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Applicability of Advanced Manufacturing Technologies for Agile Product Development in the Internet of Production: A Strategic Framework

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Abstract

Evolving product complexities and customer demands in an increasingly unstable environment are challenging companies worldwide. Agile product development can help to overcome these challenges but originates in software development. It is argued whether it is completely transferable towards the build-up of physical products. This paper aims to support agile product development for physical products by classifying appropriate advanced manufacturing technologies (AMTs) and identifying their demand for further research and development. A framework - the agile readiness level (ARL) for AMTs - is derived. It is consisting of five main factors of agile product development: testing & self-improvement, distribution & availability, accessibility for non-experts, time from idea to product, and overall flexibility. The ARL is evaluated for eight AMTs which are developed within the research cluster "Internet of Production" (IoP) at RWTH Aachen University. It is found that the ARL helps to identify similarities of diverse AMTs as well as research directions that need to be taken. It therefore contributes to the transfer of agile development methodologies from software to hardware products with the use of AMTs. Differences in technological feasibility for agile prototyping arise due to safety and complexity, targeted user group, and varying demands for support by artificial intelligence (AI) solutions.

Keywords

Advanced manufacturing technology; product development; agile prototyping; Internet of Production; technology assessment

1. Introduction

Frameworks and methodologies to foster agility have been around for more than 20 years. Commonality of different approaches like e.g., SCRUM is the recommendation of customer-centric, iterative development. This shared value was extracted by Beck et al. and condensed within the so-called Agile Manifesto in 2001. Beck et al. intended to reform software development and defined a mindset for creating digital products ever since. [1] Because of current trends like Industry 4.0 and Internet of Things (IoT), the distinction between development of physical and digital products faints. Hybrid methods of agile and stage-gate processes gain popularity. Agile development for physical products is especially considered appropriate for uncertain and ever-changing environments without a clearly defined project goal. [2,3] However, applicability of agile development methods can be limited when it comes to physical prototyping. A timely build-up of prototypes can be hindered by a lack of suitable production processes as well as required physical components like new tools or materials. Agile product development for hardware components therefore needs manufacturing technologies which can overcome these limitations. A class of manufacturing technologies which are most

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likely to be suitable for this purpose are referred to as Advanced Manufacturing Technologies (AMTs). AMTs cover diverse technologies which emphasise informational aspects: They rely on data for process setup and processing. Furthermore, data is obtained within the manufacturing process and available for analysis. Due to this characteristic, they inhere the feasibility to rapidly react to upcoming change requests during short product development cycles. While concentrating on solving the dilemma between scale and scope in manufacturing, there has been little research on integrating AMTs into agile product development processes. This paper aims to derive a method capable of presenting, interconnecting, and comparing newly developed or improved AMTs regarding their suitability of prototyping in agile development for physical products. This feasibility is measured as the technological ability to rapidly react to the scenario of engineering change requests. Such requests occur suddenly and due to data-based feedback from both users and production cycles. An example of this comes from the automotive sector: If the class of a vehicle is altered and key requirements such as safety appearance are not met, changes have to be implemented immediately. In future, decision makers will be enabled to decide based on agility factors like the ARL whether and which AMTs are suitable for the rapid implementation of an engineering change request.

2. State of the Art

2.1 Concepts and Principles of Agility

Central principles of agility are cross-domain collaboration and openness to change. Agile projects benefit from reduced development time, improved handling of changing requirements and priorities, and increased productivity [4,5]. The widely adopted approach SCRUM recommends roles and events for successful implementation of agile principles within an organization and defines iterative cycles, called sprints. Each sprint is meant to create a testable, functional product increment. [6] Recently, the principles of agility were transferred to the context of hardware development [7]. Smith considers the requirements of manufacturing companies for implementing agile processes [8]. Klein provides promising concepts towards agile engineering [9]. Cooper as well as Ahmed-Kristensen & Daalhuizen present an integrated approach of the conventional stage-gate process and agile methods [2,10]. Conforto and Amaral defined an iterative development approach integrated into a stage-gate process [11]. The term agile manufacturing is used to describe manufacturing systems that are built on decision-making at functional knowledge levels, stable unit costs, flexible manufacturing, easy access to integrated data, and modular production facilities [12]. Finally, the rapid and repeated implementation of physical prototypes is a major hurdle. Long waiting times due to dependency on internal or external suppliers, for example in tool procurement, can make sprints obsolete and thus short-cycle innovation impossible [7,13]. A sensitisation for agility through rapid prototyping technology is key to implement it in a manufacturing environment [14].

2.2 Definition of AMTs

Regarding manufacturing technologies which are efficiently transferring digital design data into physical products, AMTs are growing fields of international research [15,16]. They are expected to contribute to a company's competitive advantage by improving the performance of its manufacturing system with regards to productivity, profitability, and reliability [17]. They allow for resource efficient and precise production processes using automation, robotics and measuring systems [18]. According to the European Task Force for Advanced Manufacturing by the European Commission, AMTs foster the creation of entirely new products, processes, and business models, and allow for increased sustainability in manufacturing systems. Certainly, accompanied by non-negligible investment efforts, AMTs cover stand-alone technologies as well as integrated systems. [19] There is an ongoing and profound interest in AMTs and their integration into existing production systems and concepts like the "Internet of Production" (IoP). [20] In the context of this research, AMTs are defined as manufacturing technologies that transfer digital design into physical products as fast as possible, allow for rapid prototyping processes due to a high degree of flexibility in the manufacturing process, and are digitally interconnected with the production environment. Since additive manufacturing (AM) is considered an AMT as well as the central technology for rapid prototyping, the general suitability of AMTs as enablers for agile product development is likely. [21]

2.3 Technology Assessment Frameworks

The need for early and continuous identification, analysis, and evaluation of new technologies as a key driver for innovation is apparent and the potential of their influence on cost, quality, and performance of the product or production process is high [22]. An established assessment method is the Technology Readiness Level (TRL) defining the degree of readiness of a technology in relation to a certain goal [24,25]. Further technology related readiness levels are the Industry 4.0 Readiness Level [26], the Manufacturing Readiness Level [27], or the Supply Chain Readiness [28,29,30,31]. Readiness levels in the context of agility are defined with regards to organizations and systems. Sidky et al. apply five parameters to evaluate the agile readiness of an organization: embrace change to deliver customer value, plan and deliver software frequently, human-centricity, technical excellence, and customer collaboration [32]. Gren et al. discuss these parameters and pretest the framework as a measure for the current agility of an organization [33]. Gunasekaran et al. define five enablers for agile manufacturing companies: transparent customization, agile supply chains, intelligent automation, total employee empowerment, and technology integration. They point towards the potential of big data and the internet of things to shape the future of agile manufacturing. [23] To the best of the authors' knowledge, it is not yet known which criteria have to be met by a technology to be considered suitable for agile product development of hardware components. No method could be found which allows to compare AMTs regarding their integration in a manufacturing environment such as the IoP.

