



A strategic approach to direct manufacturing: aligning product development for additive manufacturing with principles of agile hardware development

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Abstract

Dealing with volatility, uncertainty, complexity and ambiguity (VUCA conditions) in product development requires methodologies that utilize change as opportunities, an approach pursued by agile development methodology. While the principles of agile development are established in software design, their application in hardware development remains challenging, particularly regarding the continuous delivery of physical increments. Additive manufacturing (AM) offers technological synergies with agile approaches through tool-free production and greater design freedom. However, current applications remain limited to rapid prototyping and comprehensive frameworks leveraging these synergies are missing. To establish the theoretical basis for agile development of end-use products for AM, this study adapts the twelve principles of the Agile Manifesto specifically for direct manufacturing. Based on a systematic literature analysis, new agile principles are formulated that link technological characteristics of AM with methodological aspects of agile development. Examining the agile principles in the context of direct manufacturing shows that iterative-incremental development leverages AM to deliver frequent, value-adding increments. Realising the full design for additive manufacturing (DfAM) potential requires systematic prioritisation of product features by both customer value and DfAM potential. Early development phases are crucial, as they define the design space for subsequent iterations. The study establishes a theoretical foundation for agile direct manufacturing framework. It is demonstrated how combining agile methodology with AM technology through repeated traversals of development phases and targeted application of DfAM methods realizes a greater proportion of DfAM potential in the final product compared to plan-driven approaches. This contribution provides the methodological groundwork for leveraging synergies between agile development principles and additive manufacturing capabilities in direct manufacturing contexts.

Keywords Additive manufacturing · Direct manufacturing · Agile hardware development · Agile principles · Development methodology · Design for additive manufacturing

1 Introduction

Product development is increasingly taking place in a volatile, uncertain, complex and ambiguous (VUCA) environment. Changing customer requirements in the late stages of development projects are increasingly becoming the norm rather than the exception, while expectations of product quality are rising [1]. These circumstances make competitiveness directly dependent on the ability to react quickly and adequately to change [2]. Agile development methodology is well suited for dealing with change under VUCA conditions, as this concept sees volatility as an opportunity for product improvement rather than a threat [3]. While

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plan-based approaches try to evade the influence of volatility, agile approaches instead aim to minimize the consequences of prediction errors through iteration. Agile development has its origins in the software industry, where it is largely established as a standard procedure today [4]. The software industry's role model is also increasingly sparking interest in utilizing agile principles for hardware development [5–8]. However, the continuous creation of increments in short iterations, especially in response to changing requirements in late stages of development, is particularly challenging in the context of hardware development. Realizing hardware increments under these conditions using conventional methods is challenging [9], whereas additive manufacturing (AM) processes seem particularly suitable for this purpose [10]. AM offers practically batch-size-independent manufacturing costs [11] with greater design freedom [12], and thus inherently offers synergies with iterative development under VUCA conditions from a technology perspective. Most companies practicing agile hardware development already use the potential of AM to realize hardware increments more efficiently within agile development projects [5]. However, these applications remain limited to the purposes of rapid prototyping, and the potential of AM for the series production of agile developed products remains largely untapped [13]. In this article, we hypothesise that an iterative and incremental approach to product development for direct manufacturing, can capitalise on synergies between the agile development methodology and the technological characteristics of AM, thereby facilitating the realisation of the full design for additive manufacturing (DfAM) potential in the final product. Although research on the combination of AM and agile development is increasing [14], the work proposed so far is still geared towards demonstrating basic feasibility rather than fundamental contextual adaptation of agile methodology for developing additively manufactured final products (direct manufacturing). This paper therefore aims to provide the currently missing adjustment of agile development methodology to the context of direct manufacturing. To establish a foundation for this adaptation, this study begins by analysing the extent to which the fundamental principles of agile development are reflected in the existing literature. Building upon the insights from the literature analysis, the underlying principles of agile development methodologies as defined in the Agile Manifesto [3] are adapted for direct manufacturing. Twelve adapted agile principles for direct manufacturing (APDM) are proposed. These principles lay the foundation for a strategic alignment of development resources for incremental development of additively manufactured final products. This approach leverages the potential of additive manufacturing technologies in line with agile principles to help maintain the

competitiveness of companies under VUCA conditions by improving the quality of development processes and final products.

2 Literature background

2.1 Additive manufacturing

Additive manufacturing (AM) comprises a group of production processes in which physical components are created element by element or layer by layer [15]. For production companies, the utilization of AM offers new possibilities resulting from the increased design freedom, the direct conversion of digital data into physical objects and the economic viability of small batch sizes [16]. The first industrially relevant application of AM technologies was rapid prototyping, where physical components whose characteristics and properties do not entirely match those of the final product are produced more efficiently than with conventional manufacturing methods. Technological progress has increased the quality of the manufacturing output from AM systems to a level that now also enables the production of final products, known as direct manufacturing [17].

2.2 Potentials of additive manufacturing for product development

The layer-by-layer manufacture of physical products without form giving tools enables designers to take advantage of greater design freedom during product development. The increased design freedom compared to conventional methods is based on the enhanced utilisation of the four complexity dimensions defined by [18]: shape, material, hierarchical, and functional complexity. These dimensions of complexity enable advanced geometrical designs to achieve material savings, load path adjustment and near-net-shape geometries (see [19] for a more comprehensive description). A frequently referenced compilation of the potentials AM offers for product development is shown in Table 1 [20]. This compilation is to be understood as an overall overview, in which specific potentials must be assessed in an application-specific manner. To translate this design potential into physical forms, so called Design for AM (DfAM) methods are used, whereby opportunities as well as process-specific restrictions must be considered by the designer [21]. Growing industrial interest in direct manufacturing applications has also led to the incorporation DfAM methods and design methodology into internationally recognised industry standards [22].

