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# Technology Integration into existing companies

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## Abstract

The implementation of additive manufacturing as an industrial manufacturing process poses extraordinary challenges to companies due to their far-reaching differences to conventional processes. In addition to the major differences in the production process, the pre and post process steps in particular also require a rethinking for companies and their employees. To overcome these challenges and specifically to assist SMEs in the integration of technologies five industrial companies are researching together within research project "OptiAMix", funded by the German Federal Ministry of Education and Research (BMBF) and coordinated by the Paderborn University. This paper focuses on the development of an optimal and standardized process chain and its implementation in a general integration methodology. This enables the standardized integration of additive manufacturing in order to create a uniform understanding of the procedures and tasks within the company for the industrial application of additive manufacturing at an early stage as well as the full exploitation of its high potentials. Therefore, the methodology also includes other technology-specific components such as strategic component selection, decision support for "make or buy" and the implementation of automated component marking.

## Introduction and Motivation

Companies have to deal with many problems while integrating additive manufacturing (AM). Only a few national and international standards regarding the value chain exist, expertise among engineers and technicians is still missing and the integration of a discontinuous production into a continuous line requires precise knowledge of the technology and its processes. Nevertheless, companies want and have to meet the challenge if they do not want to lose out from a technological point of view.

To enable the technology integration for companies, five industrial partners, coordinated by the Paderborn University, are researching within the project "OptiAMix - Multi-objective Optimized Product Development for Additive Manufacturing" since the beginning of 2017. As part of the ProMat_3D funding program [BMBF17] of the BMBF, the consortium is developing methodologies for the integration and application of AM in general and the specific Selective Laser Melting process in particular as well as various tools supporting the product development process. With the AM service providers Krause DiMaTec, Hirschvogel Tech Solutions, the research institute DMRC of the Paderborn University and the development service provider EDAG Engineering, the consortium has high expertise regarding AM technologies and is supported by INTES in the field of software development for topology optimization and WP Kemper as an application partner in the field of food technology.

As basis for the integration into companies, a generally applicable AM Product Development Process (AM-PDP), which is described in detail below, was developed. This process includes various AM-specific methods, such as strategic part selection or integrated component marking as well as an overarching procedure within the development of AM parts and products. In order to ensure an implementation of this AM-PDP in the company and with this the integration in general, a integration methodology was developed in addition to the process. The procedure described in the following as well as the individual methods for integrating and applying additive manufacturing into company follow the premise of a concrete challenge or a concrete need. In contrast to the implementation due to strategic goals such as technological leadership, the decisive target value of the integration methodology is not only the technological but also the near-term economic success, which significantly increases the efficiency especially for SMEs (small and medium-sized enterprises) with lower investment capital.

## Additive Manufacturing in the Context of Conventional Product Development

Additive manufacturing constitutes a completely new manufacturing technology. However, the AM-PDP does not have to be set up reference-less and from scratch. Industry standards and guidelines developed for traditional manufacturing processes, such as the VDI Guideline 2221 as a generally accepted standard procedure in design methodology [Wulf02] or the ISO 9000 series as an international standard for quality management, can also be applied to AM and used as a basis, particularly in the area of product development [VDI2221; ISO9000].

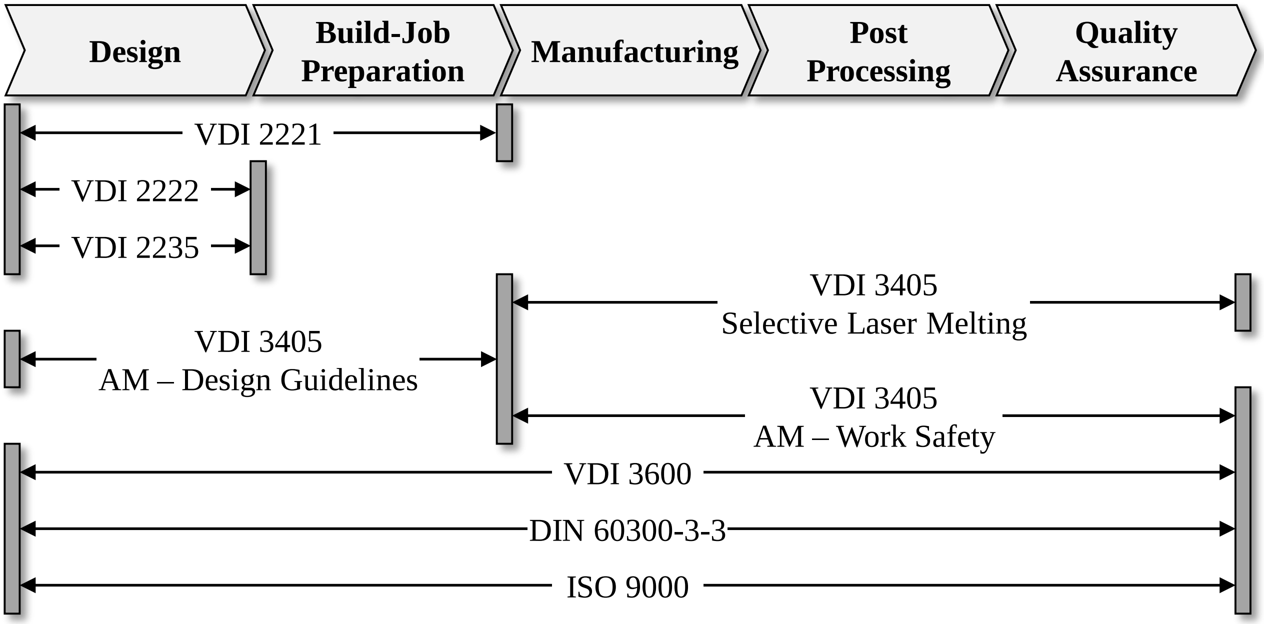

*Figure 1: Distribution of guidelines and standards to different phases of the AM-PDP / source: author*

The VDI Guideline 2221 (“Methodology for developing and designing technical systems and products”) defines the phase of product planning and development very precisely. Based on various procedural models in literature [FeGr13][Rode70][Roth00], it divides the phase into seven individual steps.