3. Methodology

Literature research is performed to identify frameworks to classify technologies with regards to their applicability for agile product development. Since no specialised method is found, the agile readiness assessment for organizations by Sidky et al. is adapted [32] with consideration of the principles for agile manufacturing companies by Gunasekaran et al. [22]. The factors are transferred to the AMT context and the logic of levels from the TRL is used to classify AMTs [34]. This results in the proposed method: the Agile Readiness Level (ARL). To test the ARL, eight AMTs are chosen and assessed within the framework. The assessed AMTs originate from the research group CRD-C.II of the Cluster of Excellence "Internet of Production" at RWTH Aachen University and represent a range of technologies for different applications and materials. A peer-reviewed expert assessment of each researcher for their technologies is conducted to classify the different AMTs in the ARL framework [35]. To be able to provide a comparable presentation which is addressing the needs within the IoP and ensures a common understanding of each technology, a profile is developed which is based on the platform architectures by Palmieri et al. (Figure 1) [36]. The relevant components are illustrated as boxes; relevant interfaces are indicated by arrows. Components are split into four essential units: user, hardware, software, and IoP. Characteristics of the components such as type, content, and size are depending on each AMT, interfaces shall be considered generally valid. Combining the technology profiles and the ARL, the classifying process is conducted in five steps:

- Presentation and explanation of the ARL to the members of the research group;
- Self-guided classification of the technology within the technology profile and the ARL with regards to both distinct level and individual reasoning for the current status and the development goal;
- Review of classification and request for additional information if needed;
- Analysis of the ARL with regards to both distinct level and individual reasoning;
- Presentation and discussion of the results with the research group.

The intended development goal is based on the current development strategy. It is not related to a certain time frame to avoid discrepancies between the technologies which are on different development stages.

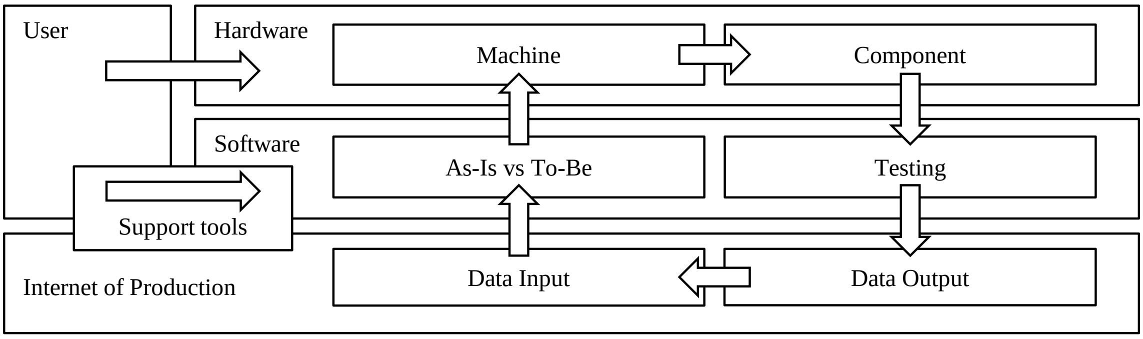

Figure 1: Suggested profile for AMT description in accordance to Palmieri et al. (2012)

4. Agile Readiness Level

The agile manifesto defines twelve principles to organise and maintain development practices in an agile way [1]. Sidky et al. condensed these twelve principles into five essential ones [32]. For the ARL they are translated towards human-centered manufacturing technologies for physical products (Table 1).

Table 1: Principles by Sidky et al. and their corresponding dimension in the ARL

Principles by Sidky et al.	Adapted principles for ARL
Embrace change to deliver customer value	Overall flexibility
Plan and deliver software frequently	Time from initial idea to a deliverable prototype
Human-centricity	Accessibility for non-experts
Technical excellence	Ability for testing & self-improvement
Customer collaboration	Distribution & availability

The matrix of the ARL with its dimensions and the corresponding levels is visualised in Table 2. In accordance with the TRL, each dimension is separated into a maximum of nine levels. For dimensions in which nine levels exceed practicability, the number of levels is reduced. The range is determined by the worst and ideal condition. The levels in between are spread on this scale and the composition is balanced with the other dimensions. A minimum of four levels has been defined for the dimension of time from initial idea to a deliverable prototype. This allows for the separation between the units of weeks, days, and hours. Level nine must not be seen as the goal to be achieved. It rather represents the overall potential in the context of agility. In contrast to the TRL, the ARL does not result in one cumulative number by the combination of all five levels or the lowest level. The five dimensions are described in the following.

Agility can be enhanced by continuous attention to technical excellence and good design. With regards to the development of AMTs, the technical excellence is refined by advancing data measurements which can be employed to improve the process and by increasing process predictability and reliability. [1] Transferred to AMTs and the context of the IoP, the ability of the process for self-improvement through data processing is essential. Data exchange and ongoing feedback loops require the existence of corresponding interfaces, simulation methods, and product testing methods. The dimension of testing & self-improvement is separated into seven levels. Until level 5, any higher level can be reached with an increase in predictability of the process. From thereon, the way of how data is employed for automatic self-improvement takes over as main characteristic for level evaluation.

Table 2: Agile Readiness Level

ARL	Testing & self-improvement	Distribution & availability	Accessibility for non-experts	Time from idea to product	Overall flexibility
1	Process is trial and error	Only some research institutes or departments	Process can only be used by developers	> 1 week	No flexibility
2	-	Some universities and a specialised company	Process can only be employed by experienced technicians	-	One parameter/one material can be changed
3	Products are analysed and basic parameters can be measured	Every university/only by few universities	Process can be employed by trained technicians	-	-
4	-	-	Process can be employed by trained non-expert	-	Flexibility is only possible with some parameters
5	Process is predictable	Technology is well established	-	> 1 day	-
6	Digital design and physical product are tied together	-	Process can be employed with the help of a manual	-	Structured preparation and utilization of flexibility
7	Data-driven testing	Machine is placed in every FabLab	-	< some hours	-
8	Data stored and processed to learn from product to process	-	No specific knowledge needed	-	All relevant parameters can be changed
9	Connected process improves itself (AI)	Machine is available for every designer	Functions are intuitive	< 1 hour	End-to-end flexibility (including environmental influences)

A closed learning loop from the customer through testing and feedback can only be created by delivery of the product to the customer [1]. Transferred to AMTs this dimension requires the availability of functions of the technology via the internet or in a physical manner and therefore distributed around the globe. These aspects enable close collaboration with customers or users in e.g., pilot projects. As a result, this category can be evaluated from availability at one certain location (level 1) to availability for everyone who desires it (level 9).

Human-centricity builds around the idea of building products that address human needs. Herein, simplicity is a core principle for efficiency. [1] The diversity of team members in agile and physical product development and the decentralization of development processes increases the interest of prototyping tools that can be used by non-experts. The accessibility for non-experts depends on the complexity of the system and the standard knowledge of the user. In conclusion, this dimension can be summarised as the simplicity of using any AMT with the help of manuals and supporting tools. The range of users spans from experts (level 9) and trained technicians (level 3) to non-experts (level 1).

In accordance with the principle of planning and delivering software frequently, the goal is to minimise the time from initial idea to a deliverable prototype [1]. The time it takes to build physical prototypes is referred to as lead time and covers the time span starting from the original idea or customer request and ending with the successfully delivered product. It therefore includes preparations and pre-processing time to set up the manufacturing process, processing times, and post-processing times. The dimension is defined on four levels which are ranging from weeks (level 1) to less than one hour (level 9).