Table 1 Potentials of design for AM for product development based on [20]

<i>Design for AM opportunities at the part level</i>	
Material choice	AM processes a wide range of materials, including metals, polymers, ceramics, food, and biological materials
Colour	AM enables full-colour production, reduces post-processing, provides durable colour integration, and uses colour as a communication tool in prototypes and models
Freeform geometry	AM enables complex free-form geometries, such as contour-following cooling channels, improving efficiency and cost-effectiveness, particularly for injection moulding tools and thermally stressed components
Topology optimisation	AM enables topology-optimised structures, delivering material-efficient, lighter designs with significant lifecycle energy savings, particularly in aerospace, automotive and biomedical sectors
Customisation	Combining digital workflows with AM's design freedom enables customisation of medical and dental products (e.g., implants, prostheses, surgical guides), as well as custom-fit packaging and personalised consumer goods (e.g., shoes, glasses, furniture). This supports both individual and mass customisation with near-unlimited variants
<i>Design for AM opportunities at the material level</i>	
Microstructure and material composition	AM enables the simultaneous production of material and geometry, allowing the properties of alloys and composite materials to be adjusted to use cases as a result of the manufacturing process
Surfaces, textures and porosity	AM with micro- or nanoscale resolution enables customised surfaces, textures, and porosities, improving fixation and osseointegration, e.g., in porous hip implants or complex surfaces for optimised primary fixation
Lattices, trusses and cellular materials	AM enables three-dimensional lattice and support structures with tailored mechanical, thermal, optical, and biological properties—from ultralight, stiff, or auxetic designs to optimised lattices for implants and tissue engineering. The design can be tuned via cell shape, volume fraction, and topology optimisation
Multi material	AM enables components with different materials or properties to be produced within a single part. Applications include wrist splints, compliant mechanisms, artworks, and integrated electronics. It also supports customised composites and topology-optimised, multi-material structures
Functionally graded materials	AM enables functionally graded parts with variable material composition, such as variable porosity, alloy mixtures, polymer combinations, or different binder blends. This allows targeted mechanical, thermal, or functional properties within the component.
Metamaterials	AM enables metamaterials with exceptional properties, such as artificial magnetism or negative refraction, due to their periodic lattice structure
<i>Design for AM opportunities at the product level</i>	
Part consolidation	AM enables multiple components to be combined into a single printable object, reducing assembly time and storage costs while improving functionality and performance
Embedded objects	AM enables the embedding of components such as cooling channels, shape memory alloys, electrical components, conductive tracks, motors, batteries and sensors, allowing complete mechatronic devices to be printed directly and functional products to be manufactured in a single step
Direct production of assemblies	AM enables the direct production of assemblies with moving parts such as gears, joints and hinges, as well as interlocking structures such as chain mail or flexible textiles that can be customised

2.3 Agile development

Agility in product development is commonly understood as ‘The ability to move quickly and easily responding to changing customer desires’ [1]. In contrast to conventional plan-driven development, agile approaches are therefore best characterized as ‘change-driven’. This conceptual distinction reflects differing underlying assumptions: whereas traditional methods presume that systems can be comprehensively specified and that meticulous up-front planning

ensures project success, agile development posits that high-quality solutions emerge through iterative cycles of development, testing, rapid feedback, and adaptive change [23]. In project management terms, this divergence translates into a shift in optimization criteria: Traditional project management primarily seeks to balance the triad of cost, time, and scope, while agile methodologies prioritize the delivery of business value and the tailoring of solutions to context-specific requirements. By enabling plans to evolve incrementally rather than mandating comprehensive, fixed baselines

Table 2 Principles of the agile manifesto [3]

Agile Principles	
I	Our highest priority is to satisfy the customer through early and continuous delivery of valuable software
II	Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage
III	Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to the shorter timescale
IV	Businesspeople and developers must work together daily throughout the project
V	Build projects around motivated individuals. Give them the environment and support they need and trust them to get the job done
VI	The most efficient and effective method of conveying information to and within a development team is face-to-face conversation
VII	Working software is the primary measure of progress
VIII	Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely
IX	Continuous attention to technical excellence and good design enhances agility
X	Simplicity—the art of maximizing the amount of work not done—is essential
XI	The best architectures, requirements, and designs emerge from self-organizing teams
XII	At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly

at project inception, the agile paradigm enhances the management of uncertainty, including technological unknowns and external constraints, through sustained learning and continuous adaptation [1]. This responsiveness to change makes agile approaches particularly suitable for projects with volatile or initially ambiguous requirements. In this vein, Highsmith characterizes agile endeavours as exploratory in nature, aimed not at producing a fully pre-specified outcome but at creating a valuable product that satisfies emergent customer needs and a viable business case as they become known [24].

2.4 Principles and values of agile development

The origins of agile development trace back to 2001, when a consortium of experts articulated fundamental values and principles for software development within the framework of the ‘Agile Manifesto’, with the explicit aim of establishing ‘better ways of developing software’ [3]. Central to the manifesto are four value pairs, each formulated as a contrast, with particular emphasis placed on the elements presented on the left side (at the beginning) of each statement. ‘Individuals and interactions’ are prioritised over ‘processes and tools’, ‘working software’ is regarded as more important

Table 3 Agile principles for direct manufacturing

Agile principles for direct manufacturing (APDM)		References
I	Provide products using additive manufacturing early and continuously to enhance customer satisfaction	[10, 29, 30, 34, 36]
II	Embrace changing requirements as an opportunity to increase customer value through the flexibility of additive manufacturing	[10, 29, 30, 35]
III	Design products for additive manufacturing in a way that allows for incremental expansion, enabling the regular delivery of valuable increments to the customer	[10, 14, 29, 30, 33, 35]
IV	Align technical and economic objectives on a daily basis to leverage the technical and economic potential of additive manufacturing	[13]
V	Motivate employees and provide targeted support with suitable conditions during the introduction of additive technologies	()
VI	Demand direct face-to-face communication within the team to effectively harness the potential of additive manufacturing	[10, 30, 35]
VII	Regularly produce physical increments additively to transparently demonstrate project development progress	[29]
VIII	Maintain a development pace in direct manufacturing projects that can be fully supported by all participants to ensure continuous project progress	()
IX	Continuously focus on the technical capabilities of additive manufacturing to effectively utilise its potential	()
X	Prioritise component features based on their customer value as well as DfAM potential and integrate them into the final product accordingly to effectively utilise the potential of additive manufacturing	[14, 29, 30, 36]
XI	Implement self-organised teams to effectively utilise the potential of additive manufacturing	()
XII	Regularly evaluate the effectiveness of the development process for additively manufactured products and adjust it as needed to ensure continuous improvement	[10, 30]

than ‘comprehensive documentation’, ‘customer collaboration’ is valued above ‘contract negotiation’, and ‘responding to change’ is given precedence over strictly ‘following a plan’. The manifesto explicitly asserts that the elements on the right of each pair are not considered dispensable but are instead consciously de-emphasised in favour of a stronger focus on the aspects to the left. Values are abstract conceptions of the desirable [25]: they guide action but do not prescribe specific actions. Consequently, the values of the Agile Manifesto, taken alone, cannot furnish direct operational guidance.

To address this, the manifesto further specifies twelve agile principles, translating the abstract values into actionable directives and providing more tangible orientation for practical implementation (Table 2).

Building on this foundation, frameworks such as SCRUM, SAFe, XP, and Kanban have been developed to provide concrete methods for operationalising these values and principles in practice. In response to the growing adoption of agile development beyond the software domain, a VDI working group formulated the ‘Manifesto for Agile Development of Mechatronic Products’ [26], adapting and expanding the principles to ensure their applicability to hardware development.