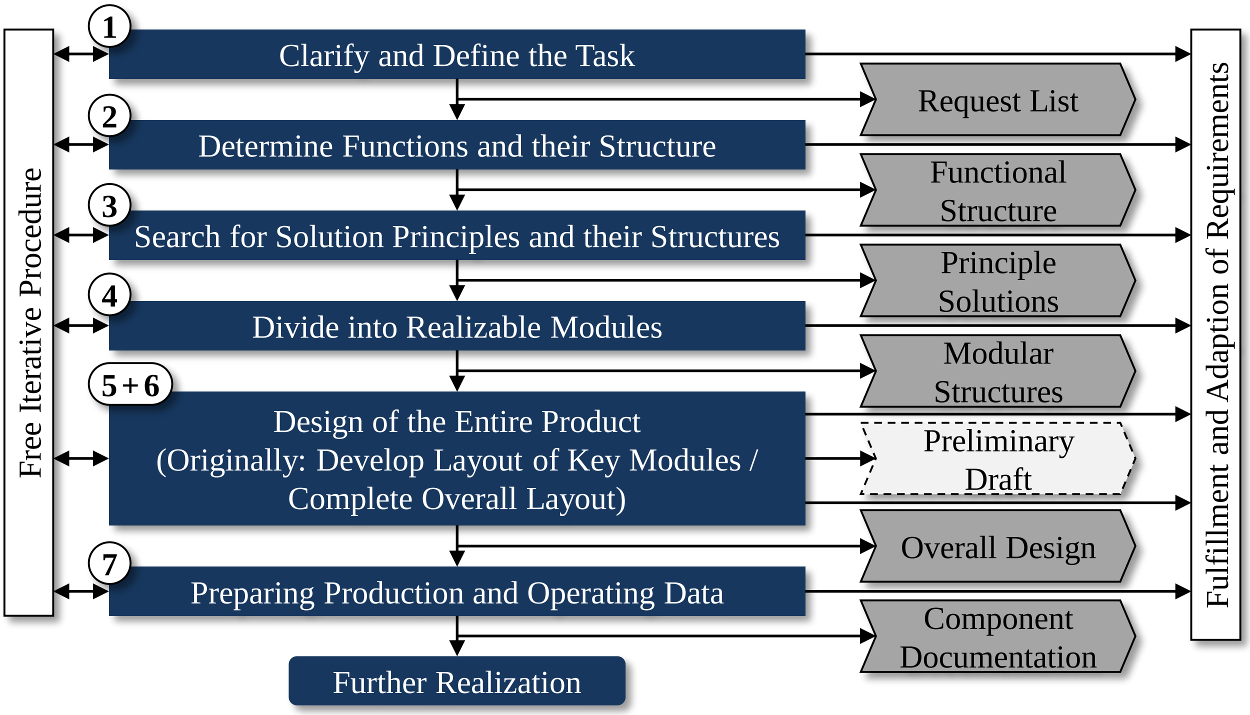

*Figure 2: General procedure for development and construction / source: author according to [VDI 2221]*

This procedure applies to AM as to most other manufacturing technologies, since only the sequence is defined, but the scope and depth remain explicitly in the employee's competence. However, a minor adjustment is particularly useful due to the limitation of AM, its high potential for functional integration and the consequent design of monolithic components. Due to the increasing proportion of automatically generated CAD data (e.g. topology optimization), the phases "Develop Layout of Key Modules" and "Complete Overall Layout" cannot be clearly separated. In the context of AM, a preliminary design is also becoming increasingly rare, as it is strongly dependent on the computer-based generation of the geometry. For the PDP, the design phases are therefore combined, but the general idea of VDI Guideline 2221 remains unchanged. Important requirements of the guideline for the AM-PDP are:

1.1 For process standardization it is necessary to define one or more specific product development processes as reference processes [VDI2221-2]
1.2 Parallel work should be preferred to sequential work [VDI 2221][VDI2221-1]
1.3 Information should be collected and made available as extensively as possible in order to achieve the highest possible transparency [VDI2221-1]
1.4 Project reviews must be defined within the product development [VDI2221-1]
1.5 Parallel to product development, a consistent cost management takes place, so that the calculation can be adjusted in the event of product changes [VDI2221-2]
1.6 Customers should be involved in the product development process on defined points [VDI2221-2]

In addition to VDI Guideline 2221, the ISO 9000 series of standards is a global set of instruments for setting up a product development process. The series of standards defines quality management systems and task-independent standards that can also be applied to the development of the AM-PDP [IS0 9000]. In contrast to VDI 2221, ISO 9000 and in particular the ISO 9001 and

9004 that are part of the series offer globally applicable rules which can be applied to every process step and phase in the product development. Selected rules of this series are:

2.1 The organization has to maintain documented information in order to support the execution of its processes and to retain documented information [ISO9001]
2.2 Customers and users must be involved in the development process [ISO9001]
2.3 The top management should determine the relevant processes and manage them so that they function within a coherent system [ISO9004]
2.4 The organization should monitor, analyze, evaluate and review the organization's performance [ISO9004]

Further standards and guidelines from related areas which are helpful for the creation of a generally applicable AM-PDP are the VDI guidelines 2222 ("Methodical development of solution principles")[VDI 2222], 2235 ("Economic decisions in design") [VDI2235] and 3600 ("Processes and process orientation in production logistics on the example of the automotive industry") [VDI3600] as well as the DIN EN 60300-3-3 ("Dependability management - Part 3-3: Application guide - Life cycle costing") [DIN60300-3-3]. The following rules have been taken from these guidelines for the design of the desired model:

3.1 The development of a principle solution according to VDI 2221 is only necessary if no exact task is specified [VDI2222-1]
3.2 During the design, cost control should be carried out after each technical specification to ensure a short control loop [VDI2235].
3.3 Individual processes must be designed with the target of short lead times, high quality and low costs [VDI3600].
3.4 A life cycle analysis should be realised in the early design phases [DIN60300-3-3].

