers to consider fewer manufacturing restrictions and offers the ability to design more functionally complex products. The reason is an increase in design freedom compared to traditional manufacturing and design (Laverne et al., 2014), which, among other things, creates the opportunity to explore new approaches for function integration (e.g. part consolidation in additive manufacturing) or to adapt existing approaches for traditional function integration (e.g. 'Einteilige Maschine' adapted by Kumke (2018)). The fast-evolving field of additive manufacturing not only presents new possibilities for function integration, but challenges in terms of trade-offs between design objectives, design complexities, and achievable resource efficiency. Function integration can lead to products with a higher value proposition, but too high of a complexity could, for example, result in an increase in product cost, difficulties in user experience, or even overengineering of simple solutions (Chiang et al., 2020).In summary, a designer needs a different approach depending on the design task. Therefore, our aim is to *understand what approaches exist for function integration in additive manufacturing and how they compare with respect to their design objective and supported design type*.

2 BACKGROUND

Function integration is not exclusive to additive manufacturing but has its origins in traditional design and manufacturing. In general, it refers to the endeavor to realize products with as few components as necessary and to expand the functionality of a product (Ziebart, 2012). Function integration implies the adoption of at least one of the four capabilities of "sharing in design" described by Chakrabarti (2001); essentially sharing in design means that several functions or properties of a design can be traced back to one and the same component.

Chakrabarti (2001) distinguishes between function sharing, which refers to the use of different physical structures (e.g. legs of a chair) to fulfill one function simultaneously, and structure sharing, which involves one physical structure fulfilling multiple functions simultaneously. Structure redundancy, on the other hand, refers to physical structures that fulfill the same function and should be reduced, whereby in multi-modal integration, a physical structure performs different functions at different times. These capabilities are depicted in Figure 1 with the intent to modify a product architecture.

A product architecture represents the connection between the functions and components of a product (Krause et al., 2021). The architecture of a product can be analyzed and modified at various abstraction levels to achieve function integration at different levels. At a high level of abstraction, the desired functions and their mutual connections are mapped. At a low level of abstraction, the physical components and their physical interactions are described. As an intermediate level, that is pragmatic

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and broad, solution principles ("working principle" in Richter et al., (2016)) fulfill sub-functions by applying physical/chemical/biological effects through the combination of structural and material properties of the product solution (Pahl et al., 2007). Since a detailed design is not required at this abstraction level, solution principles offer a high degree of design freedom, which is further enhanced by the possibilities of additive manufacturing. The design freedom further varies depending on the design type being pursued (Pahl et al., 2007): In an original design, a product designer redefines the product architecture and looks for new solution principles, which offers a high freedom of design. In the case of adaptative designs, the product structure is known. The design may be adapted to changing product requirements, but the solution principles remain the same and thus the design freedom is limited. Finally, if the product architecture remains unchanged, the configuration of parts and assemblies can be varied, resulting in variant design and little to no design freedom. These design types differ in their potential to define a product architecture that maximizes resource-efficient product design, as design freedom is constrained.

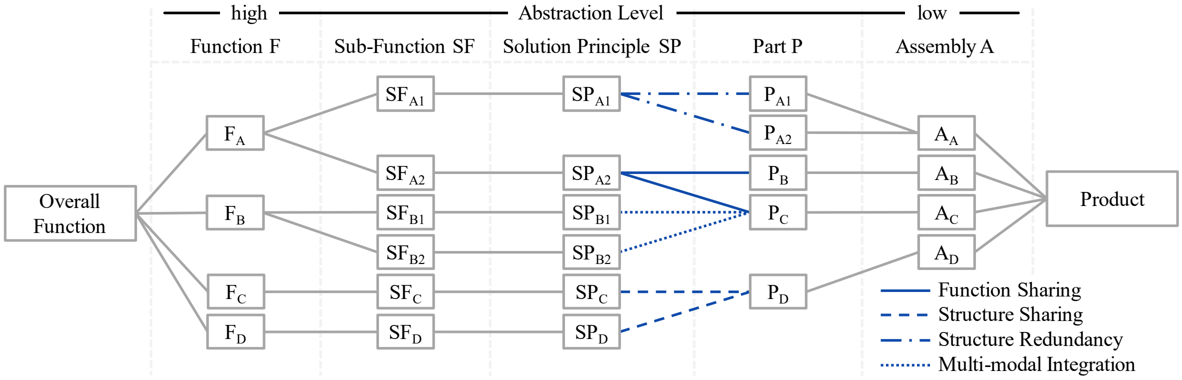

Figure 1. Mapping of capabilities for sharing in design at different abstraction levels within a product architecture based on Richter et al. (2016) and Krause et al. (2021)