Engineering change requests, especially if they occur late in a development cycle of a waterfall or stage-gate process, create costs and pressure. To overcome this, agile development is designed to embrace change to deliver customer value at any point in time. [1] Utilizing this principle results in small iterations and flexible processes that are built to react to engineering change requests. Flexibility herein can be embraced within different dimensions: the ability to handle varying input parameters or to achieve different product functionalities regarding geometry, durability, stiffness, and many more within one process. Within the ARL, flexibility ranges between an inflexible process which is built to manufacture a specific component in a specific manner (level 1) and a truly flexible process which is adjustable to environmental influences during processing (level 9). Changes in such a process can be realised even after initial process setup.

5. Considered Technologies and their ARL Assessment

In the following, the eight technologies from the CRD-C.II research group are described according to their ARL assessment. A general description of the technology according to the technology profile can be found in the appendix. The Optical Lens System Tracy, which is developed by the Chair of Technology of Optical Systems (TOS), supports users to create an optical system for given requirements by using stock lenses and a graphical user interface (GUI). Tracy's goal regarding self-improvement is to integrate continuous learning from previous data and therefore evaluate more effective lens designs. As of today, Tracy is available as a successfully tested prototyping software (level 6). In terms of flexibility, researchers are aiming for the implementation of different modes to correlate the variety of adjustable parameters with the degree of complexity that is required by the user. Currently, flexibility is given within a GUI and set parameters (level 6). Tracy can be used by trained non-experts (level 4). The challenge for a user employing Tracy remains in the definition of relevant requirements which shall be sufficiently guided in the future. There are no intentions to reduce manufacturing time since the main drivers are external delivery times of stock lenses. As of today, Tracy is a unique AMT which is solely used at the TOS (level 1). Being a highly specialised technology, Tracy is meant to only be applied within other research institutes focusing on optical systems.

The Laser Powder Bed Fusion (LPBF) is an established AM process that is continuously investigated by the Chair of Digital Additive Production (DAP) in cooperation with the IEHK Steel Institute [37]. Currently, the LPBF process is tested and improved by analysing printed components (level 3). The process is intended to enable parameter monitoring and learn to identify defects like pores (level 9). To increase flexibility in the future, the number of adjustable process parameters shall be increased. Owning a high degree of geometrical flexibility and some adjustable process parameters already, LPBF's flexibility is assessed on a level of 7. Product realisation time is dependent on the size of the object and as short as some hours (level 8). The current level is not intended to be improved. The goal for LPBF is to be well established in the manner of entering serial production (level 5). However, due to complexity in handling of powder and resulting security hazards, access will remain restricted. Nowadays, the technology is commercially available and employed by specialised companies and research institutes (level 3). The technology requires training (level 4).

The scale-independent tools for material and process simulation (SI MPS) for LPBF are built at the IEHK Steel Institute and aim to enable agile alloy development. Data- driven methods will be used to enable efficient and self-improving alloy development (level 7). Currently, the toolbox is able to predict properties and performance of a final part for a given metal (level 6). The SI MPS is under development and only available at the IEHK (level 1). The GUI shall be made available for a target group of alloying specialists on a digital platform (level 3). To this date, SI MPS requires deep knowledge and is barely usable by non-experts (level 1). The user-friendly interface is meant to allow access to the industry and trained non-experts (level 4). Simulation cycles to predict properties are reported in terms of months (level 1). The use of SI MPS is intended to shorten the process to a couple days (level 5).

The Algorithms for Production of Lattice Structures of the Chair of Digital Additive Production (DAP) aim to generate, simulate, and optimise CAD-data for production of lattice structures of the LPBF process. Flexibility shall be reached by having all parameters of the lattice structure chosen by the user through a GUI and adjusting them by the results of the simulation. Currently, the user can decide upon a couple of parameters like lattice type and size (level 4). The goal is to reach readiness for production within an hour for most components. The generation of lattice structures with described algorithms is already applicable for decorative purposes and polymer-based processes and can be used by non-experts with short instructions (level 4). Advanced modes are available to experienced technicians as plugin. Accessibility for non-experts shall be improved towards real world applications though a manual (level 6). Lattice structures are mainly used in industry and academia (level 2). The technology shall be made available in FabLabs (level 7). Testing & self-improvement is still trial and error (level 1). Current lattice generators are unreliable and do not include constraints such as the threshold for the overhang angle. The goal is to predict the behaviour of lattice structures by being able to generate fine and coarse lattice structures with fast simulations and reliable transition zones which are producible in LPBF (level 5).

At the IBF Institute, a combination of the technologies stretch forming (SF) and incremental sheet forming (IFS) is investigated [38]. SF+IFS is reported to own a high flexibility wherein all relevant parameters can be adjusted (level 8). Flexibility could only be extended by increased knowledge about process correlations. An application shall support the intuitive use of the production technology by non-experts by only requiring the geometry with little information about the part's properties (level 9). Currently, some experience is needed to use the technology (level 2). The technology shall be established with the support of a digitalised process chain and an improvement of optimisation strategies (level 5). Currently, the technology is used by very few universities and companies (level 2). Some phenomena that occur during forming are not explainable and therefore not predictable (level 5). Process planning is to be fully automated to optimise the process automatically only based on CAD data (level 6). Manual design of dies and the iterative planning of the process which is supported by simulations and experiments often takes more than a week (level 1). Researchers want to reduce this period to only a few days by optimisations described above (level 5).

At the Chair of Laser Technology (LLT) at RWTH Aachen University, a robot-based Laser Material Process (Robot-based LMP) is developed which enables a robot handling system to conduct laser processes like laser cutting, laser scanning, and sur- face structuring. By using AI-trained simulation and control, a system shall be built which is able to react during the process to e.g., distortions of the component (level 9). The process does not meet the requirements regarding sensibility yet (level 1). A novel sensor technology shall increase the flexibility of the process by matching robot movement and laser power. Few factors can be adjusted like velocity or laser power. The time it takes to realise an idea is higher than a week (level 1). The process is intended to realise ideas within a couple hours by employing a continuous flow of information from the

CAD-system to the production system and a reduction of the setup time due to integrated path planning and process simulation. The current technology is controlled by manual programming and is only used by experts (level 1). Due to the safety hazard by the laser, tests or production will always have to be carried out by trained specialists (level 3). The technology shall be established but limited to professionals due to the safety hazards (level 5). The current technology is only used at the ILT (level 1).

With 3D printing on pre-stressed textiles (4D Textiles) three-dimensional textiles with shape-changing properties are built at the ITA Textile Institute [39]. The technology is used by some universities and specialised companies (level 2). The integration of pre-stressed textiles is neither industrialised nor standardised yet. The goal is to be able to provide an add-on to any traditional FFF machines (level 9). Only some variables have been identified and can be measured yet (level 3). Data shall be stored and processed to learn from product to process if the dichotomy between form, function, and process can be overcome with a learning system (level 8). The process can be learned with support of books or videos (level 6). The goal is to provide an input guided production process which can support decisions from the user by offering a variety of build-on basis structures (level 9). Realization time is two to three days due to an iterative manner of testing the functionality of produced prototypes (level 5). With the support of an online-simulation tool and a modular pre-stressing tool, time shall be reduced to less than some hours (level 8). Flexibility is high due to the AM process but cannot yet be fully embraced (level 4). The environment shall be employed to broaden the flexibility long-term (level 5). This plays a major role in shape-changing components and offers an example for end-to-end flexibility where the environmental influences are included.

