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Integrating product function design, production technology optimization and process equipment planning on the example of hybrid additive manufacturing

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Abstract

New technologies can yield high market potential, but also challenge engineering capabilities. For example, additive manufacturing enables unlimited freedom of design and economical production of small batch sizes. However, there are huge challenges: A large variety of new additive technologies, limited choice of materials and mostly high production cost as result of long production time. Since today's production requires an economical implementation, focus needs to be on hybrid production, which combines the advantages of additive and conventional manufacturing technologies. This requires an integrated optimization of the product design, the manufacturing technology chain and the operative equipment.
The following paper presents an approach for this integrated planning approach with the aim of economically feasible hybrid production. In general, the interdependencies between product and manufacturing technology need to be used for optimization in early stages of the product life cycle. To achieve a high customer value, the product requirements have to be analyzed in detail to find an optimal product function, but also to identify degrees of design freedom, which do not influence product function and, thus, can be adapted to optimize production. Moreover, possible changes in the capabilities of manufacturing technologies and, subsequently, operative equipment and machines can be anticipated to further enhance the production. After identifying optimal combinations of product design and manufacturing technology chains, the selection and optimal configuration of the operative equipment is necessary and needs to be validate based on the final product design.
The integration of product design, manufacturing technology optimization and operative process planning enables companies to identify and realize high economic potential early in their value creation process and thus can contribute to improving competitiveness.

Keywords: integration, production planning, product development, product design and production technology optimization

1. Introduction

With shorter product lifecycles and increasing global competition between industrial companies, more cost-effective product development is necessary. To achieve this, a highly iterative interaction between product design and production is required, including the use of digitization. Furthermore, companies must be highly innovative in order to survive in the market. This is supported by the use of new technologies.

Additive manufacturing has established itself as a manufacturing process of the future. The unlimited freedom of design and the high functional integration of product features enable economical manufacturing of individualized products in small batches. These benefits of additive manufacturing come

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with great challenges. The challenges are the high production costs through the long manufacturing time of additive manufacturing processes and the high machine cost, especially for metal part production. [1]

Upcoming additive technologies, such as Wire-Arc-Additive-Manufacturing, are more cost efficient, but have disadvantages due to technological limitations, e.g. higher surface roughness due to the use of filament and internal stress due to concentrated, high heat absorption. Moreover, they are not economically competitive for large-scale production in comparison to conventional casting processes. [2,3]

Therefore, the production time has to be reduced, and the product quality has to be improved in order to establish additive manufacturing technologies [1]. These goals can be achieved by hybrid manufacturing, which is defined as combination of at least two different manufacturing technologies for producing a product [4]. In this paper, hybrid manufacturing focusses on combining conventional and additive technologies. Hybrid production serves as both, a proactive extension of technological capability and reactive elimination of existing weaknesses in technologies by integrating other technologies [4–6].

In order to obtain an economical production which balances the opportunities of new production technologies and improved product function, it is necessary to integrate product development, technology management and operative production planning. Therefore, this paper presents an approach that integrates the product function optimization, the technology planning and the machine and equipment selection in an iterative, digitized process.

2. State of the art

To tap into the potential which is achieved by automating and integrating product design, technology planning and equipment planning, it is necessary to know the state of the art in each of the three domains.

A product function embodies the fulfillment of a product purpose [7]. The current process of designing and optimizing a specific product function is often linked to product testing and product validation. Software, e.g. Finite Element Method (FEM) or Computational Fluid Dynamics (CFD), and hardware, e.g. experiments such as crash tests, are used to deduce the performance of a specific product design [8]. This design is then changed manually and tested again in a manual, iterative process. The respective tools and methods highly dependent on the company, the product specification and norms, if applicable [9]. Digital tools for designing the product, computer aided design (CAD), are common [9]. Only few, product and industry specific approaches exist, which are able to conduct a quantified, automated optimization of a product function [7,10,11]. Topology optimization is one of the furthest developed methods for quantified optimization of a products geometry [1]. Even fewer approaches exist which integrate case specific product function optimization into a quantitative production planning method, as shown in [12].