2.5 Agile hardware development

Agile hardware development (AHD) has emerged as a distinct research domain and denotes a class of product-development frameworks that aim to design, manufacture, and test physical increments in short, iterative cycles [13]. These frameworks are conceptually aligned with the agile values and principles originally articulated for software development in the Agile Manifesto [3, 5].

Transferring agile values and principles from the virtual domain of software to the physical domain of hardware, however, introduces domain-specific constraints, often labelled as ‘Constraints of Physicality’ [27] or more generally ‘hardware challenges’ [28]. The foundational difficulty lies in the fact that hardware creation is intrinsically coupled to physical manufacturing processes that exhibit lower flexibility and longer changeover times than software compilation and deployment, thereby limiting the ease and frequency with which deliverable increments can be produced [4]. Consequently, producing shippable increments within short iterations is widely perceived as more straightforward in agile software development than in AHD [6]. This tension is amplified in early development phases, where deliverable increments in hardware have traditionally been oriented toward demonstrating technical feasibility rather than delivering immediate customer value, an emphasis that can stand in contrast to core agile tenets [7, 8]. In contemporary hardware development practice, Scrum is the most frequently employed framework, followed by Kanban and Design Thinking. However, many firms substantially tailor these approaches to their specific organizational and product contexts [6].

3 Problem statement

The interest in using AM in AHD is mainly based on the advantage of being able to realise physical artifacts in a more resource-efficient way compared to most conventional manufacturing processes, since the problems associated with long lead times and tooling do not exist [9]. This

makes it considerably more feasible to frequently provide hardware increments, which are essential for realizing the full potential of AHD [29]. A study by Atzberger et al. has shown that by 2020, most companies practicing AHD utilize additive manufacturing to support agile product development [5]. However, the application of AM is limited to the scope of rapid prototyping, since the final products are not manufactured additively. To this day, the focus of studies on agile development with additive manufacturing remains on accelerating the development process through rapid prototyping [13]. Comprehensive frameworks for direct manufacturing based on agile development methodologies are missing. Despite technological advances in AM, product development processes remain largely unchanged [30], with development frameworks for direct manufacturing still primarily reliant on plan-based approaches [31]. The limitation of these frameworks is that, beyond the DfAM potential linked to the integrated DfAM methods, they do not exploit additional potentials arising from development-methodological and technological synergies, such as those emerging between the iterative and incremental approach of agile development methodologies and AM. The necessary understanding of how technological and methodological synergies can be exploited for direct manufacturing is still insufficient due to the objectives set so far. Studies [6, 32] have also shown that agile frameworks and methods require significant adaptation to individual contexts of manufacturing enterprises, which has not yet been done for direct manufacturing. By adapting the principles of the Agile Manifesto to the context of direct manufacturing, this contribution establishes the necessary understanding of how these synergies can be leveraged within an agile framework for direct manufacturing.

4 Methodology

The research approach of this paper is based on a systematic literature review of publications addressing the combination of additive manufacturing and agile development methodology. Relevant publications are analysed for approaches that align thematically with the principles defined in the Agile Manifesto [3], to derive the new agile principles for direct manufacturing (APDM) in the synthesis step. Scopus was used for the literature search. For a publication to be included in the final dataset of this study, it must meet two specific criteria in addition to general scientific quality standards. The work must:

- I) Demonstrate a clear thematic link to agile product development.

- II) Address synergies between agile development and AM from either a methodological or technological perspective.

Criterion I primarily serves to exclude publications that use the keyword ‘agile’ in a context other than development methodology. It is therefore the decisive criterion for the analysis of abstracts in the first iteration before proceeding with the full-text analysis. Assessing compliance with criterion II requires a deeper content analysis of the material and is therefore central to the second iteration. As the publication landscape on agile product development with additive manufacturing is still emerging, a deliberately broad search string with only two keywords (‘additive manufacturing’ and ‘agile’ as loose phrases) was used to ensure no relevant literature was excluded. For this reason, the subject area filters commonly used in our research field (e.g. engineering) were also omitted. The search string (‘additive manufacturing’ AND ‘agile’) yielded 146 initial results in the Scopus database. In the first iteration of the analysis, 100 results were excluded upon reviewing the abstracts for the use of the keyword ‘agile’ in a semantic context unrelated to agile development methodologies. A further 19 publications were excluded for using both keywords in the context of ‘agile manufacturing’, which does not align with the thematic focus of this study. The remaining 27 studies met criterion I and underwent full-text analysis in the second iteration. Fifteen additional papers were excluded as a result, as they did not focus on the synergistic use of AM technologies in the context of agile development methodology, thus failing to meet criterion II. This applies to studies that mention an agile framework like Scrum as the development approach for a specific case, but do not further evaluate the coupling of AM with the development methodology. The remaining 12 references therefore constitute the final dataset for this study and are analysed with respect to the reflection of agile principles. Based on these results, the new agile principles for the context of direct manufacturing are formulated. The aim of the following synthesis step is to extract the technological and methodological synergies identified according to Criterion II, assign them to the corresponding underlying agile principles, and adapt the original formulations to the context of direct manufacturing.

The formulation of the new agile principles for direct manufacturing is intended to follow the same syntax and semantics used in the original ‘Manifesto for Agile Software Development’ [3] and the derived ‘Manifesto for Agile Development of Mechatronic Products’ [26]. An agile principle for direct manufacturing thus begins with an action that is either executed with additive manufacturing, enabled by additive manufacturing, or necessary to realise an AM-related potential for development or the final product. A

principle concludes with the formulation of a goal, which can either be a generic objective of product development (e.g. increasing customer value), a specific goal in the context of incremental development (e.g. regular delivery), or a specific goal related to AM (e.g. realising DfAM potentials). From a semantic perspective, the connection to the agile values must be maintained, meaning that a principle either specifies or expands on one of the four values from the Manifesto. The principle should also include implementation guidance and be phrased positively. Concerning the syntax, it is defined that a principle begins with a verb, establishing the action-guiding character, and that a conjunction between the action and the goal is required to establish a purpose relation.

Following the presentation of the results, the relevance and application of the newly formulated agile principles for direct manufacturing are discussed. This discussion draws on both the literature identified in the review and industrial studies on agile hardware development from 2019 to 2023.