Based on the four capabilities of sharing in design, various design strategies for function integration exist to modify the product architecture. Systematic approaches can then be derived from these strategies. Ziebart (2012) systematizes existing approaches for traditional function integration according to their design objective and design type and extracted the following five design strategies (S#): (S1) exploiting untapped properties to integrate new functions; (S2) expanding on functionalities via design variation, a change in manufacturing process, or even a variation of the function structures; (S3) incorporating existing, previously integrated solutions, e.g. via design catalog; (S4) removing redundant separations between components via part consolidation and integral design by combining several components; (S5) abstract thinking to develop functionally integrated parts.

While a function integration in additive manufacturing is advisable (Richter et al., 2016; Hwang et al., 2021), explicit steps on how to integrate often remain unclear (e.g. Valjak et al., 2022). In addition, each approach sets its own conditions and constraints and defines the product architecture at various levels.

The level of product architecture is not only determined by the design objective, but rather by the design type pursued.

While many approaches toward the design of functionally integrated parts for additive manufacturing emphasize the part consolidation of existing 3D models (e.g. Crispo and Kim, 2020), a major shortcoming is that at early design stages, designers tend to refer to a conventional product design and thus previously defined product architectures, which limits the design freedom and the level of resource efficiency that can be achieved. Instead of just adopting an existing product architecture, the hypothesis is that *the potential of function integration in additive manufacturing should be exploited during conceptual design with the exploration of new solution principles* (Wagner, 2018).

3 RESEARCH METHODOLOGY

The main objective of this paper is to systematize available approaches that support different design strategies for function integration enabled by additive manufacturing. These approaches comprise:

- Methods: procedures guiding the performance of function integration – e.g. guidelines, frameworks
- Tools: instruments supporting the execution of function integration – e.g. software
- Case studies: artifacts representing a detailed description of a procedure for function integration

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With additive manufacturing, designers are given the opportunity to develop complex products through layer-by-layer manufacturing with several materials, as well as a combined manufacturing process. While function integration can be achieved through different forms of hybrid manufacturing (e.g. Steffan et al., 2022), the literature focuses more on the technical side of integrating different processes and embedding components (e.g. Bellacicca et al., 2018) than the methodical integration of aforementioned design complexities along the product architecture. Thus, we exclude literature that describes a non-methodical exploitation of these complexities.
Based on the overall objective, a systematic literature review was conducted according to de Almeida Biolchini et al. (2007) to answer the following research questions (RQ):
RQ1: What are existing approaches for function integration in the context of additive manufacturing?
RQ2: What abstraction levels of a product architecture and what design type do they support?
RQ3: How do they compare with each other?

3.1 Data collection

The first iteration of data collection involved searching for and selecting approaches for the development of function integrated components in the context of additive manufacturing. The search was conducted in Scopus and Web of Science in September 2022 (see Table 1) and resulted in 495 distinct publications. 28 publications (see Figure 2) relevant to this work were selected according to the following criteria:
(1) Literature addresses at least one design strategy for function integration as defined in section 2
(2) Detailed information about the approach presented, including applied logic and examples