One of the earliest phases of production planning is interlinked with technology planning. Within technology planning, the possible manufacturing technologies for the production of a product are analyzed, evaluated and selected [13]. Decision-making basis is not a specific machine, but an average about the technologies capability in terms of its functional principle. Capabilities of manufacturing technologies are compared with product requirements to determine technological feasible production alternatives [6]. Technology planning is critical for determining the production cost of a product, because the selected technology is used to produce the entire amount of a specific product and several long term machine and equipment investments are based on this selection [13]. Changing a technology of a product already in series production, results in complex product and equipment changes, especially for basic forming technologies. The main obstacles of technology planning are the interdependencies between manufacturing technologies and uncertainty about the performance of new technologies [13]. There are many approaches focusing on the quantitative technology planning for manufacturing. More recent approaches handle the before mentioned topics of uncertainty management and interdependencies [14,15] as well as focus on specific aspects, for example integrating quality assurance into technology planning [16]. An integration of technology planning and machine and equipment planning, can be found in literature, especially because of the fuzzy distinction between the terms technology, process and machine [12,15,17].

To conduct machine and equipment planning, technology chains or process plans are used as input. In order to obtain a selection of the manufacturing technology in additive manufacturing, equipment dependent process chains are generated and evaluated in advance [18,19]. In detail, alternative process chains are generated whereby additive and conventional production in combination can achieve a better and more cost-effective result. The resulting parameters of the process chains can be used as criteria for machine selection or specify the machine directly [20]. In order to be able to select an efficient machine, usually a multi-criteria evaluation is conducted. Criteria such as cycle time, material costs and tolerances are included in the evaluation [21]. Nonetheless, the examination of technical feasibility regarding machine capability is bound to experiments and test production [21].

As depicted above, there are advancements in each of the three domains. In spite of that, the integrative, quantitative planning of any pair of these three domains is uncommon and highly product specific [12,17,22]. Moreover, to achieve the highest potential, an integration of all three domains is necessary. An approach to orchestrate this integration will be presented in the following chapter.

3. An integrated design and planning model

The integration of product design, technology planning and equipment planning is conducted based on a product function optimization, a product model, production technology models and a respective machine database. Figure 1 depicts the integrated model including its dependencies and the respective sub-chapters, which explain the method in detail.

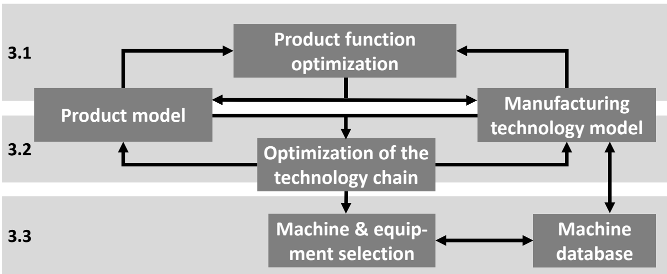

Fig. 1. Integrated planning and design model.

The product function optimization is based on the product model and the relevant manufacturing technology model. Adaptions to the product design and to the manufacturing technology capabilities can be deduced from alternative improved product function values. Similarly, the optimization of technology chains can lead to suggestions for improved product designs or desirable manufacturing technology improvements, from a production point of view, such as production cost or time [6]. The manufacturing technology model is based on a respective machine database, which consecutively is used to select the relevant machines and equipment to detail a technology chain into an operative production sequence. In the following, the three domains of product function optimization, technology chain optimization and the machine and equipment planning are detailed.

3.1 Product function optimization

The calculation of product functions is, until today, not possible in a unified, generic model. As presented in [7] there exist three possible quantitative approaches, which are selected based on the specific product function, financial possibilities and methodological competences in companies:

- Simulation based models, e.g. via Finite Element Method or Computational Fluid Dynamics
- Statistical models, e.g. multiple regression models
- Machine Learning (ML) based approaches, such as Artificial Neuronal Networks or Support Vector Machines

The aim of the presented approach is to take the quantitative result about a product function fulfillment into account, when a product characteristic is adapted. Therefore, the product characteristics are modelled in parameter model, as presented in [6]. According to the object oriented design approach, a method for calculation of a specific product function is implemented in the product model class. To handle all of the three mentioned approaches for quantifying a product function, this method has the ability to automatically run pre-allocated simulation software, regression models or pre-trained ML models with changed product input parameters. The choice of the simulation, regression or ML-based approach depends on the specific product and the respective function. The relevant product parameters are also modelled in the product model class [6]. Within the product function method, the specific kind of product function simulation or model is referred to and the requested product parameters are read from the product model class and sent to the product function method. Figure 2 shows the Unified Modelling Language Class Diagram for the product model class including the product function method.