5 Results

5.1 Overall analysis of the literature body

The literature largely agrees that the technological properties of additive manufacturing processes exhibit synergies with the methodological principles of agile hardware development. These synergies are primarily based on the increased flexibility compared to conventional methods [10], as physical increments can be produced directly from CAD data without specific tooling [30]. This reduces lead time [9], enabling the frequent realisation of physical increments, which are of high importance for agile hardware development [29]. Leveraging these synergies in development can enhance the quality of additively manufactured end products, even if the process is not strictly agile but follows some of these agile principles, as demonstrated by [33, 10]. highlight that the flexibility of additive manufacturing can be leveraged to support product development by quickly producing and testing physical artefacts, thereby generally reinforcing the concept of agility. The authors thus propose an agile framework that involves the customer in each iteration to use their feedback for adapting the product backlog for subsequent iterations [34]. describe additive manufacturing technology as virtually predisposed to agile workflows, as it offers the potential to support early stages of product development by providing physical products [35]. defined seven value-adding clusters for the industrial use of additive manufacturing, with prototyping, incremental product launch, and customisation linked to agile development principles [14, 33, 36]. demonstrate that incorporating

agile principles, even in projects not strictly following agile methodologies, enhances resilience to VUCA influences and improves the quality of additively manufactured spare parts [29]. highlight the importance of additively manufactured physical increments in agile hardware development to mitigate issues associated with the Constraints of Physicality as defined by [27]. Both [30] and [31] propose Scrum frameworks adapted for additive manufacturing. The framework by [30] addresses the increased efficiency in realizing a functional prototype with AM, as the hardware equivalent of a Minimum Viable Product, compared to conventional methods. The proposed framework is further used to demonstrate how the direct production of increments from CAD data using AM mitigates challenges in transferring agile development methods to the hardware domain.

5.2 Reflection of agile principles in the literature body

The following section presents the results of the literature analysis regarding the already addressed approaches and aspects related to the agile principles. For each principle addressed in the literature, relevant examples from the corresponding works are presented, illustrating how these principles have been interpreted or implemented in the context of agile product development with AM.

Principle I: early and continuous delivery

The manifesto assigns the highest priority to customer satisfaction through early and continuous product delivery [3]. The framework proposed by [10] adheres to this principle by leveraging the flexibility of additive manufacturing to involve the customer in the cyclic design, production, and testing of additively manufactured increments from the first iteration onwards [34]. suggest using AM to produce a Minimum Viable Product early to generate additional customer feedback [30]. also adopts this principle by proposing to provide the customer with a functional prototype implementing prioritised features after the first sprint of his adapted Scrum framework. To enable the continuous delivery of such physical increments in short iterations [29], propose intentionally keeping component features simple at first, refining them only after customer validation [36]. emphasise the importance of this principle, particularly for metal-based AM, as early polymer increments can help reduce uncertainties together with the customer before transitioning to more expensive technologies like PBF-LB/M.

Principle II: welcoming changing requirements

This principle illustrates a significantly different approach to volatility compared to plan-based development methodology. However, it poses challenges relating to manufacturing techniques. AM technologies offer the inherent advantage of tool-independent manufacturing. Therefore, even late requirement changes that lead to design adjustments can be welcomed as opportunities to enhance the product according to customer needs. In line with this principle [30], view integrating customer feedback into the development process as an opportunity to improve the product, even if it means changing requirements or functional structures at a late stage [29]. demonstrate how to put this principle into practice by only refining features after a simplified version has been validated by the customer. In this way, the flexibility of AM is used to refine, add or remove features depending on customer feedback. Additionally [35], explain how customers could benefit from a business model based on this principle. One example is an incremental hardware launch, where additively manufactured products continue to receive design updates after their launch.

Principle III: regular delivery of valuable increments to the customer

Regularly delivering physical increments to customers requires producing them in short iterations. AM is ideal for this because it allows for tool-free manufacturing with low lead times. To bring added value to the customer, the increments should represent an expansion of the previous increment [37]. The literature provides approaches for incorporating this incremental expansion into AM designs. In the context of DfAM, the incremental expansion of the product design can be understood as scaling the product [14, 33, 36], changing materials or processes [14, 33, 36], increasing feature complexity [29], adding details [10] and personalization based on customer data [35], expanding the functional scope [30, 35], or integrating interfaces for system integration [29].

Principle IV: alignment of technical and economical perspectives

In line with the fourth principle of the Agile Manifesto, technical and economic objectives should be closely aligned throughout development [13]. illustrates how the use of AM in agile hardware development leads to a shift in the business model canvas compared to plan-based approaches. Although aspects such as daily coordination are not explicitly addressed, these findings provide a valuable foundation for further considerations in aligning technical and economic perspectives.

Principle VI: face-to-face communication within the team

For many manufacturing companies, integrating AM and the necessary design skills is a relatively new undertaking. In a 2024 industry study, the authors found that a lack of communication between AM experts and designers without relevant AM experience often results in inefficiencies and disillusionment [38, 10] and [35]. address the team dynamics associated with this agile principle, which explicitly highlights the importance of short communication paths [30]. also adhere to this principle by adopting elements that facilitate this type of communication, such as the daily stand-up meeting from the Scrum framework.

Principle VII: the product demonstrates the project development progress

The agile manifesto stipulates, that the functional product should be regarded as the primary measure of project progress [3, 29]. propose the ‘Protomap’ approach to project planning, in which different physical increments reflect the development status.

Principle X: the art of maximizing the amount of work not done

This principle advises against implementing product features or development processes that do not add value for the customer. It is therefore reflected in elements of agile development frameworks like the minimum viable product. The utilization of AM allows for a minimum viable product to be delivered quickly by physically realizing prioritized features and functions according to customer value early in the project [30]. demonstrate how the Quality Function Deployment (QFD) method can be employed within a Scrum framework to collaborate with customers in prioritizing features and adding them to the product backlog. According to this prioritization, the product backlog is transferred to sprint backlogs, forming the basis for the incremental expansion of the product’s functional scope [14, 33, 36]. employed feature prioritization in accordance with this principle to demonstrate how design features that do not contribute to customer value can be systematically excluded due to the flexibility of AM. The suggestion by [29] to first validate complexity-reduced features with the customer and then refine them also reflects the purpose of this principle.

Principle XII: regularly evaluate the effectiveness of the development process

The last principle of the Agile Manifesto is reflected in the analysed literature, particularly in the works of [10] and [30], which emphasize the importance of project and sprint retrospectives, respectively.

5.3 Synthesis: formulation of the agile principles for direct manufacturing

Based on the results of the above analysis, the agile principles of the original manifesto can be adapted specifically to the context of direct manufacturing. The analysis has revealed existing approaches that already thematically address or adhere to some of the original agile principles. A structured transfer and extension of all agile principles to the specific context of direct manufacturing will lay the basis for a comprehensive agile development methodology utilising AM. The following table summarises the twelve agile principles for direct manufacturing that have been derived. For each principle, examples of literature sources in which corresponding approaches or partial aspects are discussed are provided. However, as was evident from the presentation of the analysis results, not all principles are supported by corresponding evidence in the literature. In these cases, no references are listed. Nevertheless, these principles were formulated in line with the text template described in the methodology section, ensuring that the agile principles for direct manufacturing are consistently and comprehensively adapted (Table 3).