In addition to the established guidelines for traditional manufacturing, first guidelines for AM have recently been published or are currently being developed (e.g. VDI 3405, part 6.1, Draft, Published: 06/29/18). These mainly aim at the manufacturing process itself, but individual elements can be extracted very well and converted into rules. This allows a process flow to be derived, particularly in the area of post-processing:

4.1 The integrated component marking is recommended to ensure traceability [VDI3405-3].
4.2 Together with the components, tensile test specimens shall be prepared in accordance with DIN 50125 [VDI3405-2].
4.3 For non-destructive testing of components, penetration testing (DIN EN 571-1, DIN EN ISO 3452-1) and radiographic testing (X-ray regarding to DIN EN 444 and CT regarding to DIN EN 13068-3) are recommended [VDI3405-2].
4.4 Used powder has to be collected to the highest possible extent and prepared for further use [VDI3405-6.1].
4.5 Post-processing is carried out in the steps "transport", "cleaning of removed components", "separation from the build platform", "removal of support structures", "blasting of components" and further traditional processing steps (e.g. machining, heat treatment) [VDI3405-6.1]

## New Product Development Process for Additive Manufacturing

In accordance with VDI Guideline 2221, part 2, reference processes were used to develop the generally applicable AM-PDP. The companies involved in the project and the DMRC have been using AM as manufacturing technology for many years and have thus already defined their own procedures for AM product development. Within OptiAMix these were analysed, documented and combined to form a consolidated overall process, which serves as a reference and basic framework for the general AM-PDP [Bue17]. Then the previously identified rules from guidelines and standards were implemented into the reference process. For this purpose, the established rules were checked for their applicability for AM, adapted and integrated as further process steps if necessary (e.g. Life Cycle Analysis as a consequence of rule 3.4).

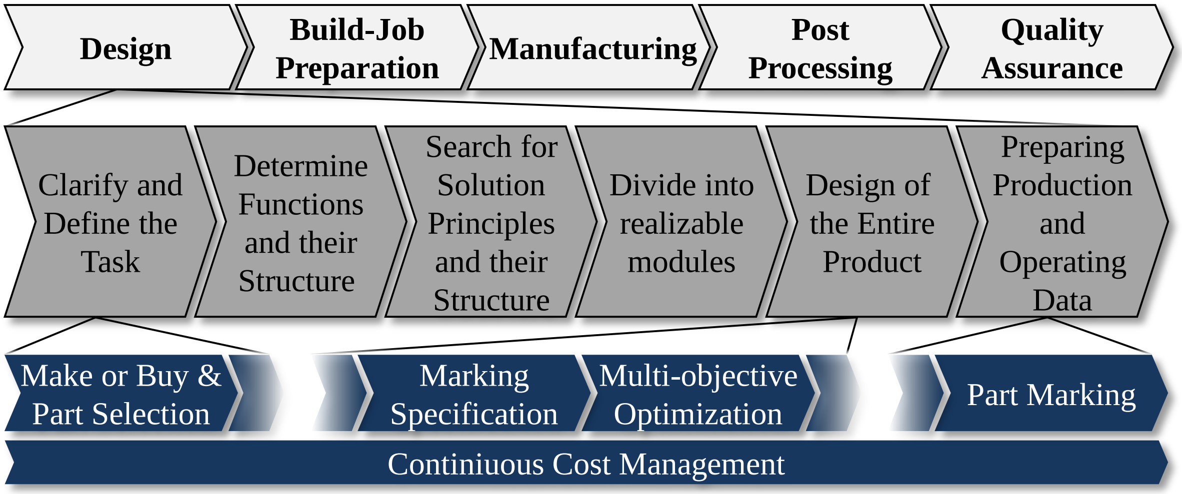

*Figure 3: Structure levels of the AM-PDP / source: author*

In a third step the process was analyzed with regard to the previously defined premise of technology integration based on a concrete challenge and extended by AM-specific elements. The specific challenge based on a specific product inevitably leads to the question of the place of production and responsibility of the implementation and thus to the make or buy decision. For this purpose, the "Make or Buy & Part Selection” process step was added to the overall process. The strategic analysis of one's own product portfolio for suitable component candidates contradicts at first glance the premise set out above. Although it can also be a logical consequence if the concrete challenge is not a specific product but the market or competitive situation. It can be a follow-up process if the make or buy evaluation results in insufficient machine utilization. In this case, it is useful to look at other products to identify possible alternative products that increase utilization. A further consequence of the make or buy analysis is the necessary consideration of both in-house production and outsourcing of production to a service provider. Both integration alternatives must be covered within the AM-PDP. Therefore, additional factors, in particular traceability and quality assurance across company boundaries, are implemented in the process. These are “Integrated Component Marking” and “Continuous Component Documentation and Continuous Cost Efficient Design”. The implementation of AM-specific elements is completed with the “Multi-objective Optimization”, developed within OptiAMix. The software solution developed by the partner INTES will enable not only load-related optimization but also cost, post-processing and production-related optimization. The resulting design phase changes are taken into account and implemented in the PEP at an early stage.