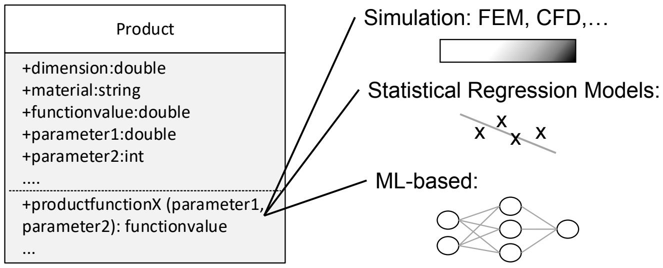

Fig. 2. Integration of product function optimization.

Several product functions can be used for simultaneous analysis by implementing one product function method for each desired product function. The results of all product functions are aggregated by applying a utility value analysis with pre-allocated weights for each individual function. Moreover, criteria for technical failure of product function fulfillment, is taken into account by checking for a specific product function value limit.

The calculated product function value results are compared to desired product function values, to deduce the success of the design adaption or production technology capability, from a product function point of view.

3.2 Product and technology chain optimization

The design of the product, as modelled in the product model, can in parallel be used to allocate and evaluate the optimal production technology.

In [6] a parameter model based optimization approach has been introduced. This approach enables the automated planning, evaluation and optimization of product feature specific technology chains. First, technical feasible technologies are allocated to each product feature. Second, possible technology chains consisting of sub-chains per product feature are designed and evaluated. The evaluation is based on case specific criteria, such as production time, piece cost and specific technical product or technology chain requirements. Based on this evaluation, an optimal technology chain for the product is selected, for which subsequently possible product parameter or technology parameter gaps are identified. This gaps are used as basis for adapting product design and technology model parameter. Consecutively, the adapted product design and technology models are used to generate and evaluate new technology chain alternatives. This new alternatives are compared to the evaluation results of the old technology chains to determine the improvements due to the adaptions.

This is continued by starting the process of adaption, feature-technology-allocation, evaluation and technology chain planning again, forming a recursive, iterative optimization process. The process ends, if by adapting parameters no improvement is possible or if a fixed value of iterations has been reached. Based on the outcome of the optimization, which is the optimal technology chain, the concrete selection of machine and process equipment is started.

3.3 Machine and equipment selection

The selection of machines and equipment consists of three steps. In the first step, the parameters from the previously created technology chain are used to formulate the technical requirements for machines and equipment, which embody the respective technologies in the technology chain. In the second step, a detailed analysis is executed to deduce the technical feasibility of machines and equipment for each technology. The third step consists of a multi-critieria analysis to rank the best machine and equipment for a required technology. The criteria are similar to the technology chain selection criteria as mentioned in chapter 3.2. Figure 3 depicts the overall equipment selection process.

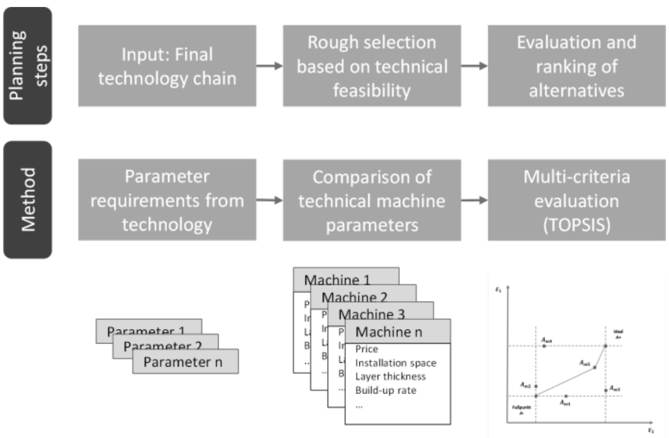

Fig. 3. Equipment selection process.