Thermoplastic multi-material additive manufacturing (MMAM) offers the potential to vary material properties along a component's dimensions in a single step process. Realization time shall be in the duration of an hour by employing high-throughput AM machines (level 9). It is currently between a day and a week since effects like lag extrusion during material change must be optimized iteratively (level 3). Use is restricted due to the not yet standardised process and requires training (level 3). The technology shall be made accessible to anybody who is using extrusion-based AM processes for prototyping or production (level 9). The processing parameters and their influence on the properties of the built part are currently investigated and basic parameters can already be adjusted and measured (level 3). The process shall be monitored continuously, controlled automatically, and learn from previous building processes (level 9). A prototype exists at the investigating lab, but similar approaches are tested within other labs (level 2). The technology shall be made available as a modular hardware add-on for any desktop machine while high-throughput machines may have a smaller target group (level 5). So far, only one material combination is used (level 2). In the future, material mixing for location-dependent material properties shall enable a structured utilization of flexibility (level 7).

6. The Agile Readiness within the Technologies of the IoP

Within the following subchapters, ARL results of the IoP are separately compared for each dimension. This allows for an evaluation of both determined dimensions as well as chosen scales. It is further used to detect trends in the current research environment of the CRD-C.II research group. The results are visualised in set of spider diagrams in Figure 2.

6.1 Overall Flexibility

The flexibility of the considered technologies as specific variants of the original technologies ranges between level 1 to level 8 and averages at a level of 4. Participated researchers describe the flexibility of their technologies between being lacking, utilised within certain areas and being systematically flexible. The latter is embraced by the implementation of GUIs which allow the user to adjust a defined set of parameters for simulation or processing. Flexibility in certain areas focuses on the opportunity to employ different materials.

According to the survey, these material choices can be differentiated in being restricted to few materials, being open to a couple of materials without standardised corresponding parameter sets or being able to process multiple materials without exactly understanding cause-and-effect relationships between occurring phenomenon. The aimed ARL for the dimension of flexibility lies between level 4 and level 9. On average, technologies shall reach a level of 8 according to the interrogated researchers. The desired flexibility not only addresses a widened range of adjustable processing parameters, but also intends to enable the process to automatically adjust to unforeseen events during processing. The technology of 4D Textiles goes one step further and is planned on flexible behaviour of the manufactured components even after manufacturing: components shall be able to react to environmental changes. Most processes however focus on an intentionally provided amount of flexibility to the user to enable the production of component for various applications. The simulation strategy shall even be refined to offer different levels of flexibility to correspond to the complexity of the considered problem.

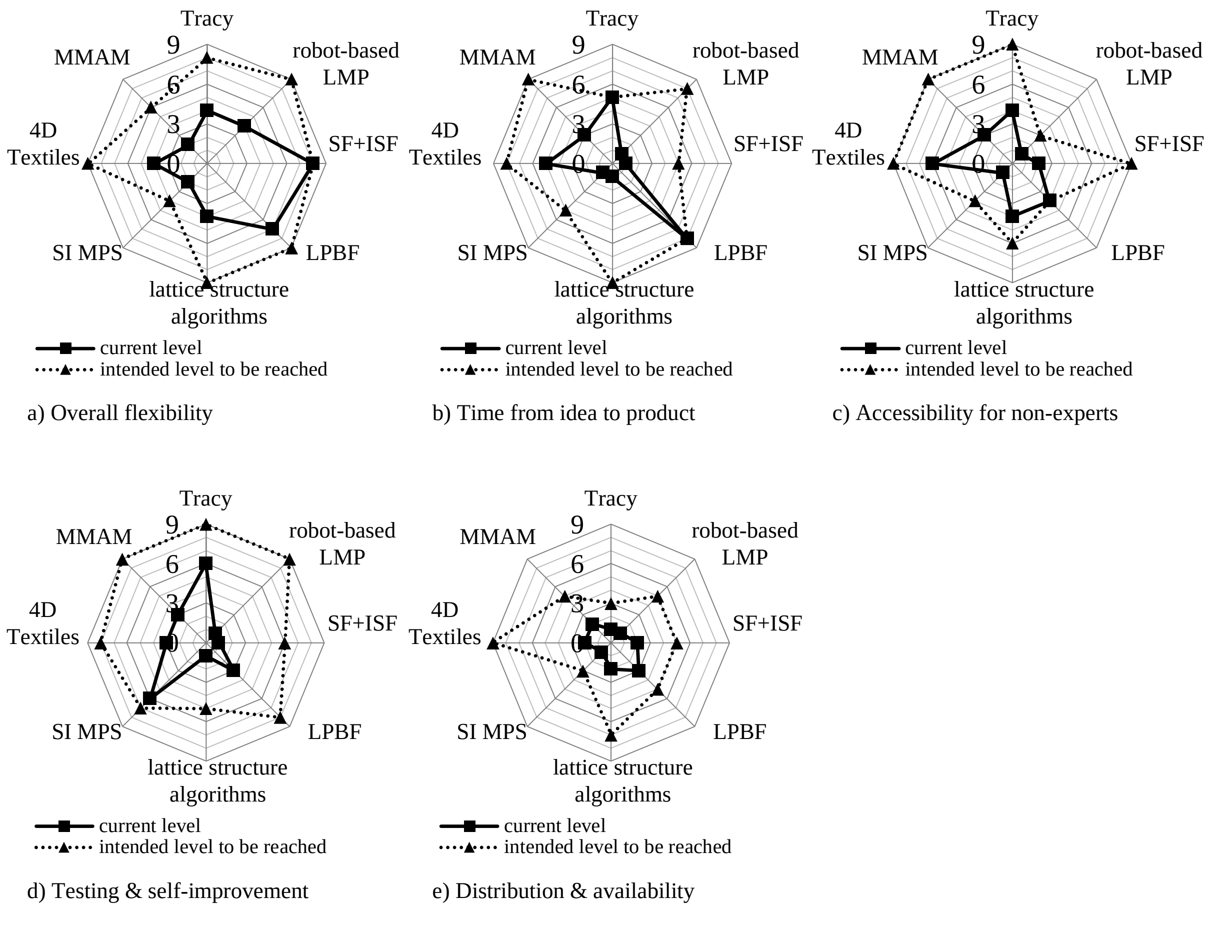

Figure 2: Summarised rankings for each dimension of the ARL.

6.2 Time from Idea to Product

The ARL of time from idea to product varies within the range from level 1 to level 8, where 1 corresponds to a lead time of more than a week and level 8 corresponds to a lead time of less than a few hours. On average, the ARL of the technologies is on level 3. The dimension of time from idea to product shows the highest standard deviation of all investigated dimensions. On average, the ARL to reach is level 7. All technologies shall be developed in a manner that allows lead times of less than a week. Two technologies intend to reach lead times of less than an hour: the algorithm for production of lattice structures and the LPBF process. According to the survey, the length of the manufacturing lead time is influenced by different factors, which can be divided into three main categories: process-related factors, product-related factors and input-related factors. Process related factors are dealing with the manner of prototype-build-up. Manual processes will take longer most of the time. Processes that are still trial and error will be used iteratively to build the prototype. The lead time herein is unpredictable and will vary in its extent from small changes to rather large interventions. Product-related factors are shown to be strongly influenced by the size of the required prototype. A good example are AMTs, in which process time is merely to present scientific findings proportional to part size. Input-related factors are most likely to be external factors such as order and delivery times for standardised components or computing capacities. External factors can be impediments in the agile framework and may be outside the influence of the user. All researchers aim to shorten the lead times of the technologies. Different strategies are introduced and include the improvement of processing times by advanced hardware components, automated data flows, and capacity-oriented software development.