# The AM PDP in General

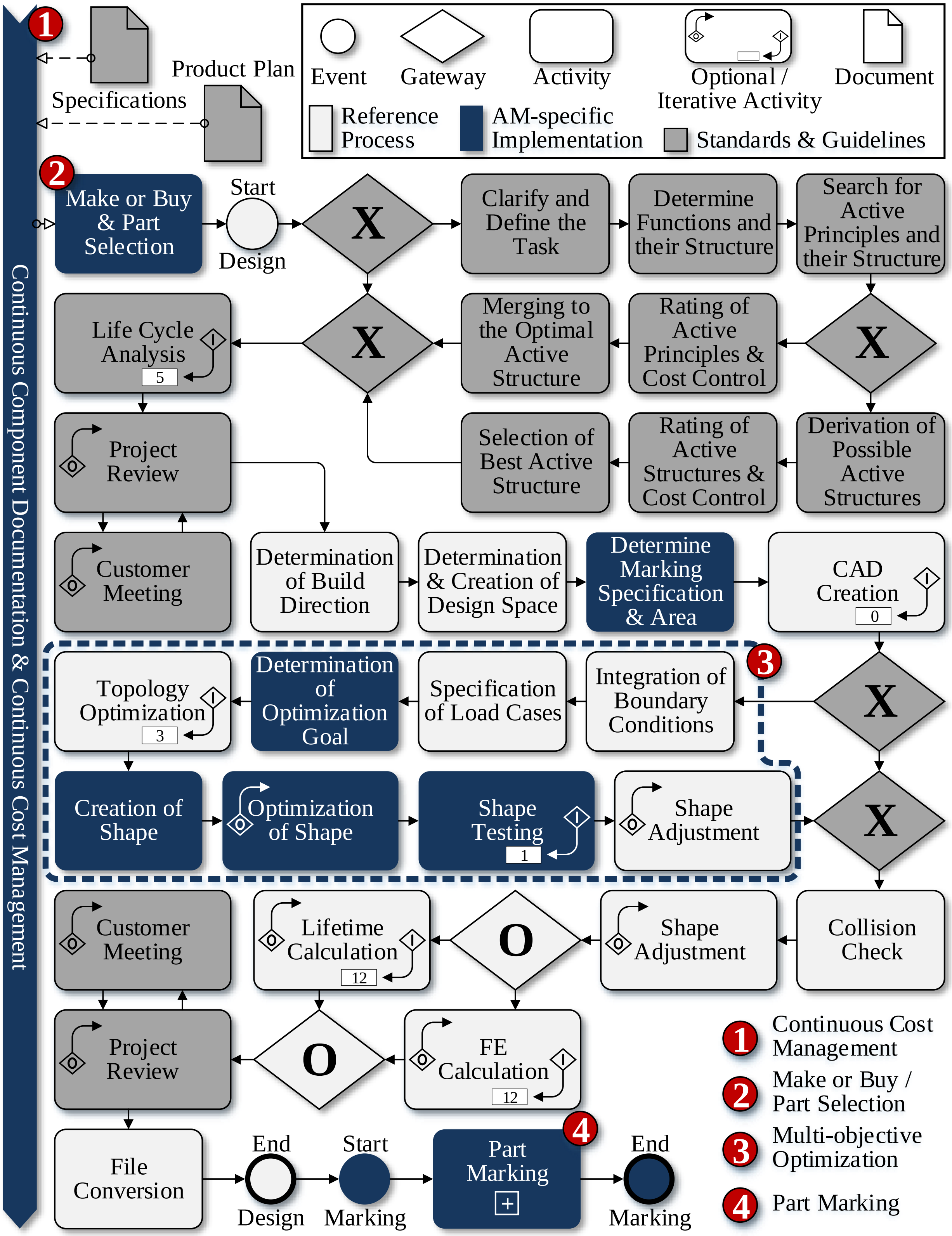

*Figure 4: The AM-PDP for the design phase / source: author*

The AM-PDP has been finalized for the phases "Design", "Data Preparation", "Manufacturing Process", "Post Processing" and "Quality Assurance". Figure 4 above shows the process using the example of the design phase, built in adapted BPMN 2.0 (Business Process Modelling and Notaton 2.0). BPMN 2.0 provides different elements for the construction of processes. These are events (start and end of a process step), gateways (X, OR and XOR decisions), activities (process steps) and documents. In addition, optional, iterative and optional-iterative activities were introduced in OptiAMix to reduce the number of junctions and to make the overall process clearer. The AM-PDP starts with Make or Buy evaluation and strategic part selection (2). This is followed by the planning-intensive steps of VDI 2221 and, following the first "Project Review", the phase "Design of the Entire Product". This includes the first AM-specific step of part marking and the process of multi-objective optimization (3). The entire process is completed with the process sequence of part marking (4) as part of the seventh step of VDI 2221 and as initiation for the data preparation (not shown in the figure). Parallel to the AM-PDP, the continuous component documentation and the continuous cost efficient design are performed (1).

## Discussion of Specific Process Steps of the Additive Manufacturing PDP

### Section 1: Continuous Cost Efficient Design

Cost Efficient Design may only be achieved if the overall part costs can be estimated in the different iterative steps of the PDP. The knowledge about the process steps and the respective cost drivers are prerequisites to set up a specific costing model. The knowledge about the importance of a cost driver is a significant aspect for the product design which is a viable option to understand the relevant workflows and to extract the relevant information with the help of business process analysis [VDI5610-1]. Cost Efficient Design and its methodologies should be embedded into a systematic Product Development framework as presented before in order to be efficient [Fisc08] [EKH+07][PBF+07]. This implies that the discussed tools, which shall support a Cost Efficient Design with the AM technology, also need to be embedded into an (existing) framework. There are no requirements to the type of structured process, which means that the discussed contents are subject to be integrated into any well structured Product Development Process. This may be a process published by a standardization body, e.g. the VDI 2221, but as well a company dependent Product Development framework or in this case the standard AM-process. To achieve the goal of integrating AM technologies and the developed concepts into the Product Development Process, the designers need exactly these structured ways to find economically feasible part candidates. In addition, tools need to be integrated in this structured process. This allows to estimate AM part costs with the available information at a given point during the design and planning activities. Keeping this and the requirements in mind, a structured process needs to be reproducible, systematic and simple to execute. It should propose tools and needs to consider Lifecycle Costs.
To achieve this aim, the framework is not only based on the three different methodological approaches from the VDI 2221. The VDI 2235 guideline for economic decisions in design and the DIN EN 60300-3-3 shall also become a crucial part of the methodology. By this the designer should get the awareness of Lifecycle Costing and AM part costs during the design and planning phases.