Table 1. Parameters for the search strategies

Databases	Scopus and Web of Science
Fields	(1) title AND (2) title, abstract, keywords
Search strings	(1) ((function* NEAR/2 shar*) OR (structur* NEAR/2 shar*) OR (part* NEAR/2 shar*) OR (integrat* NEAR/2 function*) OR (integrat* NEAR/2 structur*) OR (integrat* NEAR/2 part*) OR (consolidat* NEAR/2 function*) OR (consolidat* NEAR/2 structur*) OR (consolidat* NEAR/2 part*) OR (consolidat* NEAR/2 *assembl*) OR (combin* NEAR/2 function*) OR (combin* NEAR/2 structur*) OR (combin* NEAR/2 part*) OR (combin* NEAR/2 *assembl*) OR (monolithic* NEAR/1 design) OR "integr* design*" OR "integr* construction*" OR "single part" OR "single-part" OR unibody OR multifunction* OR multi-function* OR (function* NEAR/1 redundan*) OR (structur* NEAR/1 redundan*) OR "multimode integration*" OR "multi-mode integration*") (2) ((method* OR approach* OR framework* OR procedure* OR strateg* OR guid* OR tool* OR technique* OR practice*) AND ("additive* manufactur*" OR "rapid manufact*" OR "rapid prototyp*" OR "advanced manufac*" OR "digital manufact*" OR "additive* fabricat*" OR "freeform fabricat*" OR "direct tooling" OR "3d print*" OR "3d-print*" OR "generative* manufact*" OR "generative* design*"))
Database filters	Language: English, German Research area: engineering, material science, computer science, automation control systems, science technology, polymer science, metallurgy engineering, mechanics, environmental science, ecology, education research
Type	article, book, book chapter, conference paper

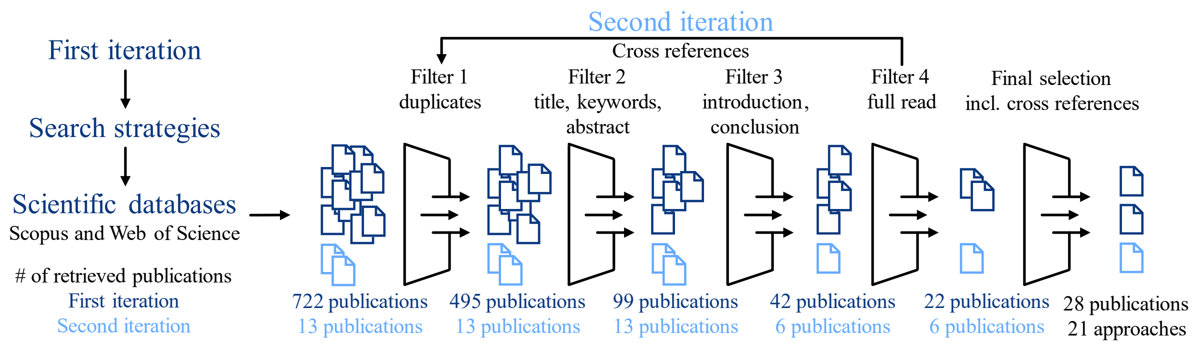

Figure 2. Review process

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Due to the fast-evolving nature of additive manufacturing and the variance in function integration strategies, a second iteration was conducted for data collection. A backward snowballing technique was applied to capture existing work (through cross-referencing) that was not included in the database searches. Therefore, the references of the initially selected publications from the scientific databases were screened and additional publications were selected according to their relevance (based on their title and the background of the author(s)) to function integration. The additional publications identified were subjected to the same screening process (filters and aforementioned criteria) applied to the scientific databases. The literature review resulted in 28 publications selected for further analysis.

3.2 Data analysis

From the set of 28 publications, 21 unique approaches (one approach was referenced three times and four approaches were referenced two times) were identified (RQ1) and mapped to the five abstraction levels of a product architecture as shown in Figure 1 (RQ2), characterized by the type of design support (original design, adaptive design, or variant design) and matched according to the design objective for function integration in section 1 and the design strategies for function integration in section 2.
First, the systemic view of approaches that cause a change in product architecture shall be explored. In relation to the research questions, the aim is to discover which approaches are available in literature and which design type they support. In addition, the characteristics of each approach shall be examined. The goal is to clarify how the approaches compare with each other (RQ3).

4 DESCRIPTIVE FINDINGS

From a total of 508 publications from both iterations, only 28 publications were relevant. Approx. 45% of the excluded publications feature multifunctional metamaterials. Although these make up a high percentage of the literature, they were disregarded according to the selection criteria in section 3.1. Either newly developed composite materials were introduced or case studies on metamaterials were not detailed enough to derive a systematic approach for function integration.
Overall, approx. 61% of the 28 publications (from 2010 to 2022) were journal articles. Moreover, ten conference papers and only one book chapter were identified as relevant publications. Only one approach for function integration was published before 2014. Publications show a continuous increase after 2014. In addition, the level of abstraction in approaches for function integration has been increasing (Garrelts et al., 2021; Green et al., 2022). Moreover, a trend is to make new approaches more viable in practice by considering trade-offs along a product lifecycle (Yang et al., 2019) and a holistic view of production cost and time (Nie et al., 2019; Nie et al., 2020). From an industrial perspective, the rising trend might be associated with the abrupt growth in industrial implementation of additive manufacturing (e.g. LEAP fuel nozzle by GE Aviation) since 2013 (Wohlers Report, 2015). Research into part consolidation has seen a rapid growth since 2015 (Yang et al., 2019).