As described in Chap. 4, each APDM includes an action for which AM can act as an enabler. At this point, the term AM Enabler is defined more precisely. We propose distinguishing between two types of AM enablers for implementing APDM: Technological enablers describe synergies with agile product development that arise directly from technological characteristics (e.g. no need for specific tooling). Methodological enablers, on the other hand, require a context-specific adaptation of the DfAM approach to exploit additional synergies or prevent the loss of potential. The following table provides a concise overview of the adaptations made from the original manifesto principles to the APDM. The APDM are categorised according to the corresponding AM enablers. Principles that cannot be assigned to either type of enabler are considered non-specific to the use of AM, as they describe organisational measures that are essential to the agile approach but not distinctive in the context of manufacturing technologies.

6 Discussion

This section discusses key aspects regarding the relevance of the proposed agile principles for product development for direct manufacturing. References to Scrum elements, events, and artifacts are made frequently, as Scrum is the most widely used agile framework in hardware development [6] and thus provides a practical basis for discussion.

6.1 The role of agile principles for direct manufacturing in the context of agile development

By evaluating the results, it becomes apparent that the approaches described in the literature particularly emphasize the principles (I, II, III) that constitute an iterative and incremental development process. This appears to be the fundamental synergy between agile hardware development as a methodology and AM as a technology. The agile development methodology benefits from the flexibility of AM in providing physical increments in short iterations. The design of the additive final product benefits from the iterative utilisation of DfAM methods such as function integration and customisation for the purpose of providing increasing customer value. However, no implementation guidelines are provided. The original agile principle III specifies only what (‘working software’) and when (at intervals of a ‘couple of weeks’) it should be delivered [3]. Schmidt et al. found that the main challenge in the practical use of agile methods in the hardware industry is not the time-boxed iterative process itself, but rather the creation of presentable increments during each iteration [39]. For this reason, our adapted principle III also specifies how presentable increments can be created as the result of individual iterations. We propose viewing Design for AM as an incremental design-driven extension of the product. A variety of successful application examples resembling this approach has already been presented in the previous chapter.

To highlight the practical significance of this finding, we refer to the results of a 2023 study [8] in which users of agile hardware development were asked which Scrum framework elements (events, roles, and artifacts) caused them difficulties in practice. Since frameworks such as Scrum serve to make agile principles applicable in practice [40], tracing the degree of agreement on using the defined Scrum elements back to their underlying principles offers the following insights. Of the Scrum framework elements, only the ‘minimum viable product (MVP)’ (26%) and ‘increment’ (40%) received less than 50% approval for ‘always/often’ use in this study. These two elements are based on the principles that constitute an iterative and incremental development process (I, II and III), which is precisely where the fundamental synergy between AHD and direct manufacturing

lies. This further demonstrates that the problem identified by Schmidt et al. [39] remains a central issue in agile hardware development even four years later. It confirms the need for descriptive approaches to support the creation of presentable increments, as proposed here with the adapted agile principle III for direct manufacturing. However, it should be noted that not all literature references apply these principles of iteration discussed above in a manner consistent with this synergy [34]. For example, focus primarily on the early stages of development, when data and information are characterized by uncertainty and volatility. However, they fail to acknowledge that this circumstance is becoming the de facto standard in product development and may persist throughout the project. In this context, the flexibility of AM should be used to leverage volatility, aligning with agile principle II (changing requirements may present a chance to increase customer value). In the agile framework proposed by [10], the opportunities and limitations of AM are considered only at the start of development and not in subsequent iterations. This explicitly contradicts agile principle IX, which demands continuous consideration of technical capabilities throughout the project. Only [30] emphasise that the possibilities offered by DfAM and the responsiveness of the materialisation process should be viewed as an opportunity to enhance the product and increase customer value, even if this necessitates modifications in late project phases. Other approaches recognise this opportunity to a lesser extent, leading the authors to suspect that the significance of all opportunities based on this synergy is not yet firmly established in the literature.

In this context, it is also important to consider what constitutes an ‘increment’ in a direct manufacturing development project. According to the Scrum Guide, an increment must be usable and provides value for the customer [37]. In hardware development, increments are primarily used for demonstrating technical feasibility. A consistent shift towards generating customer value with each increment, as established in agile software development, has yet to be realised in hardware development practice [7, 8]. Direct manufacturing provides new ways to implement the agile principle of iterative value creation through increments more effectively within the realm of physical products. The seamless digital process chain closely links digital 3D models and their subsequent physical realisation. We therefore propose to treat the digital model as an increment of the product that can be reviewed by the customer and can be materialised into a physical increment at any time. By formulating product backlog items in such a way that their digital realisation fulfils a clear definition of done, digital artefacts such as 3D models can be systematically integrated as valuable and reviewable increments within agile frameworks for direct manufacturing. Given the ability to

use AM for the early realisation of physical increments, it is also important to address the process of DfAM in the early stages of development.

Although the early design phases are important for both additive and conventional manufacturing, as the definition of the concept significantly influences the final product [41], this is particularly crucial for DfAM. To take full advantage of the larger design space offered by DfAM, it is essential that this space is not irrevocably restricted at the outset of the design process. The industrialisation of AM exposed a lack of early-phase DfAM methods [42, 43], shifting research towards design-priming methods that aim to make DfAM expertise available in the early, geometrically indistinct development phases for supporting the generation of AM-compatible concepts [44]. We argue that the importance of the early development phases for DfAM increases further in an agile framework, for the following reasons: Unlike plan-driven development approaches, agile frameworks repeatedly iterate through the traditional phases of concept, design and detailing. This makes DfAM methods tailored specifically for the concept phase particularly important, as they must reliably support the generation and evolution of AM-compatible solutions throughout repeated development cycles. The initial iteration plays a particularly pivotal role in determining the trajectory of subsequent development. Decisions made during this iteration can significantly restrict or expand the design space for subsequent iterations, as the minimum viable product (MVP) establishes the product's fundamental architecture and functionality. If suboptimal decisions are made at this early stage and subsequently validated by the customer, the advantage of agile development in realising the full DfAM potential of the final product through iterations may be lost. Therefore, to fully harness the potential of AM within an agile development methodology, we propose to prioritize product features not only according to customer needs but to DfAM potentials, which is stated in the APDM X (prioritise component features based on their customer value as well as DfAM potential).

In Scrum, prioritization is used to move items from the product backlog to the sprint backlog. However, the case study by [30] shows that prioritising functions in the first sprint without considering their DfAM potential can predefine parts of the product design in a way that restricts the design scope in later iterations. In this case, the low prioritisation of the 'conduct mechanical loads' product backlog item resulted in an external component shell resembling the conventional product design after the first sprint, which was not reconsidered in subsequent iterations. Consequently, the remaining DfAM potential had to be realised within this predefined geometry.