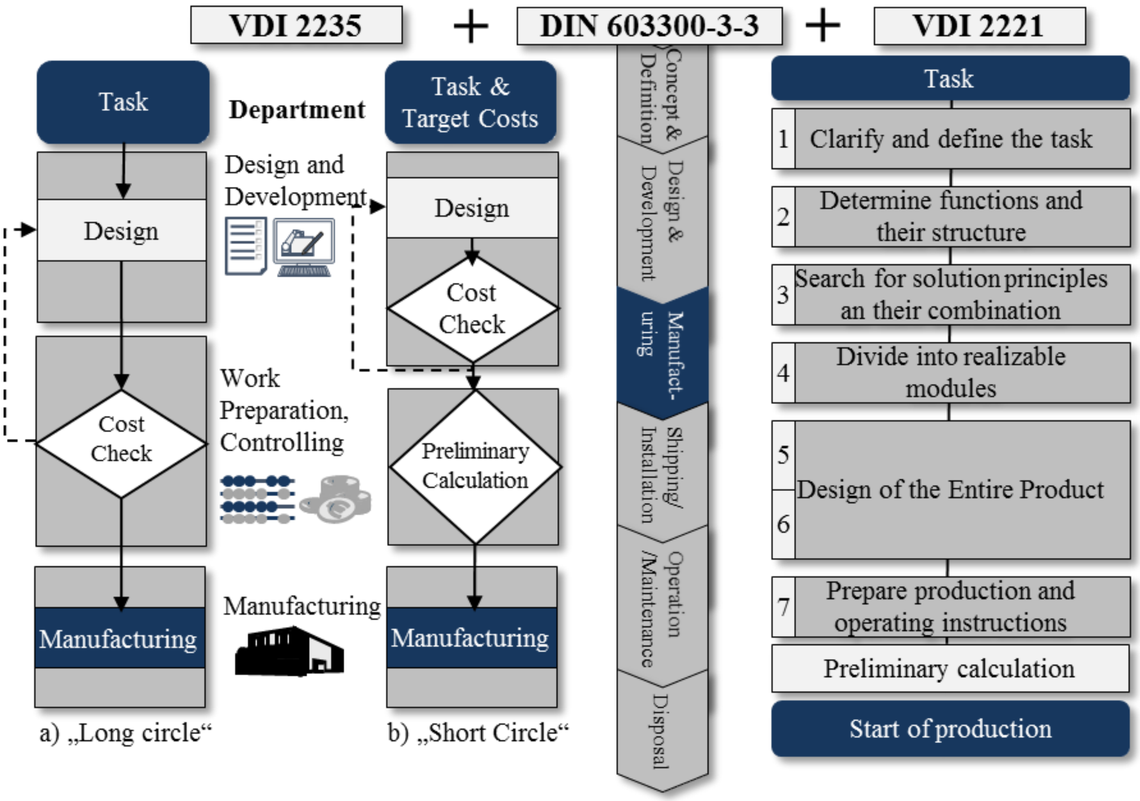

*Figure 5: Combining different approaches framework enabling a Cost Efficient Design / source: [Lind18]*

The integration has several advantages for the selection of an appropriate product design and production technology. It supports

- the awareness about costs among the design engineers,
- a direct economical assessment of a given part / part candidate,
- a structured repeatable approach, which is viable for Cost Efficient Design,
- the consideration of Lifecycle Costs during the design process.

## Section 2: Part Selection & Make or Buy

The strategic part selection and the make or buy evaluation are inseparable elements with regard to the AM integration into existing companies. Following the given premise of a concrete challenge, different triggers can lead to the necessity of a more exact consideration of AM and thereby influence the chronological sequence of part selection and the make or buy decision. If the trigger for the analysis is a product only a technological verification is carried out. Subsequently, it has to be clarified whether the component can also be manufactured economically using AM – by investing in an AM machine or by outsourcing the production. If the investment in a machine is not worthwhile due to a lack of capacity utilization, a detailed evaluation of the entire product

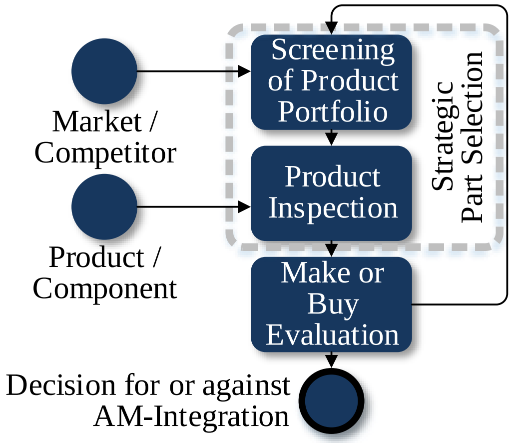

*Figure 6: Procedure for Part Selection and Make or Buy Evaluation / source: author*

portfolio follows to identify further part candidates. If, on the other hand, the market or competitive situation triggers the analysis, the detailed component selection must be the first step and the make or buy evaluation follows in second place.

## Part Selection

As AM is a comparably new manufacturing technology, finding the right applications and application fields is a crucial prerequisite for the economic deployment. The uncertainty about part candidates is also created by the lack of knowledge and confidence in this technology [LJM+13]. The selection of suitable parts for this technology is a complex process as there are multiple relationships between different attributes of a build (e.g. build direction and mechanical strength). With a sufficient understanding of the processes and the given attributes, meaningful information can be gained [GRS10]. Still, the emphasis in literature has rather focused on finding a certain manufacturing machine for a given part than vice versa (e.g. [MZC+15], [BoGo11]). Published approaches for part selection are mostly qualitative and not quantitative. Many of these quantitative processes rather focused on deciding if AM might be an option for the company in general (compare e.g. [WoCe15], [Mate16-ol]). And so far no approaches have been investigating the optionality to add further components or parts to a certain build job to increase the economic value of the production. One of the key factors for the success of AM is the selection of appropriate part candidates. The part selection shall be a systematic and repeatable process [LRJ+15]. According to Eisen the human is one of the main influence factors on the achievable quality for parts in the SLM process to be controlled [Eise10].

As the utilization of the build chamber has a high impact on the machine productivity [Lin18], looking for additional parts to increase the occupancy rate of the building chamber may influence the later make or buy decision in a major way. AM has some further peculiarities with regards to the selection process. They change the way of how an engineer needs to think and due to this reason needs special attention during the PDP. In the phases conception, design and elaboration the engineer needs to have a certain knowledge about the possibilities and limitations of the considered manufacturing technologies. Here, task number four “divide into realisable modules” is of special interest. As discussed in the sections before, the possibilities of what is realisable change significantly using the layer by layer manufacturing.