5 COMPARISON OF APPROACHES TOWARD FUNCTION INTEGRATION IN ADDITIVE MANFUACTURING

Our objective with this comparison is to provide an overview and systematize the state of the art for function integration approaches in additive manufacturing. We consolidated key characteristics of individual approaches in Figure 3. Each approach is assigned a design type (row in matrix) and an abstraction level (column in matrix). If the approach is located between two types or levels, both assignments apply. For example, the approach referenced with [A10] is mapped to original design and adaptive design because it can be applied to both design types, which is not uncommon in practice (Pahl et al., 2007). In addition, the function level and sub-function level have been combined as their separation does not add any value to the differentiation of all approaches. And irrelevant cells have been grayed out because as per definition in section 2: The same solution principles are maintained when designing a variant. And an original design cannot be analyzed based on non-existing parts and assemblies, otherwise this would be contradictory. Finally, derived *key elements* for a new framework for function integration are in *italic*.

Figure 3 shows that 18 out of 21 approaches focus on adaptive design and/or variant design. Only three approaches deal with function integration to achieve an original design. This indicates a trend in additive manufacturing whereby function integration is often applied to existing product architectures, which is

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followed by topology optimization. However, it is advisable to *further support function integration in original designs and early adaptive designs* to take advantage of the design freedom in additive manufacturing (see section 2) while limiting the required iterations when function integration is applied.