At this point it should be emphasised that in contrast to the relatively infrequent use of the Scrum elements 'MVP' and 'increment', the elements 'product backlog' and 'sprint backlog' are employed much more regularly in practice, with 78% and 75% of respondents reporting 'always/often' use, respectively [8]. However, it is important to recognise that while these elements are routinely used, practitioners may not always be consciously aware of the underlying principle of prioritisation that informs their function, nor is the use of the backlog artifact itself what generates product value. By thematically adapting the agile principle towards the concrete prioritisation of backlog items based on their DfAM potential, we create an opportunity for practitioners to develop a deeper understanding of the underlying principle itself. In this context, it is not the mere existence or maintenance of the backlog that brings value, but rather the prioritisation of the contained requirements. Therefore, to fully leverage the benefits of DfAM, it is essential to adopt a prioritisation approach that systematically considers the DfAM potential of each backlog item. We propose retaining the familiar structure of product and sprint backlogs while updating the prioritisation logic to focus explicitly on DfAM potential. This adaptation constitutes a fundamental prerequisite for enabling an agile development framework to facilitate the realisation of the maximum DfAM potential in the final product through iterative and incremental development.

As a final observation before evaluating the APDM in the context of development frameworks we want to note that the proposed approaches to agile development with AM rarely address DfAM methods applied within these frameworks. Only [30] directly incorporate a DfAM method, the Design Pattern Matrix for AM, into their adapted Scrum framework. A variety of sources discuss the importance of DfAM methods for realizing the design potential offered by AM. The transition from rapid prototyping to direct manufacturing requires implementing development methodologies in which these methods can be applied. Currently, complete development frameworks that include methodology and methods exist only for plan-based approaches (e.g. [45]).

In summary, the literature combining AM and agility primarily focuses on technical and physical development aspects. At the strategic and organisational level, only a few approaches are discussed, such as project management methods [29] or adaptations of business models [13, 35]. However, proposals like an incremental hardware launch [35] using AM and agile development methods face major challenges, particularly concerning certification and customer acceptance. In the organisational implementation of agile practices within companies, several aspects remain unexplored in this literature body, including the potential

Table 4 Contextual adaptations of the original principles in the formulation of the APDM

	Description of the contextual adaption ('Manifesto' → APDM)	AM enablers
I	The content of the original principle is retained, but AM is explicitly identified as a means to achieve the intended benefit	Technological
II		
III	While the original principle specifies only <i>what</i> and <i>when</i> to deliver, the APDM provides a methodological concept for achieving the intended benefit. A DfAM approach that enables the incremental extension of a physical product forms the basis for applying this principle and is particularly advantageous for AM compared to conventional methods through the targeted exploitation of the extended design space	Methodological
IV	The principle has no direct technological implications but can be applied in the context of direct manufacturing to mitigate known challenges	None/generic
V		
VI		
VII	'Working software' is represented by the 'additively manufactured physical increment'	Technological
VIII	The principle is mainly organisational and is retained in its original sense	None/generic
IX	The principle has no direct technological implications but can be applied in the context of direct manufacturing to mitigate known challenges	Methodological
X	The original principle is adapted through the conceptual introduction of a prioritisation logic based on DfAM potential. Product features should be implemented in a way that the realisation of one feature does not restrict the design space available for subsequent features or characteristics	
XI	The principle has no direct technological implications but can be applied in the context of direct manufacturing to mitigate known challenges	None/generic
XII		

need for agile AM teams and the transition towards agile digital manufacturing ecosystems.

6.2 Evaluation of the agile principles for direct manufacturing in development frameworks for direct manufacturing

The APDM were derived based on the technological and methodological relationship between AM as a production technology and agile development as a methodological approach in product development. Chapter 5 introduced the concept of differentiating this relationship using so-called AM enablers (see Table 4). APDM I, II and VII, whose synergies between AM and agile development arise directly from technological characteristics, are distinguished from APDM III and X, where achieving a synergistic effect requires specific methodological adaptations within DfAM. The technological enablers, which arise for example from the lower tooling effort compared to conventional manufacturing processes, explain the use of AM for rapid prototyping in the context of agile hardware development, which was already understood and adopted in industry by 2020 [5]. For the remaining principles (IV–VI, XIII, IX, XI, XII), no manufacturing technology specific synergies exist. They have a generally applicable validity for agile development frameworks. Nevertheless, synergies can also be identified beyond specific technological contexts, as a well-known issue in product development with AM is that experts on DfAM are often involved too late and face non-AM-compliant concepts [38]. Principles such as frequent coordination between functional areas (APDM IV) and the emphasis on the value of communication (APDM VI) are expected to help mitigate this problem.

As discussed in Chap. 6.1, we recommend that future proposals for agile development frameworks for DM consider the implementation sequence of product features in a way that prevents early increments from irreversibly constraining the design space enabled by DfAM. This represents a necessary methodological adaptation in the context of DM, as expressed in APDM III and X. We propose applying DfAM as a design approach within agile development so that the product is conceived as incrementally extendable. In the practical implementation through work methods based on these principles, questions should be asked such as: How can premature solution fixation be prevented when early increments are delivered? How can prioritised features be implemented without excluding design options for further development? The works of [14, 29, 33, 36] provide starting points for answering these questions and for developing corresponding work methods.

This study highlights the methodological and technological synergies between agile development and AM. Technological AM enablers facilitate the use of flexibility advantages inherent to AM technologies within agile frameworks, enabling iterative and incremental development and the delivery of physical prototypes for feedback. Methodological AM enablers, in contrast, require adaptations of existing agile frameworks at the principal level to ensure that the full DfAM potential is transferred into the final product. When both synergy categories are considered, expected outcomes include a higher likelihood of successful product validation, increased customer satisfaction, earlier detection of manufacturing issues, greater development flexibility, enhanced responsiveness, and earlier identification of the added value provided by AM.

6.3 Limitations

A limitation of this study lies in the technological bias of the underlying literature, which results from the use of the key-word ‘additive manufacturing’ during the literature search. Literature on agile development regardless of specific manufacturing technologies provides more insight into non-technical aspects, such as employee motivation (Principle V) and team organization (Principle XI), but this literature was not included in the scope of this study. This explains why the data set contains few or no references to the agile principles whose relation to AM technologies is classified as ‘none/generic’ (see Table 4). It is also important to note that all results and insights proposed in this paper only cover cases where the final product, is developed for and produced entirely by AM. Technical products often comprise complex assemblies incorporating both additively and conventionally produced components. The immediate practical applicability of the agile principles for direct manufacturing proposed and discussed here may be limited, when assemblies involve non-AM components, especially so-called long lead items, as they require long up-front planning, which contradicts agile principles. However, this limitation is mitigated by the fact that this work’s primary contribution lies on the level of guiding principles. It is neither realistic nor the intention to propose a development framework that can be adopted without considering the specific corporate context. To avoid possible disillusionment, it must be explicitly stated that the agile principles for direct manufacturing, as well as the associated considerations presented here, should be understood as a methodological foundation. They only realise their full potential when they are actively interpreted and adapted to the practical implementation context. In this context, it must be considered that agile principles form the foundation of the agile elements applied in practice. This is particularly important for the implications of the results presented here, as the APDM are formulated closely in line with the original wording of the Manifesto [3]. Accordingly, for example, the term ‘daily’ was adopted in APDM IV (see Table 3). As shown in the findings of [32], the agile element of a ‘daily’ (cf [37]), which is based on this principle, can only be meaningfully implemented literally if the organizational context requires and allows it, and may need to be adapted if this is not the case.