In literature on conventional manufacturing, the general approach is to find a manufacturing technology for a part, rather than to find a part for a manufacturing technology. The choice of the manufacturing technology is always supposed to be a comparison of different production variants [PBF+07] [WWD+11]. The overall aim in finding an appropriate manufacturing technology is to achieve a result which is efficient, systematic and free of intuitive decisions. Currently lot sizes and the complexity of a product may lead to a preselection in favour for or against AM. The technology will be one further option amongst all other manufacturing processes. In the future, this shall also be the general approach used for AM-part selection. As the knowledge about AM is still scarce today, it improves the tool for a dedicated screening of AM part candidates and their selection. Based on the requirements of a part candidate which is to be manufactured, a comparison of different production alternatives is necessary. Westkämper et al. [WWD+11] propose to evaluate criteria for the choice of manufacturing technology concerning product/-process-/economical/-as well as environmental and social criteria. Each of these main categories consists of different sub-criteria. Depending on the application area of a part, the most important sub-criteria from each main category need to be selected to determine the most promising manufacturing method. Some of these criteria are quantitative whilst others are rather qualitative. To be able to rank some of these decision criteria proposed by Westkämper [WWD+11] with regards to AM, a specific knowledge is necessary (compare figure 7). This knowledge can be split into three categories requiring different sets of knowledge. The engineering knowledge is subject to rank product- / part related criteria while the AM-Manufacturing knowledge is necessary to rank process and economic related criteria. The knowledge about business administration deals with economic criteria and the integration of business administration knowledge. Each of these knowledge fields enables a reasonable decision with regards to the manufacturing method. These may be in practice be incorporated in one person but normally are split up to different people in an organization. Whereas the engineering knowledge is clearly located at the design engineers, the other knowledge areas may be performed by other roles.

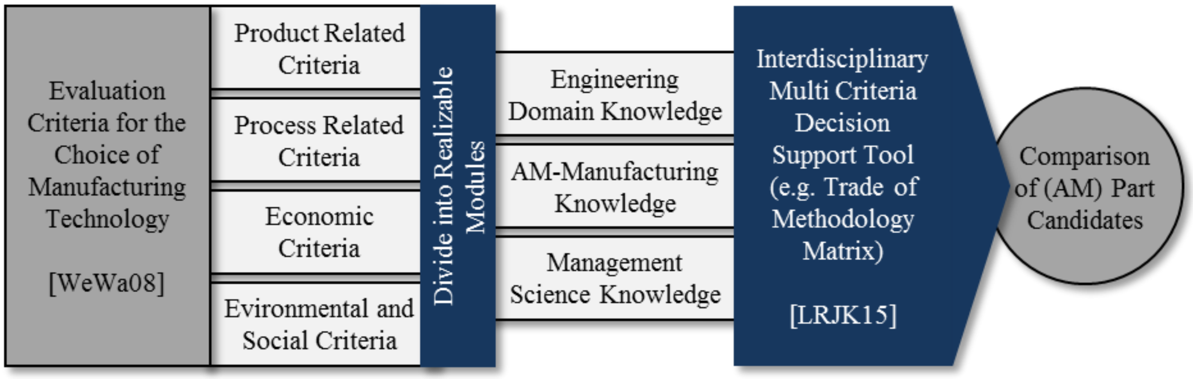

*Figure 7: From Manufacturing Technology selection to parts selection for AM / source: [Lind18]*

### Make or Buy-Decision

In most conventional manufacturing processes, the make or buy decision is a simple cost comparison calculation, since cost drivers are normally known and the productivity is clearly proven by the OEM. In AM, however, the evaluation of the costs becomes an optimization problem. One of the main objectives of in-house production is the optimum utilization of machine capacity. This is the only way to achieve economic success despite high system costs [WoCe15]. Three factors are decisive for this in AM: the build time, the discontinuous production and the flexible part placement within the build chamber.

The build time is one of the most important cost factors in AM [LJM+12]. The simplest, but neither standardized nor specified method is the use of the manufacturers data. However, since important influencing variables (material, support structure, recoating time, etc.) are not taken into account, the use of this data is only recommended to a limited extent [Lind18]. In addition, there are various more precise cost models available in literature which, in addition to various factors, consider scan speed and recoating time as influencing variables [GRS10][Lind18][MeRe10] [RuHa07]. This segmentation makes it clear that optimum build space utilization also leads to better assembly rates and thus to lower costs per component, since the recoating time is a factor independent of the utilization. On the other hand, it becomes clear that build rates have to be calculated depending on the component and thus complicate the make or buy evaluation.

The discontinuous production of SLM results in a second challenge in achieving maximum capacity utilization. In Germany, for example, only 14% of employees work three or four shifts

[LTT13]. So at least 86% of companies have to distinguish between operating and closing times. The logical consequence of this is the necessary reduction of the build chamber utilization to let build jobs end if possible at the beginning or during the operating times and thus to avoid production downtime. Discontinuous production is therefore a factor that conflicts with the maximization of the build rate.

The third factor is the flexible part placement within the build chamber. This factor is crucial for the achievement of an optimum compromise between maximum build rate and manufacturing times adapted to the operating times. Since the height of the build job in particular has an effect on the build time due to the recoating time, a variation of the build chamber utilization for different components can contribute to the optimization of the manufacturing times with constant platform utilization. However, since component orientation and nesting are decisive factors, the advantage arising from a technological point of view becomes a calculatory challenge.

In order to solve the optimization problem regarding the three factors and thus reduce the make or buy evaluation to a level of complexity corresponding to traditional manufacturing processes, an investment calculation tool was developed at the Paderborn University, which determines an optimal plant utilization depending on the operating times [Bues18]. This also includes all cost factors for the cost comparison calculation and thus ensures an efficient make or buy evaluation, especially with regard to the different scenarios to be considered due to the part selection.

## Section 3: Multi-objective Optimization

Multi-objective optimization is the core topic of the research project OptiAMix and accordingly also considered in the AM-PDP. Previous solutions for component and topology optimization only provide the load-related design of components (e.g. Altair OptiStruct [Alta18-ol]). The OptiAMix consortium and especially the software developer INTES wants to expand this and additionally enable cost, post-processing and production-related optimization. For this purpose, design guidelines for the corresponding targets are developed at the Paderborn University, converted into a machine-readable format and implemented by INTES in their software Permas in order to create a sustainable optimizer [ToLa18][FWW18].