The first step of the equipment selection process requires the interlinkage of technology and equipment capabilities as depicted in figure 4. An exemplary examination of the technical feasibility of a machine based on their achievable surface roughness is shown. The upper part shows the capability of the technology and the product requirement. In the lower part three different machines are shown, which are the foundation of the overall technology capability.

In the second step, the fulfilment of product requirements through specific equipment and machines is examined. In Figure 4 only one of the three machines shown can meet the product requirements and therefore fulfills the technical requirement to manufacture the product. This procedure is repeated for all parameters of all selected technologies and compares the modelled product requirements and respective machines and equipment.

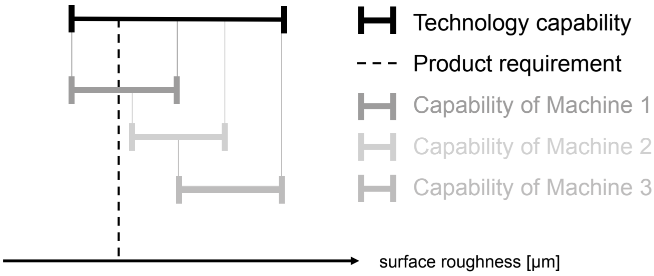

Fig. 4. Matching technology and machine parameters with product requirements.

In the third step, the selection of the possible machines is based not only on technical feasibility, but on a performance evaluation. Similar to the evaluation of technology chains [6], this is conducted by a decision analysis based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Algorithm. Criteria from technology planning, economic parameter as well as case specific criteria on machine level, such as available plant space, are considered. The TOPSIS evaluates the criteria based on a case specific weighting and creates a ranking of the technical feasible machines, which takes all requirements into account. Based on this ranking, the most efficient machine for a specific product and a pre-planned technology is selected.

Eventually, by combining the selected machines and respective equipment for all technologies, which are given in the optimized technology chain, the production sequence for a product is finalized.

4. Exemplary Application

In this chapter, the methodical procedure will be depicted based on a practical example of agricultural machinery of John Deere GmbH & Co. KG, which is part of the research project "KitkAdd - Combination and integration of established technologies with additive manufacturing in one process chain".

The product in this example is a sun gear with shaft, located in an epicyclic gear train in an agricultural machine transmission. This epicyclic gear train is working in an oil bath. The sun gear is designed in two modules: The lower half, the output shaft, and the upper part, the actual sun gear, around which the planet gear is cycling. To improve the oil lubrication, oil canals are designed inside the sun gear. The product schematic is depicted in figure 5.

The beginning of the planning approach is marked by modelling the product and researching the technology data according to [6]. Moreover, in this example the product function for lubrication is modelled based on the centrifugal