6.3 Accessibility for Non-Experts

Excluding one technology (level 6), all other technologies are ranked between level 1 and level 4. Either the setup, technology, process, or the combination of them is too complex to be run by a non-expert and only some of them are yet available for technicians. Low quality, the need for expert knowledge due to not yet explainable behaviour, only few coherent material definitions and the lack of knowledge about the requirements by the user are reasons for that. Although, parts of the process might be accessible if run as stand-alone solutions the whole process still might not be accessible. From a product perspective, decorative purposes might be possible but functional are not. For the higher ranked technology 4D Textiles, tutorials on how to use the technology exist but the material properties are not coherent. For four out of eight technologies, level 9 should be reached. The accessibility of the technology for non-experts can be increased by decreasing barriers and complexity. The strategies include the offering of a handbook, helping guidelines and easy to understand GUIs. In addition, the decrease of the amount of input parameters to a minimum of one parameter such as e.g., the target geometry is a supportive approach. A similar approach on machine level is taken when adoption of an existing technology can be easily done with modular additions. Some technologies are not intended to be accessible for non-experts ever due to safety issues or based on strategic decisions. A two-step approach is suggested to increase the technologies' accessibility. This can be done e.g., by first offering 2D and 3D simulations for semi-experts and using this expert knowledge and experience to communicate the technology in a subsequent step to non-experts.

6.4 Testing & Self-improvement

The AMTs are ranked in very diverse levels with some technologies being ranked in multiple levels caused by an iterative development process. The given reasons can be clustered in the lack of a corresponding requirement within the scope of development, an existing lack of understanding of occurring phenomena and a lack of successful validation. With regards to the scope of the development in the digital support system, physical constraints are not yet considered. As another example, the data collection in the robot-based LMP is done manually but not digitally so far. For SF+ISF and 4D Textiles phenomenon are not yet explainable. For LBPF material changes result in a new trial and error process. The non-existence of a data structure is mentioned which also includes the hypothesis that to develop a self-improving system not enough data might be generated. Requirements are not met either internally or externally. Moreover, some cases are lacking adequate measuring systems to determine whether requirements are met. Additionally, statistical distributions do not allow for clear statements in the development of the robot-based LMP. The levels to be reached are between 5 and 9 and thus a bit more homogeneous. Higher levels should be reached to increase process stability, improving the process setup or process simulation. A reason for a lower level includes the absent necessity of AI. Process stability is reached through automatic in-process control and the use of data. To reach automated planning for SF+ISF it is aimed for an independence of experience knowledge. To improve process control, technologies which are already existing but not validated for the AMT are considered. Overall requirements for higher levels are fast simulations.

6.5 Distribution & Availability

The distribution and thus availability is currently very low (level 1-3). The reason for non-distribution is the current low quality of the technologies. For two technologies the modules of the technology are already commercially available which results in a potentially higher distribution though they lack standardization in the application and appear with different machine designs and no consistent results. Additionally, knowledge about the actual distribution is not available. The expected level to reach spans from level 3 to 9 with a focus on 5 and 9. The defining factors are mass production and process limitation. For mass production the accuracy needs to be increased. For process limitation safety and the size of the machines are mentioned. Solution strategies include digitization of the process chain, integration and explanations on existing digital platforms, variations in the level of details available and standardised additions to existing machines. Open source and community research is only considered for software not for any of the physical technologies so far. For some of the technologies the need to identify their potential user or customer exists to be able to decide about the degree of distribution & availability.

7. Results

To validate the relevance of each dimension, a comparison of the spider webs of each dimension for all eight technologies is conducted. The relevance of each dimension is compared both in the status as-is (case 1) and the status to-be (case 2). If for one dimension all ratings are higher than for another, the later can be considered less relevant within the context of AMT development in the IoP. This is especially interesting if it appears to be valid for both the current and the planned status (case 3). Case 3 is true for the comparison of overall flexibility and distribution & availability. Within the IoP, overall flexibility is therefore generally considered more relevant than distribution & availability. Case 1 can be observed for the comparison of accessibility for non-experts and distribution & availability. All assessed levels of accessibility for non-experts are currently higher. Therefore, accessibility for non-experts is currently considered more relevant than distribution & availability. For the planned status only LPBF drops out. Case 2 is not applicable. With exception of the algorithms for production of lattice structures, the planned levels for testing & self-improvement are higher than for distribution & availability. To evaluate the chosen levels of each category the utilization of the entire spectrum is analysed. For the categories overall flexibility, testing & self-improvement, and accessibility for non-experts four technologies are planned to reach level 9. The definition of the levels can be considered practicable. In the dimension distribution & availability only one technology is planned to reach level 9, the median is 5.25 which needs to be discussed. For the dimension time from idea to product two technologies are planned for level 9, three for level 8. None of the AMTs has already reached nor has the goal to reach level 9 in all dimensions.

8. Discussion

The authors are aware of the dependence on the evaluator. Future research needs to include different AMTs outside the IoP and needs to expand the investigation to more developers for a statistical evaluation. Feedback from the participants has indicated a need for a comparative result with regards to clarity. The results have shown that no clear statement on the weighting of dimensions can be drawn which would be needed for a cumulative result. The status although allows for identifying discrepancies between dimensions which can indicate a barrier for deploying the technology in an agile development process. High aimed rankings within the dimension overall flexibility compared to the dimension of time from idea to product point towards the necessity of versatile processes which can build diverse products of lot size one which might be caused by the chosen scenario of an engineering change request. It could further demonstrate the need of correlating complexity or part size with required lead times and therefore refer to a relative time from idea to product. The ranking of distribution & availability might be generally lower because this factor is part of the commercialization strategy for a technology and of less focus for researchers. An ARL assessment should therefore also be conducted with researchers and developers from industry.

9. Conclusion & Outlook

The ARL represents a supplement to the TRL in identifying technological suitability for agile developments. The ARL points out directions for further development of AMTs to increase the suitability for agile processes. It therefore can be employed as a tool for self-assessment of the technologies, and a measure to identify promising research directions, respectively. The ARL can furthermore be employed when it comes to decisions regarding investments in the research and development of AMTs or in organizational departments in which time might be a critical resource.

It becomes apparent that some AMTs in the workstream of the cluster of excellence CRD-C.II do not intend to reach higher levels due to e.g., safety reasons. Further refinement is needed regarding relevance of the dimension distribution & availability as well as a potential modification of the suggested stages. Additional stages can be defined to allow for precise evaluation. To allow for increased customer engagement and account for concepts of prosumerism, an additional stage for private use may be introduced within the dimension distribution & availability. Agility works on a spectrum and the ARL incorporates main principles of agile approaches to build a guideline. It allows easy assessment of technologies regarding agile prototyping. Further research needs to broaden the scenarios to evaluate the applicability of the framework for other agile processes and AMTs outside the IoP. Same applies to both evaluating the ARL from an industrial perspective as well as applying the ARL to technology developments from industry.