## Section 4: Part Marking

### Objective

Marking of parts to be manufactured additively is considered in the general PDP in section 4 as a crucial bunch of activities to achieve traceability and to connect physical parts with its digital twin and the digital process chain for example secured by blockchain technologies. This connection is often mentioned as one fundamental requirement to reach the vision of Industry 4.0, the next industrial revolution [ReMe15]. Additive Manufacturing (AM) as a technology with high relevance in the scope of Industry 4.0 offers the potential to directly produce markings for traceability during the manufacturing process. Even industries that are not focusing on products with critical functionality can benefit from markings for quality management and liability exclusion. The identifiability of products is a valuable outcome. Markings can be understood as a kind of individualization of parts. As individualization does not increase production costs when using AM the only effort results from the integration of markings in the digital product data. [JBK16]

A solution to mark products individually for AM is highly desired by industry. Using usual CAD software tools it is possible to integrate a marking for traceability manually. Doing the same for a whole batch of products that need an individual marking, the effort is not reasonable in relation to the achievable benefits. Therefore a software-driven solution has been developed by Additive Marking, a spin-off of Paderborn University, to allow efficient integration of markings in digital product also for high batch production. [Jahn18-1]

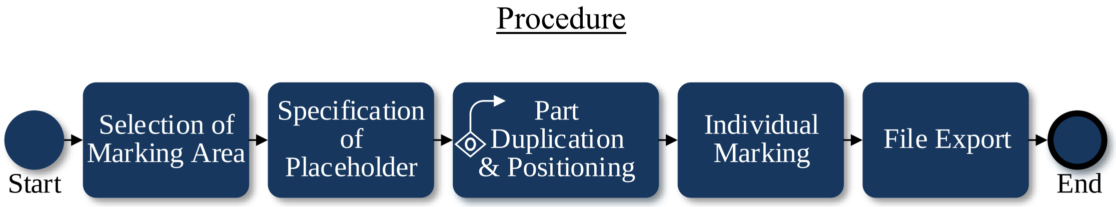

*Figure 8: Procedure of AM Part Marking*

- *Selection of Marking Area*
  As a first step the marking area has to be selected based on design data created during the PDP. The application of product marking to be generated during AM affects the geometry of a part in the specific area. Depending of selected formats "in", "on" or "under" a surface markings can influence the structure. Therefore for loaded structural parts it is recommended to consider the markings and the area already in the early design phase.
- *Specification of Placeholder*
  Based on the selected area, a placeholder / pattern has to be placed on that area specifying dimensions in X, Y and Z direction as well as the format of the marking to be generated. The formats defines how the marking will be readable on the manufactured part. For visible markings "in" or "on" a surface are recommended while "under" a surface is the right option to achieve invisible markings for example for authentication matters. This steps results in an "pre-marked" digital model.
- *Part Duplication & Positioning*
  Digitally "pre-marked" models can be duplicated or even automatically multiplied in a virtual building chamber representing the selected AM system. Thus for example for Polymer Laser Sintering a 3-D and for Selective Laser Melting a 2-D filling algorithm supports the multiplication automatically just requiring the X, Y and Z distances between the parts. Each part inherits the defined pattern so that the marking effort is no longer depending on a batch size.
- *Individual Marking*
  For each single part individual markings can be generated based on the "pre-marked" pattern following specific rules of creation. The content of the marking is only limited by imagination. Alphanumeric or machine readable codes (EAN, QR, Datamatrix etc.) are possible as well as braille or anything that is following definable rules. The position and orientation of each single part defined in the previous step of duplication and positioning can become part of the content as well.
- *File Export*
  Marked parts can be exported out of the software solution as single parts for further preprocessing or just as the whole build chamber that has been filled automatically. The main benefit of this solution is that all parts are already oriented in relation to each other to ease further pre-processing and to support serial production.

### Promising Applications

Promising fields for the application of AM part marking are:

- Marking of spare parts e.g. usually manufactured by injection molding so that the products‘ marking has generated by the mould.
- Test specimen with a need of traceability to its position, orientation and process parameters
- Products for safety critical applications with need to traceability following legal regulations

## Integration of the AM-PDP into Existing Companies

With the development of the AM-PDP an efficient and traceable procedure for the application of AM is intended. To ensure this, an integration methodology has been developed in addition to the process. This provides a four-step approach, whose main component is the merging of the existing business process with the AM-PDP.

### Analysis of the Company's Value-Added Process

In the analysis of the overall process, existing processes must be prepared and described for AM integration, similar to the integration according to ISO 9001 [Fuee14]. Process owners get appointed, a project team is formed and business processes are documented. For AM, two fundamentally important conditions for the success of integration must be considered: When forming the project team and the subsequent documentation, all departments with direct contact to product development as well as future stakeholders planned for AM must be taken into account. Also an expert from the field of AM technologies should be part of the team. By this it can be ensured that employees are willing to accept the integration of the technology. The second important aspect in the actual analysis of the existing processes is the choice of an optimal level of detail. If processes are only documented superficially, optimal connection points in the process may not be correctly selected or even ignored. If the selected level of detail is too high, the documentation and analysis effort becomes unmanageable.