7 Conclusion and future directions

The main contribution of this paper is the formulation of twelve new agile principles (APDM) that are specifically adopted from the Agile Manifesto [3] and tailored for direct manufacturing. Based on a comprehensive analysis and

synthesis of the literature, we discuss the implications of these principles for agile development frameworks in the context of direct manufacturing. Our findings highlight that the central principles to be considered in such frameworks are, firstly, an iterative and incremental approach that is aligned with the technological characteristics of AM. This synergy enables the flexibility of AM to be exploited for producing physical artefacts without tooling, to realise frequent, value-adding increments throughout the development process. Secondly, we identify the systematic prioritisation of backlog items according to their DfAM potential as a requirement that is fundamental to prevent the inherent design space of AM from not being restricted prematurely during the early stages of development. In this context, the role of the increment artefact in agile hardware development for direct manufacturing also needs to be re-evaluated. We argue that a shift is necessary, from focusing on technical feasibility in the late stages of the project to generating customer value early by incorporating rapid feedback cycles and the continuous adaptation of products through DfAM to evolving requirements. This contribution establishes a theoretical foundation, illustrated by a schematic comparison of DfAM potential trends in agile versus plan-driven development processes. This comparison shows that, when combined with the flexibility of AM, the principle of iteration makes a larger proportion of the total DfAM potential of the final product available in each iteration. In contrast, plan-driven approaches conflict with the characteristics of AM because they require most design decisions to be made early in the design process. This restricts the available DfAM potential, as well as the ability to react adequately to changes that could benefit the customer in later phases. Accordingly, realising the benefits of combining agile development methodologies and AM technologies is made possible through the repeated traversing of design phases and usage of DfAM methods. Early iterations play a particularly decisive role in this process, as they establish the boundary conditions that determine the extent to which DfAM potential can be realised in subsequent development cycles. It is only by actively shaping these initial cycles with a focus on DfAM criteria that the agile approach can sustainably exploit the unique advantages of AM throughout the entire product development process. Future research will focus on establishing holistic, agile development frameworks for direct manufacturing that incorporate the proposed APDM as guiding principles. A key step towards practical validation will be to examine the acceptance of these principles in industrial practice. An international study with this objective is currently in the data collection phase. The principal level established by the APDM, provides a theoretical basis for evaluating existing AM-specific development frameworks regarding how they primarily link DfAM potential to the

final product. This will gain practical relevance, as DfAM research has so far focused mainly on method development, thereby tying much of the DfAM potential to individual practitioners who are only gradually entering industry as engineers and designers. To accelerate the industrial adoption of AM technologies, it is therefore beneficial to also integrate DfAM potential directly into the methodological framework of product development wherever possible. This represents the overarching long-term goal of the agile development frameworks based on the APDM.

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Declarations

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References

- Anantatmula V (2021) Be agile do agile. New York: Business Expert Press, [Online]. Available: <https://asmedigitalcollection.asme.org/bep-ebooks/book/352/Be-Agile-Do-Agile>
- Atzberger A (2021) Agility in Mechatronics unveiled: a value model for describing the interdependencies of agile development in mechatronics, Dissertation, Institut für Technische Produktentwicklung, Universität der Bundeswehr München, München
- Beck K, Beedle M, van Bennekum A, Cockburn A, Cunningham W, Fowler M, Martin RC, Mellor S, Thomas D, Grenning J et al (2001) Manifesto for Agile Software Development. Available online: <https://agilemanifesto.org/> (accessed on 15 March 2026)
- Schmidt T, Paetzold K (2016) Agilität als Alternative zu traditionellen standards in der entwicklung physischer produkte: chancen und herausforderungen
- Atzberger A, Nicklas SJ, Schrof J, Weiss S, Paetzold K (2020) Agile entwicklung physischer Produkte 2020. https://doi.org/10.18726/2020_5
- Michalides M, Nicklas SJ, Weiss S, Paetzold-Byhain K (2022) Agile Entwicklung physischer produkte 2022. https://doi.org/10.18726/2022_3
- Nicklas SJ, Michalides M, Atzberger A, Weiss S, Paetzold-Byhain K (2021) Agile entwicklung physischer produkte 2021. https://doi.org/10.18726/2021_3
- Weiss S, Paetzold-Byhain K, Michalides M, Pendzik M, Scharold F, Stoiber L (2023) Agile entwicklung physischer produkte 2023. <https://doi.org/10.25368/2023.213>
- von Petersdorff-Campen K et al (2018) 3D printing of functional assemblies with integrated polymer-bonded magnets demonstrated with a prototype of a rotary blood pump. Appl Sci. 8(8):1275. <https://doi.org/10.3390/app8081275>
- de Almeida JF, Amaral DC, Coelho RT (2021) Innovative framework to manage new product development (NPD) integrating additive manufacturing (AM) and agile management. Procedia CIRP 103:128–133. <https://doi.org/10.1016/j.procir.2021.10.020>
- Lackmayer R, Ehlers T, Lippert RB (2022) Bauteil Auswahl. In: Lackmayer R, Ehlers T, Lippert RB (eds) Entwicklungsmethodik für die Additive Fertigung. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 21–36
- Gebhardt A, Kessler J, Schwarz A (2019) Produktgestaltung für die additive Fertigung (Hanser eLibrary). Hanser, München
- Omidvarkarjan D (2024) Enhancing the adoption of additive manufacturing in industry using principles of agile hardware development, Dissertation, ETH Zurich, Zurich
- Montero J, Weber S, Bleckmann M, Paetzold K (2020) A methodology for the decentralised design and production of additive manufactured spare parts. Prod Manuf Res 8(1):313–334. <https://doi.org/10.1080/21693277.2020.1790437>
- Verein Deutscher Ingenieure e.V (2014) VDI 3405 - Additive fertigungsverfahren Grundlagen, Begriffe, Verfahrensbeschreibungen
- Jiang R, Kleer R, Piller F. T. (2017) Predicting the future of additive manufacturing: a delphi study on economic and societal implications of 3D printing for 2030. Technol Forecast Soc Chang 117:84–97. <https://doi.org/10.1016/j.techfore.2017.01.006>
- Gibson I, Rosen D, Stucker B, Khorasani M (2021) Introduction and basic principles. In: Gibson I, Rosen D, Stucker B, Khorasani M (eds) Additive manufacturing technologies. Springer International Publishing, Cham, pp 1–21
- Gibson I, Rosen D, Stucker B, Khorasani M (2021) Design for additive manufacturing. In: Gibson I, Rosen D, Stucker B, Khorasani M (eds) Additive manufacturing technologies. Springer International Publishing, Cham, pp 555–607
- Ehlers T, Lackmayer R (2021) In: Konstruktionslehre PB, Bender B, Gericke K (eds) Gestaltung für additive fertigung. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 755–828
- Thompson MK et al (2016) Design for additive manufacturing: trends, opportunities, considerations, and constraints, CIRP Annals, 65(2):737–760. <https://doi.org/10.1016/j.cirp.2016.05.004>
- Laverne F, Segonds F, Anwer N, Coq ML (2015) Assembly based methods to support product innovation in design for additive manufacturing: an exploratory case study, J Mech Design, 137(12):121701. <https://doi.org/10.1115/1.4031589>
- Günther F, Koch A (2024) Design for additive manufacturing – application system based on design methodology in industrial Standards, in Entwerfen Entwickeln Erleben 2024: menschen,