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Notes on contribution

H.C.K. and L.S. contributed equally to the research. Conceptualization, framework design, data acquisition and visualization, H.C.K. and L.S.; literature review, H.C.K., L.S. and J.J.F.; writing—original draft preparation, H.C.K. and L.S.; writing—review and editing and supervision, G.L., G.B., T.G., G.S. and C.G. All authors have read and agreed to the published version of the manuscript.

Appendix

10. Detailed Technology Profiles

10.1 Technology Profile Tracy

The system Tracy developed by the TOS Institute of RWTH Aachen University supports users to create a suitable optical system for given requirements by using cheap stock lenses and a graphical user interface (GUI). Its goal is to evaluate a suitable lens system in only a few seconds instead of many days. The user defines the type of optical system -either beam expansion or focal system- and the parameter for the input beam. If a meticulous analysis is required by the user, Optic Studio (Zemax, Kirkland, WA) is used as a support tool. User requirements and system refinements are matched with available stock lenses. Herein, effects of lens combinations and the distance between multiple lenses will also be included (software, as-is vs. to-be). Based on the results, lenses are bought off-the-shelf from a vendor and are put in a lens holding system (hardware, component), which is manufactured via AM (hardware, machine). A comparison of the results from Optic Studio and Tracy is performed. The optical quality of the physical system is evaluated using a wave front sensor to be able to also consider influences that result from the assembly (software, testing). The information about the optical system prototype for individual requirements are fed as data output to the IoP level. The specific combination of certain lenses as well as the evaluated focal lengths are main results. The knowledge about validated optical systems and their accuracy is used as data input to the software level.

10.2 Technology Profile LPBF

The Laser Powder Bed Fusion Process (LPBF) is a commercially established AMT and provides geometrical freedom for manufactured parts. It is continuously investigated within the Cluster of Excellence by the RWTH Aachen Chair of Digital Additive Production (DAP) in cooperation with the IEHK Steel Institute of RWTH Aachen University. Within the process, the user typically prepares a 3D-model, chooses parameters like applied power, employed materials, and makes a choice between protective atmospheres like argon or nitrogen. The user is herein supported by commonly available CAD-software as well as by hardware-specific job preparation tools. Set, monitored, and controlled parameters include layer thickness, scanning speed, laser power, laser spot size, and hatch distance (Software, As-Is vs To-Be). Relevant hardware components of the LPBF machine are the laser source and the powder bed. The machine can build physical components with unique material properties with reduced geometrical restrictions. Data will be gathered from a software perspective by testing material properties as well as collecting data from process monitoring. The goal of the research which is conducted at the DAP is to build an in-situ controlled and adapted process by employing the IoP. Collected data which is fed into the IoP consists of data about geometrical properties, material properties, and temperature maps. These datasets will be used for adjustment processes as well as returned towards different software tools to simplify subsequent processes with information about relevant parameters and producible 3D-models. Two support tools with different foci will be described in the subsequent sections in the research and development of AMTs or in organizational departments in which time might be a critical resource.

10.3 Technology Profile SI MPS

The scale-independent tools for material and process simulation (SI MPS) to be applied within the LPBF are built at the IEHK Steel Institute of RWTH Aachen University and aim to enable agile alloy development. A digital, low-dimensional representation of the micro-structure as a descriptor for process parameters and final material properties is to be found. Product requirements which are defined by the user among the typical

LPBF-specific ones are e.g., energy absorption, weight, and corrosion. Support tools which are used to build test specimen are commonly available CAD-tools. Monitored and controlled parameters include laser scan speed, scan direction and various temperature values (Software, As-Is vs. To-Be). A standard LPBF machine is used which can build complex part geometries with a large variety of properties. These components are typically tested within tensile and impact testing, and properties like stress-strain behaviour and porosity, as well as additional details about the micro-structure are obtained. To create comprehensive data for the IoP, test data is supplemented with data gained from FEM or MC simulation. Based on this data and deep-learning approaches (IoP, Data Output), process parameter recipes are generated, and an alloying concept is developed. Both items will be available within the IoP, fed into the software for processing, and employed in subsequent production cycles (IoP, Data Input).

Technology Profile Lattice Structure Algorithms: The algorithms aim to generate, simulate, and optimise CAD-data for production of lattice structures to be manufactured within the L-PBF process especially for light weight structures. The algorithms are in development at the Chair of Digital Additive Production (DAP). The user chooses the AM technology, lattice type, and geometrical parameters which are derived from use-case specific requirements. A user interface is provided for easy access, and decisions are supported by simulation tools like Ansys and Abaqus. The software requires the earlier mentioned information about lattice type and its parameters, as well as the lattice domain and the technology-dependent building orientation. Subsequently, a set of algorithms simulates, compares, optimises, and refines lattice structures automatically (Software, As-Is vs. To-Be). The algorithms are currently available for the two AM processes L-PBF and Fused Filament Fabrication (FFF). Targeted geometries are lattice structures, lattice integrated structures, and tree structures for lightweight applications (Hardware, Component). Information about the components is gathered via process monitoring, testing of mechanical properties, and testing of surface roughness. These data sets, geometrical data as well as data from simulation processes are secured within the IoP. Based on this data, the IoP can provide a CAD-file as well as relevant L-PBF process parameters for building producible and optimised lattice structures.

10.4 Technology Profile SF+IFS

At the IBF Institute of RWTH Aachen University, a combination of the technologies stretch forming (SF) and incremental sheet forming (IFS) is investigated. The combined technology (SF+IFS) aims to enable highly customised sheet metal production with inexpensive tools: a simplified basic geometry is realised by traditional stretch forming and complexity is added by using incremental sheet forming practices which are based on a 5-axis system. Product requirements which are defined by the user include the target geometry and mechanical properties of the part. The commonly available CAD-software NX by Siemens is used as a support tool. Process parameters include forming speed, tool diameter, path parameters and the die orientation. The 5-axis ISF forming machine is extended with stretch forming modules. Geometrical accuracy of produced sheets is determined using a 3D-scanner and input CAD-datasets. These measurements are correlated with temperatures during processing and are available within the IoP. They shall build the basis for a software tool to support the user by setting up the SF-IFS process for new geometries.

10.5 Technology Profile Robot-based LMP

At the Chair of Laser Technology (LLT) at RWTH Aachen University, a robot system which is typically used for handling processes is enabled to conduct different laser material processes like laser cutting, laser scanning, and surface structuring. Currently, the path accuracy of available systems is too low to meet the requirements of surface quality or geometrical accuracy. These restrictions shall be overcome with (1) a newly developed tool centre point adaption technology which enables sensors to use surfaces as references as well as (2) the potential of contactless manufacturing by lasers. Unlike conventional machining methods such as milling the trajectory accuracy as a function of control data from previous processes can be used to further improve current and subsequent trajectory planning since different processes do not differ significantly from each other. A relative position determination allows an in-process reaction to a component distortion. Product requirements which are defined by the user are a defined geometry with a high-quality surface. Support tools which are used are commonly available CAD-tools. Monitored and controlled parameters include the robot path, sensor-based geometry data and laser process parameters such as laser power while cutting and the pulse duration while surface structuring. A robot for laser material processing with sensors and kinematics is used which can build metal components with a high geometric accuracy. The path accuracy is controlled in-time and used to adapt the running process accordingly. Part and path accuracy in correlation with the laser process data are available within the IoP. The path adaption from previous production cycles and AI are used to simulate paths for new geometries.