### Definition of PDP Limits

Following the analysis, the existing structures have to be prepared for the integration. This involves the definition of interfaces of the traditional PDP, the isolation of the process from previous and subsequent activities and its removal from the overall process (figure 8). The transition from previous activities to traditional PDP is usually defined by an internal release, but must generally take place before the design phase. The transition to subsequent work steps, on the other hand, is more dependent on existing company structures. If the company has standardized processes for quality assurance in production, the end of the PDP is defined with the changeover to this area. In this case, the adjustment of subsequent process activities only takes place in the last step of the implementation methodology. Without consistent quality management, the individual processes are separated from the remaining steps with the completion of all production and assembly activities. In addition to start and end of the PDP, there are often breaks (e.g. Customer Feedback). Here, the project team has to decide

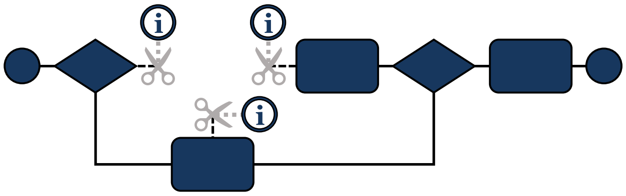

*Figure 9: Overall process with defined product development process limits / source: author*

whether these process changes are related to the specific manufacturing process or are a general procedure in product development. In this case the regarding process steps have to be separated and preserved. To complete the definition of the PDP limits, the resulting open process ends are analyzed and documented with all input and output variables with regard to their process customers and suppliers.

### Unification of the Processes

The combination of the entire process with AM-PDP is the main step in the methodology. For this purpose, the interfaces of the developed AM process are connected to those of the overall process and then the output variables previously documented at the defined process boundary are compared with the input variables of the additive product development. Individual processes whose information are not used within the AM-PDP are adapted or removed. Missing input variables are analyzed and associated activities are integrated into the preceding overall process. If all output and input variables match, the same procedure is performed at the end of the process until a closed information flow is ensured. Finally, the process interruptions must be integrated. Here, too, input and output variables are checked after connection to the AM-PDP and any necessary changes are integrated.

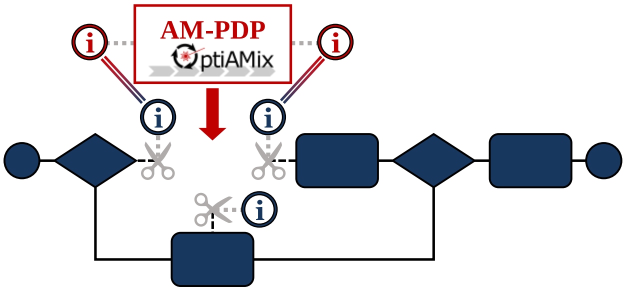

*Figure 10: Integration of the AM-PDP / source: author*

### Consolidation of the Overall Process

AM can not directly replace other manufacturing processes. Not all properties of conventional manufacturing processes can be fulfilled by AM, although various further potentials can be exploited. Accordingly, the simple integration of AM in the PDP is not sufficient. The new overall process has to be analyzed in detail by the project team with regard to further possible applications as well as existing weaknesses. Typical additional application fields are the establishment of AM as an emergency technology, for example in the event of delivery delays for purchased parts. Weaknesses include, for example, supplier management, which has not yet been standardized. The project team must find solutions and take them into account in the overall process. Quality management must also be addressed again at this point. If standard processes are defined in the company, activities anchored in these processes have to be applied or adapted to AM.

## **Application**

The potential of AM-PDP and AM-specific methods could already be demonstrated by a practical example introduced into the project by the DMRC. Although the conventionally manufactured variant of the sample tube station appears unsuitable for AM at first glance, the methodical part screening showed high potential, especially with regard to a possible function integration. The sample station is part of an automated sampling system for biochemical applications, in this case for testing the saturation of a liquid solution. The holder can hold 20 sample vials so that samples can be continuously "drawn" without human intervention. In order to obtain a reliable and representative sample, the supply tube must be emptied from the rest of the previous sample into a sample glass before filling, so that a temporal allocation to the contents of the sample glass is possible. In the conventional design, the sample station consisted of six individual components that were assembled using additional connecting elements. A tank for emptying the residues in the hose was purchased as a further component and loosely connected to the station. Labels for traceability and mutual authentication of the sample station with the sampling system were not given in the initial design. Also the cleaning could not be carried out sufficiently due to the non-optimal shape and the high demands on the biochemical cleanliness.

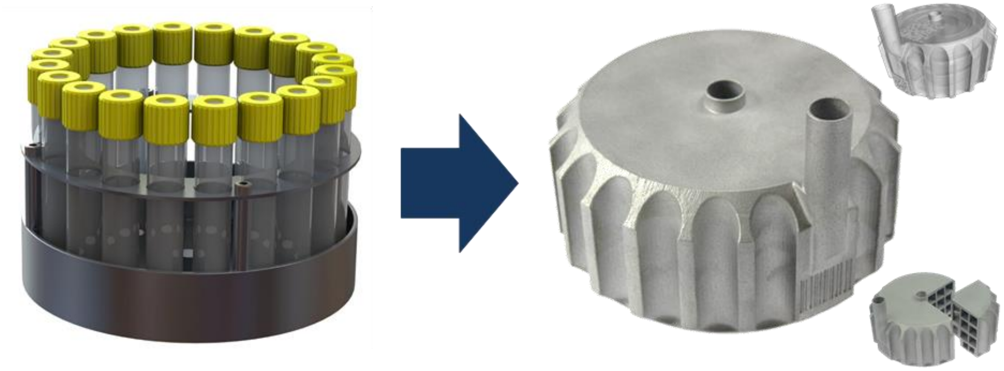

*Figure 11: Practical example of applied methods with sectional view and CT scan / source: author according to [Jahn18-2]*

These weaknesses were eliminated by the integration of a channel for flushing with high water pressure according to AM-specific design rules in the version shown (Figure 11). Thanks to the barcode and embossed DataMatrix codes (CT scan representation in cooperation with GE Digital Solutions), it is now also possible to automatically assign sample tubes to a respective station, which prevents measurement and analysis errors and ensures traceability of the product throughout the entire process.

## Summary and Outlook

With the systematic approach for technology integration and the first evaluation based on the shown sample tube station as validation basis, the desired AM integration into existing companies can be achieved. By relying on reference processes already in use and established standards and guidelines the AM-PDP provides a sound basis as well as the AM-specific methods and the integration methodology for the integration of additive manufacturing in the industrial field. However, the example shown is not sufficient to achieve a general validation of the procedure described. For this, the entire approach must be evaluated, verified and finally validated in the near future on a concrete case of complete AM integration in a company. This will be pursued in the further course of the OptiAMix research project and promoted by the DMRC.

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