- technik und methoden in produktentwicklung und design, pp. 134–146. <https://doi.org/10.25368/2024.EEE.012>
23. Sridhar Nerur RK, Mahapatra, Mangalaraj G (2005) Challenges of migrating to agile methodologies. *Commun ACM*, 48, 5
 24. Highsmith J (2009) *Agile project management*, 2nd edn. Pearson Education, Inc, Boston, MA
 25. Kluckhohn C (1951) Values and value-orientations in the theory of action: an exploration in definition and classification. In: Parsons T, Shils E (eds) *Toward a General Theory of Action*. Harvard University Press, Cambridge, pp 388–433. doi: <https://doi.org/10.4159/harvard.9780674863507.c8>.
 26. Verein Deutscher Ingenieure e.V (2025) *Agiles Manifest für mechatronische Produkte*. https://www.vdi.de/fileadmin/pages/vdi_de/redakteure/ueber_uns/fachgesellschaften/GPP/dateien/Agiles-Manifest-fuer-die-Entwicklung-mechatronischer-Produkte.pdf Accessed: Jul. 24
 27. Ovesen N (2012) *The challenges of becoming agile*, Dissertation, Aalborg University, Aalborg
 28. Ullman DG (2019) *Scrum for hardware design*
 29. Omidvarkarjan D et al (2020) Prototyping Strategies for the agile development of additive manufactured products: a case study from the COVID-19 Pandemic, in *Proceedings of the 31st symposium design for X (DFX2020)*, Dec. pp. 161–168. <https://doi.org/10.35199/dfx2020.17>
 30. Reichwein J, Vogel S, Schork S, Kirchner E (2020) On the applicability of agile development methods to design for additive manufacturing. *Procedia CIRP* 91:653–658. <https://doi.org/10.1016/j.procir.2020.03.112>
 31. Schmitt P, Siewert L, Gericke K (2024) A proposal for guiding the selection of suitable DfAM support based on experiential knowledge, *Proc Des Soc*. 4:1829–1838. <https://doi.org/10.1017/pds.2024.185>
 32. Michalides M, Weiss S, Gadzo E, Paetzold-Byhain K, Koch A (2024) Relation between purpose of individual agile elements and the need for their adaptation in product design & development. *Proc Des Soc* 4:305–314. <https://doi.org/10.1017/pds.2024.33>
 33. Montero J, Weber S, Bleckmann M, Atzberger A, Wirths L, Paetzold K (2019) Spare part production in remote locations through additive manufacturing enhanced by agile development principles, in *2019 IEEE international conference on engineering, technology and innovation (ICE/ITMC)*, Valbonne Sophia-Antipolis, France, pp. 1–8. <https://doi.org/10.1109/ICE.2019.8792631>
 34. Enkler H-G, Sporleder L (2019) *Agile product development—coupling explorative and established CAX methods in early stages of virtual product development*, *Procedia CIRP*. 84:848–853. <https://doi.org/10.1016/j.procir.2019.04.221>
 35. Fontana F, Klahn C, Meboldt M (2019) Value-driven clustering of industrial additive manufacturing applications, *JMTM*, 30(2):366–390. <https://doi.org/10.1108/JMTM-06-2018-0167>
 36. Montero J, Atzberger A, Bleckmann M, Holtmannspotter J, Paetzold K (2019) Enhancing the additive manufacturing process for spare parts by applying agile hardware development principles, in *2019 IEEE 10th international conference on mechanical and intelligent manufacturing technologies (ICMIMT)*, Cape Town, South Africa, pp. 109–116. <https://doi.org/10.1109/ICMIMT.2019.8712045>
 37. Schwaber K, Sutherland J (2020) *The Scrum Guide*,
 38. Günther FJ, Tüzün G-J, Kreimeyer M, Koch A (2025) Current challenges in the development of products for additive manufacturing - an interview study, *Proc Des Soc*. 5:1061–1070. <https://doi.org/10.1017/pds.2025.10120>
 39. Schmidt T, Atzberger A, Gerling C, Schrof J, Weiss S, Paetzold K (2019) *Agile entwicklung physischer produkte 2019*
 40. Dingsøyr T, Nerur S, Balijepally V, Moe NB (2012) A decade of agile methodologies: towards explaining agile software development. *J Syst Softw* 85(6):1213–1221. <https://doi.org/10.1016/j.js.s.2012.02.033>
 41. Matthiesen S (2021) In: *Konstruktionslehre* PB, Bender B, Gericke K (eds) *Gestaltung – Prozess und Methoden*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 397–465
 42. Laverne F, Segonds F, Anwer N, Le Coq M, DFAM in the design process (2014) : A proposal of classification to foster early design stages
 43. Pradel P, Zhu Z, Bibb R, Moultrie J (2018) Investigation of design for additive manufacturing in professional design practice. *J Eng Des* 29:4–5. <https://doi.org/10.1080/09544828.2018.1454589>
 44. Pearl S, Meisel NA (2024) Assessing the manufacturability of students' early-stage designs based on previous experience with traditional manufacturing and additive manufacturing, *J Mech Des*. 146(1):012301. <https://doi.org/10.1115/1.4063564>
 45. Kumke M (2018) *Methodisches Konstruieren von additiv gefertigten Bauteilen*, Dissertation, Technische Universität Braunschweig, Wiesbaden

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