10.6 Technology Profile 4D Textiles

With the 3D printing on pre-stressed textiles (4D Textiles) technology built at the ITA Textile Institute of RWTH Aachen University three-dimensional textiles with shape-changing properties are produced. Bi-stable structures using the energy storage properties of elastic textiles can be activated by an external stimulus. Product requirements which are defined by the user are the intended change, the stimulus, and the component geometry. Support tools which are used are CAD- and slicer tools. Today, monitored, and controlled parameters include the pre-stress of the textile. In future, process parameters such as the viscosity of the polymer, the temperature of the printer head and bed, and the distance between nozzle and textile will be monitored and controlled as well. A standard Fused Filament Fabrication (FFF) 3D-printer is used with an adapted pre-stressing unit for textiles as the new build surface. Polymer- textile hybrid structures with a designed bi-stability are produced. Tested properties are the geometries, the shape change energy and the adhesion between polymer and textile, and results shall be available within the IoP. The correlation between textile properties, polymer processing and the geometry will be used for the simulation of further product development cycles.

10.7 Technology Profile MMAM

Thermoplastic multi-material additive manufacturing (MMAM) offers the potential to vary material properties along a component’s dimensions. The process is initiated by a user who defines use-case-dependent mechanical or thermal product requirements. Conventional CAD-software is employed to design the component, and a material-mixing add-on shall be developed to support the integration of location-dependent variations in material composition. Information from both sources shall be bundled and used to prepare the process. During processing, parameters shall be monitored and reported. Such parameters are e.g., temperatures of bed and hot end, extruder velocity, and pressure within the die. Machine hardware consists of an extrusion-based AM machine with a second extruder and a mixing nozzle. The process can generate three dimensional components with location-dependent part properties. Properties tested to gain information about qualities of both process and component are e.g., tensile strength and interlaminar bonding. Thereby, data is generated which correlated process parameters and mixing factors with desired properties. Within the internet of production, models shall be created which enable the formulation of parameter recipes. These recipes shall cover all relevant parameters such as the bed and hot end temperature, material dependent extruder velocity, and mixing ratios. They are used to support process setup for subsequent cycles.

11. ARL per Investigated Technology (Figure 3)

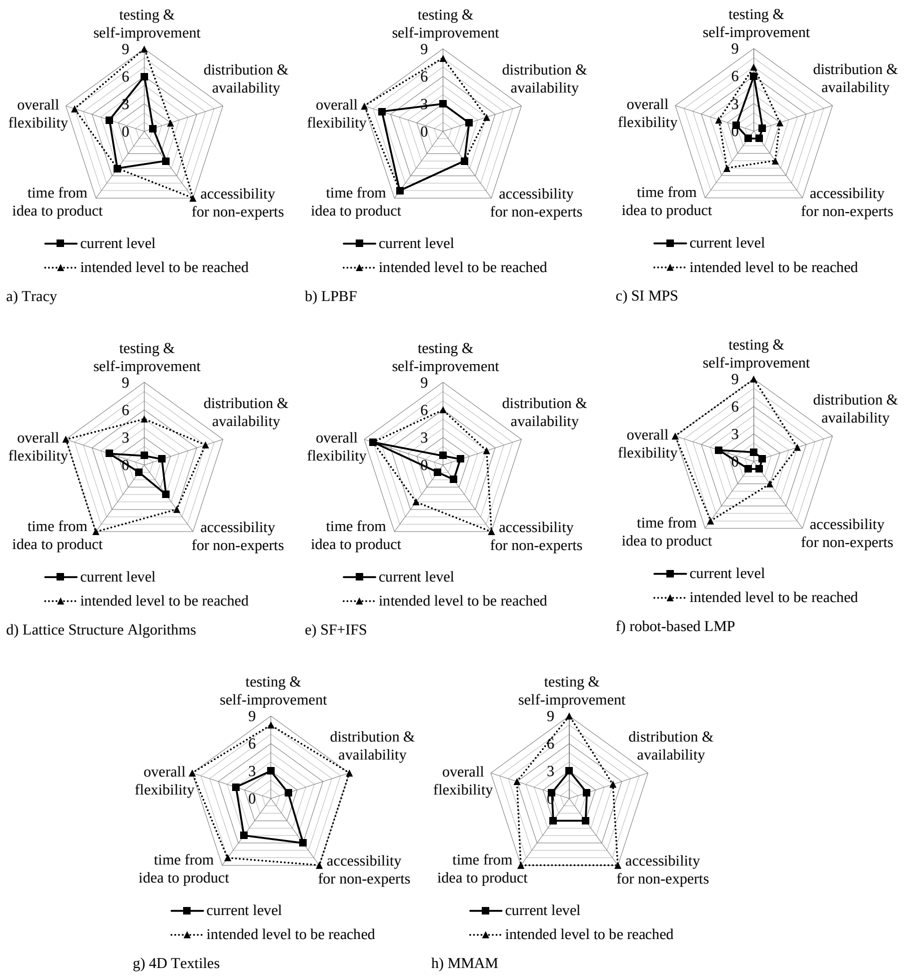

Figure 3: ARLs for Tracy, LPBF, SI MPS, Lattice Structure Algorithms, SF+IFS, robot-based LMP, 4D Textiles, MMAM

References

[1] Beck, K., Beedle, M., van Bennekum, A., Cockburn, A., Cunningham, W., Fowler, M., Grenning, J., Highsmith, J., Hunt, A., Jeffries, R., Kern, J., Marick, B., Martin, R.C., Mellor, S., Schwaber, K., Sutherland, J., Thomas, D., 2001. The Agile Manifesto. https://agilemanifesto.org/.

[2] Cooper, R., 2016. Agile-Stage-Gate Hybrids. Research-Technology Management 59 (1): 21– 29. doi: 10.1080/08956308.2016.1117317.

[3] Ays, J., Dölle, C., Schuh, G., 2019. Constitutive Features of Agile and Plan-Driven Processes in Hybrid Product Development. WGP 2018: Advances in Production Research. Heidelberg: Springer.

[4] Serrador, P., Pinto, J. K., 2015. Does Agile work? — A quantitative analysis of agile project success. International Journal of Project Management 33 (5): 1040–51. doi: https://doi.org/10.1016/j.ijproman.2015.01.006.

[5] Digital.ai. 2021. 14th Annual State of Agile Report. Accessed April 29, 2021. https://stateofagile.com/ufh-i-615706098-14th-annual-state-of-agile-report/7027494.

[6] Schwaber, K., Sutherland, J., 2017. The Scrum Guide: The Definitive Guide to Scrum: The Rules of the Game. Creative Commons, 2017. https://scrumguide.org.

[7] Atzberger, A., Nicklas, S. J., Schrof, J., Weiss, S., Paetzold, K., 2020. Agile Entwicklung physischer Produkte: Eine Studie zum aktuellen Stand in der industriellen Praxis. Neubiberg: Universitätsbibliothek der Universität der Bundeswehr München.

[8] Smith, P. G., 2007. Flexible product development. Building agility for changing markets. 1st ed. San Francisco: Jossey Bass. http://catalogue.nlb.gov.sg/cgibin/spydus.exe/ENQ/EXPNOS/BIBENQ?BRN =12925236.