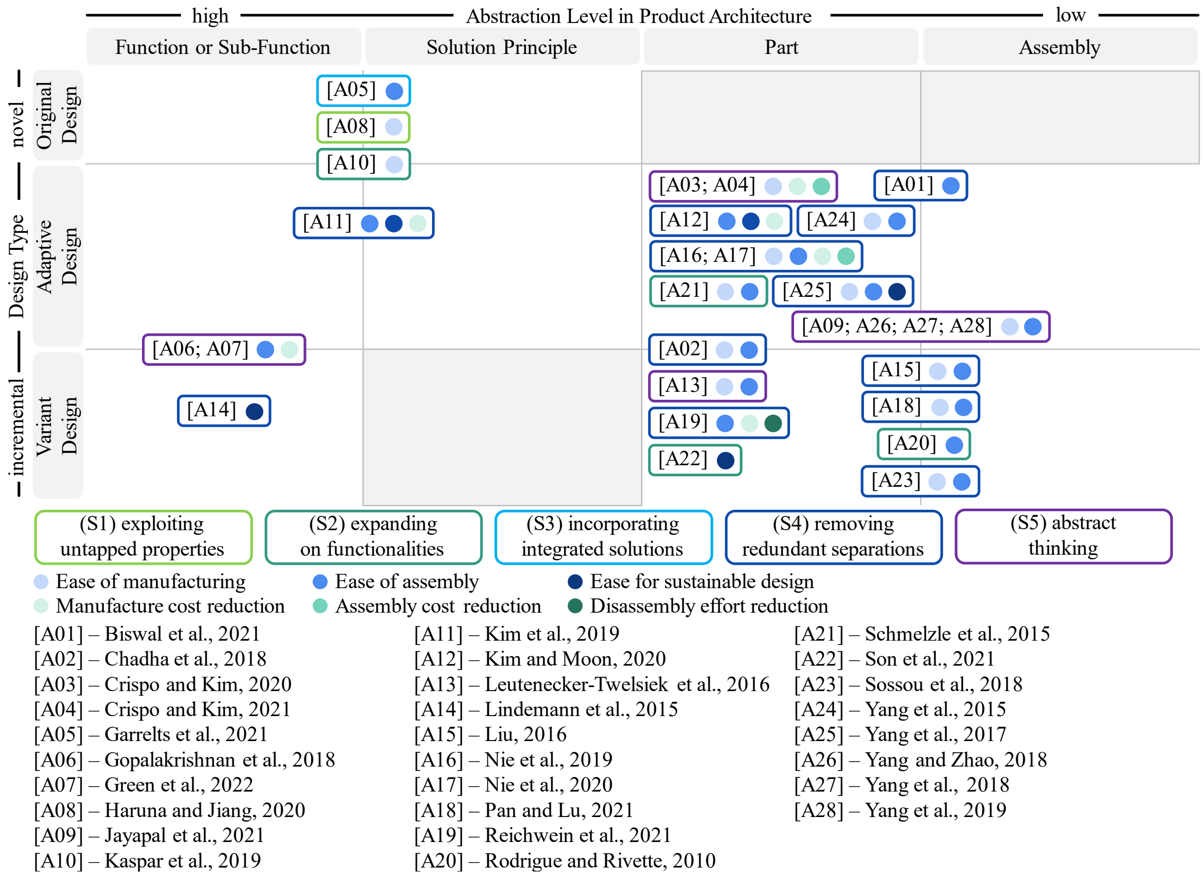

Figure 3. Key characteristics of approaches ("A" stands for "Article"; color-coded outline represents a strategy for function integration; color-coded circle marks a design objective)

Furthermore, there are only three approaches to function integration [A06; A07; A14] that define the product architecture exclusively at the function level. This tendency supports the trend that an adequate approach for function integration considers the *relationship between functions and embodiment design*. In addition to the function level, little support is provided at a solution principle level with only four approaches, while the part and assembly level are supported the most with 16 approaches. It is assumed that this is because the low level of abstraction is more common in practice and the use of additive manufacturing needs to be justified, leading to an subsequent part identification and hence an entry in product architecture at function level. But *considering solution principles* could bridge the gap between analyzing functions and parts while increasing design freedom through the higher level of abstraction.

Although many approaches start with an abstract function analysis of an existing assembly or an original design problem (e.g. [A11]), they do not attempt to change the solution principle or integrate new solution principles at the part and assembly level. This can be linked to the design type of an approach. A change at the solution principle level basically leads to an original design (Pahl et al., 2007). However, since in most cases a redesign of the product is motivated by a change of the manufacturing process, manufacturing restrictions deny a change of the solution principle. Few existing approaches support the conceptual design stage through a combination of function analysis and provision of design opportunities in additive manufacturing (e.g. integrated design catalog by [A05], calculating a novel configuration of geometries by [A06; A07], or design pattern matrix by [A10]). These approaches to function integration in additive manufacturing employ different types of *stimuli that trigger a remapping of functions within a product architecture or a change in solution principles*. Thus, designers are given examples that convey integration opportunities, while *considering manufacturing and material constraints* ([A05], [A08], and [A10]). However, aspects like costs or energy consumption are not considered. This is due to the design objectives of each approach.

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From the perspective of design objective, the ease of assembly (16 mentions) and ease of manufacturing (13 mentions) are the primary motivations for function integration. While seven approaches focus on reducing manufacturing and/or assembly costs, only three approaches overtly address sustainable design aspects, and one approach targets the reduction of disassembly effort. This leads to an underestimation of the additional benefits that could be achieved with additive manufacturing, evident in the *lack of consideration of sustainability and trade-offs* outside of production. Furthermore, in addition to function integration, a *separation of functions should be investigated* more intensively, as described e.g. in [A19].

Looking at the distribution of the design strategies (S1 to S5) for function integration, it is noticeable that no approach pursues a combination of several strategies and thus limits the extent to which the potential of function integration is exploited. At the very least, it can be stated that each approach assumes a previous *abstraction of a product architecture* (e.g., when defining the function structure).

Twelve approaches are concerned with the elimination of redundant structures (S4) as seen in methods and tools for part consolidation (e.g. [A15] and [A21]). These approaches exploit the concept of structure sharing with some consideration of trade-offs and performance indicators (e.g. [A04]). While four approaches were found that rely purely on abstract thinking (S5), seven approaches expand on functionalities and address strategy S2. In contrast, only one publication was found for each of the strategies S1 and S3. [A05] analyzed products from additive manufacturers and publications to collect integrated designs and consolidate them in a design catalog. Similarly, [A10] utilizes a repository of design capabilities in additive manufacturing to combine them into innovative designs.