[9] Klein, T. P., Reinhart, G.; 2016. Towards Agile Engineering of Mechatronic Systems in Machinery and Plant Construction. Procedia CIRP 52: 68–73.

[10] Ahmed-Kristensen, S., Daalhuizen, J., 2015. Pioneering the combined use of Agile and Stage-gate Models in New Product Development – Cases from the Manufacturing Industry. Paper presented at the IPDMC, Copenhagen, June 14-16.

[11] Conforto, E. C., Amaral, D. C., 2016. Agile project management and stage-gate model - A hybrid framework for technology-based companies. Journal of Engineering and Technology Management 40 (C), 1–14. doi: https://doi.org/10.1016/j.jengtecman.2016.02.003.

[12] Gunasekaran, A. 1999. Agile Manufacturing: A Framework for Research and Development. International Journal of Production Economics 62: 87–105.

[13] Schuh, G., Brecher, C., Klocke, F., Schmitt, R., ed. 2017. AWK Aachener Werkzeugmaschinen-Kolloquium 2017 Internet of Production für agile Unternehmen. Aachen: Apprimus Verlag.

[14] Vinodh, S., Sundararaj, G., Devadasan, S.R., Kuttalingam, D., and Rajanayagam, D. 2009. Agility through rapid prototyping technology in a manufacturing environment using a 3D printer, Journal of Manufacturing Technology Management 20 (7): 1023–1041. doi: https://doi.org/10.1108/17410380910984267.

[15] Behera, A. K., Verbert, J., Lauwers, B., Duflou, J. R., 2013. Tool path compensation strategies for single point incremental sheet forming using multivariate adaptive regression splines. Computer-Aided Design 45 (3): 575–590. doi: https://doi.org/10.1016/j.cad.2012.10.045.

[16] Deutsche Akademie der Technikwissenschaften. 2016. Additive Fertigung. Stellungnahme. Halle (Saale), München, Mainz: Nationale Akademie der Wissenschaften Leopoldina, acatech - Deutsche Akademie der Technikwissenschaften, Union der deutschen Akademien der Wissenschaften.

[17] Olfati, M., Yuan, W., Nasserie, S. H., 2020. An Integrated Model of Fuzzy Criteria Decision Making and Stochastic Programming for the Evaluation and Ranking of Advanced Manufacturing Technologies. Iranian Journal of Fuzzy Systems 17 (5): 183–196.

[18] Verzijl, D., Nagtegaal, F., Lengton, M., Rouwmaat, E., Probst, L., Monfardini, E., Frideres, L., 2013. Advanced Manufacturing - Smart Value Chains. Accessed May 11, 2021. https://ec.europa.eu/growth/content/smart-value-chainsen.

[19] Small, M. H., Yasin, M., 1997. Advanced Manufacturing Technology: Implementation Policy and Performance. Journal of Operations Management 15 (4): 349–370.,

[20] Stornelli, A., Ozcan, S., Simms, C., 2021. Advanced Manufacturing Technology Adoption and Innovation: A Systematic Literature Review on Barriers, Enablers, and Innovation Types. Research Policy 50 (6): 104229.

[21] Chen, L., He, Y., Yang, Y., Niu, S., Ren, H., 2017. The research status and development trend of additive manufacturing technology. International Journal of Advanced Manufacturing Technologies 89: 3651-3660. doi: https://doi.org/10.1007/s0017001693354.

[22] Schimpf, S., Lang-Koetz, C., 2010. Technologiemonitoring: Technologien identifizieren, beobachten und bewerten. Stuttgart: Fraunhofer-IRB-Verl.

[23] Gunasekaran, A., Yusuf, Y. Y., Adeleye, E. O., Papadopoulos, T., Kovvuri, D., Geyi. D. G., 2019. Agile manufacturing: an evolutionary review of practices. International Journal of Production Research 57:15-16, 5154-5174, doi: 10.1080/00207543.2018.1530478.

[24] Sadin, S. R., Povinelli, F.P., Rosen, R., 1989. The Nasa technology push towards Future Space Mission Systems. Selected Proceedings of the 39th International Astronautical Federation Congress: 73–77.

[25] Flinn, P. 2019. Managing Technology and Product Development Programmes: A Framework for Success. Bridgewater: Wiley.

[26] Akdil, K. Y., Ustundag, A., Cevikcan, E., 2018. Maturity and Readiness Model for Industry 4.0 Strategy. Industry 4.0: Managing the Digital Transformation. Heidelberg: Springer.

[27] Jones, M. B., Webb, P. F., Summers, M., Baguley, P., Valerdi, R., 2015. A Cost-benefit Framework for assessing Advanced Manufacturing Technology Development: A Case Study. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 229: 1654–1668.

[28] Tracey, M., Tan, C. L., 2001. Empirical analysis of supplier selection and involvement, customer satisfaction, and firm performance. Supply Chain Management 6: 174–188.

[29] Lin, C.-T., Chiu, H., Chu, P.-Y., 2006. Agility index in the supply chain. International Journal of Production Economics 100 (2), 285-299, https://doi.org/10.1016/j.ijpe.2004.11.013.

[30] Shams, R., Vrontis, D., Belyaeva, Z., Ferraris, A., Czinkota, M. R., 2021. Strategic agility in international business: A conceptual framework for "agile" multinationals. Journal of International Management 27 (1), 100737, doi: https://doi.org/10.1016/j.intman.2020.100737.

[31] Vinodh, S., Sundararaj, G., Devadasan, S.R. 2009. Total agile design system model via literature exploration, Industrial Management and Data Systems, 109 (4), 570–588. doi: https://doi.org/10.1108/02635570910948678.

[32] Sidky, A., Arthur, J., Bohner, S., 2007. A Disciplined Approach to Adapting Agile Practices: The Agile Adoption Framework. Innovations in Systems and Software Engineering 3: 203–216.

[33] Gren, L., Torkar, R., Feldt, R., 2015. The Prospects of a Quantitative Measurement of Agility: A Validation Study on an Agile Maturity Model. Journal of Systems and Software 107: 38–49.

[34] International Organization for Standardization. 2013. Space systems - Definition of the Technology Readiness Levels (TRLs) and their Criteria of Assessment. ISO 16290:2013.

[35] Ward, M., Gruppen, L., Regehr, G., 2002. Measuring Self-assessment: Current State of the Art. Advances in Health Science Education 7: 63–80.

[36] Palmieri, M., Singh, I., Cicchetti, A., 2012. Comparison of Cross-platform Mobile Development Tools. 16th International Conference on Intelligence in Next Generation Networks 179–186.

[37] Ewald, S., Voshage, M., Hermsen, S., Schaukellis, M., Köhnen, P., Haase, C., Schleifenbaum, J. H., 2021. Tailoring of AM Component Properties via Laser Powder Bed Fusion." 3D Printing for Energy Applications, edited by A. Tarancón and V. Esposito, New Jersey: Wiley.

[38] Brecher, C., Bleck, W., Feldhusen, J., Hirt, G., Klocke, F., Reisgen, U., Schmitt, R., et al. 2017. Multi-technology Platforms (MTPs). Integrative Production Technology. Cham: Springer.

[39] Koch, H.; Schmelzeisen, D., Gries, T.: 4D Textiles made by additive manufacturing on pre-stressed textiles. In: Actuators 2021, 10, 31.https://doi.org/10.3390/act10020031.

Biography

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