6 DISCUSSION

The field of additive manufacturing has evolved rapidly in recent years. Function integration, as a common motivation, is gaining more popularity with the newly granted design freedom of additive manufacturing. Different approaches support the different design objectives by implementing an adequate design strategy for function integration. Most approaches focus on cost reduction and the ease of manufacturing and assembly by removing redundant structures. The current literature for adaptive design and variant design shows that sharing existing structures to enhance functionality is a viable approach in order to realize a unique design for additive manufacturing and make use of the possible design complexities. Nevertheless, the literature review revealed a research gap: *There is a lack of support for resource-efficient function integration and function separation in additive manufacturing that combines all five design strategies in original and adaptive design, considering trade-offs of design objectives as well as manufacturing constraints*. Moreover, from the comparison of the approaches, essential key elements could be derived, which should be consolidated in a framework for resource-efficient function integration. The following section discusses these findings and provides initial suggestions for developing a framework for resource-efficient function integration.

The limited coverage of the original design type and the high density of part-level approaches indicate an insufficient diversity of methods and tools for function integration. Existing approaches such as Kaspar et al. (2019) and Garrelts et al. (2021) manage to combine a function-based approach with additive manufacturing capabilities, but do not address the actual detailed thought process behind the integration. Thus, an ideal framework for resource-efficient function integration shall not only analyze the potential of function integration, but also describe support for design synthesis step-by-step.

To fill the research gap, the framework shall support the principle level of a product architecture. The relationship between functions and embodiment design remains, while the design freedom increases. An ideal framework abstracts the product functions and describes the relationship between functions and embodiment design algorithmically, following the trend from the literature. For defined functions, additively implemented solution principles and integrated solutions shall be proposed. This shall be followed by an analysis of the design complexities in additive manufacturing to determine the possible integrations and separations of solutions principles. The result would be a variety of product solutions with different product architectures. In order to find the most resource-efficient solution, the algorithm should determine an optimum of function integration based on the data of chosen solution principles. An adoption of complexity indicators as suggested in Kim et al. (2020) seems viable for selecting and eliminating functionally integrated solutions while considering optima for function integration. Moreover, subsequent optimization of the structural behavior is often proposed without a limitation on

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the optima, except in Nie et al. (2019; 2020) and Crispo and Kim (2021). Yet most approaches lack an application to complex use cases where trade-offs play a significant role.

The limitations of this study are related to the literature review. Searches of scientific databases excluded studies of additive manufacturing materials and hybrid processes that could play a significant role in function integration. Studies on multifunctional metamaterials were excluded, because of missing information on the design steps to integrate different functions by implementing metamaterials.

There is a bias in deciding whether the data presented are extensive enough to consider for further analysis. In addition, recent development of this research field has led to many new publications in a brief period. Many of the approaches analyzed are still being validated or refined with case studies on highly complex products. Their extensive usefulness is not yet confirmed. Based on the comparative analysis of the 21 approaches, we formulate the need for further research in section 7.

7 CONCLUSION AND OUTLOOK

The aim of this study was to identify and systematize approaches for function integration in additive manufacturing available in literature, in order to provide an overview of this topic and identify a research gap. Visualizing the capabilities and differences, this work systematically identified and compared 21 unique approaches for function integration based on four properties: level of abstraction, design type, design objective, and design strategy for function integration.

The analysis revealed that the approaches are moving toward multi-criteria, computer-aided methods for function integration to redesign or design product variations. However, methods are still provided that can be applied manually, but only take manufacturing restrictions into account and disregard trade-offs in design objectives. In addition, there is little support for original designs, which has the highest potential for resource-efficient product design.

By systematizing a comprehensive collection of approaches currently available to support function integration in additive manufacturing, this study provides contributions for:

- Practitioners: an overview of existing approaches for function integration in additive manufacturing based on their properties,
- Researchers: a focused view of function integration for understanding the fundamentals of different approaches and providing guidance on where to focus future research, and
- Community: starting points for discussing potential links to various research fields within additive manufacturing, plus the incentive to explore newfound opportunities for product development.

Based on this work, we propose the following research plan to advance the design for function integration enabled by additive manufacturing:

- The comparison of literature and industry perspective on trends in function integration,
- The expansion of our review with a study on function integration using metamaterials, and
- The conceptualization of a framework on how to exploit the design complexities in additive manufacturing to improve function integration in the context of a product's resource efficiency.

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