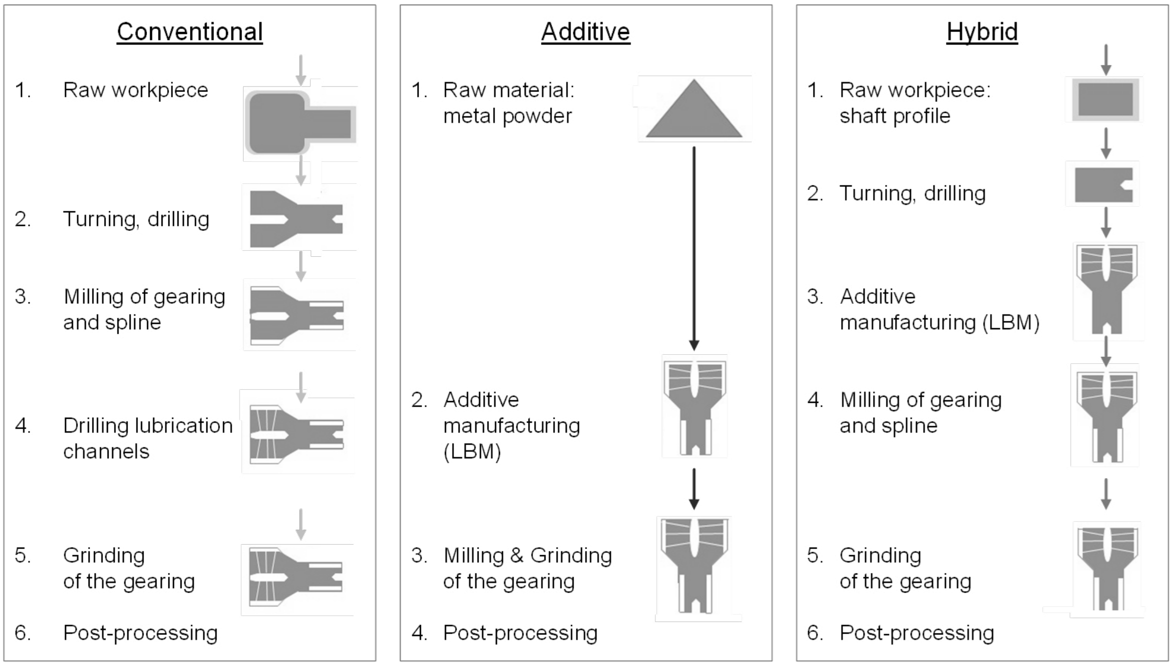

Fig. 5. Product and process chains for sun gear production

force, oil characteristics and geometric characteristics of the oil canals. The product function value for the lubrication is expressed as milliliter per second.

Based on the technology chain optimization, two technical feasible chains are suggested: The first technology chain is based on a Laser Beam Melting (LBM) process to additively manufacture the complete product. The second technology chain is a hybrid process chain which is based on casting and milling the output shaft. The sun gear is printed on top of the milling shaft via Laser Beam Melting. The resulting cost by piece for a production volume of 100.000 gears for the hybrid process chain is 40% cheaper than the LBM technology chain.

Additionally, the technology chain optimization tool shows, by adapting the oil canal geometry, a conventional production of the sun gear with internal oil canals is possible and approximately 90% cheaper than the LBM technology chain. This is achieved by drilling the oil canals in a casting part instead of printing the sun gear. These three process chains and the respective product modules are depicted in Figure 5. The cost estimations have been validated by comparing to dedicated process simulations for each technology chain alternative.

The impact of oil canal geometry adaption for enabling drilling is analyzed via the product function calculation, which is part of the product model. The results show that this product adaption will decrease the lubrication below a minimal threshold in comparison to the printed canal geometry. Thus, the technology chain based on drilling the oil canals is rejected.

Eventually, the most economic, technological feasible alternative is selected: The hybrid technology chain. Consecutively, the chain is detailed in terms of machine and equipment selection.

Based on the information of high number of pieces, an industrial LBM-machine with a high build-up rate, but also a large build chamber is necessary. Alternative LBM machines considered in this example are the FormUP 350, the MetalFAB1 LBM module and the SLM 800. Due to the check of technical feasibility, only those machines are selected which can demonstrate a technical feasibility for the product. For example, a build chamber length of at least 380 mm is required. Due to a Build Chamber of 350x350x350 mm the FormUP 350 is removed from the selection process. Continuing the process, a TOPSYS has been conducted comparing the investment cost, the piece cost, the build chamber volume and the build rate for the MetalFAB1 and the SLM 800. Piece cost has been calculated according to [23]. The considered machine criteria are depicted in table 1.

Table 1. Exemplary machine selection criteria

Machine	Investment cost [€]	Piece Cost [€]	Build chamber [cm³]	Build rate [cm³/h]
SLM 800	2000000	149.48	119000	171
Metal FAB1	1800000	164.68	70560	114
FORMUP 350	775000	142.39	42875	100

In this example, the SLM 800 is more suitable for the sun gear production, as it offers lower piece cost and a sufficient build chamber.

The exemplary application and the respective interlinkage in the integrated planning and design model are summarized and depicted in figure 6. First, two possible technology chains are generated (LBM, hybrid) and an adaption of the canal geometry is suggested to enable a third alternative, drilling the oil canals (1). Following this, the geometry is adapted and the fulfillment of product function is calculated (2). The decrease of the product function value leads to rejecting the adaption of canal geometry (3). Consecutively, the most economic, technological feasible chain is selected (4), which serves as input to analyze and select respective machines and equipment (5). Eventually, the optimal technology chain and the selected, necessary equipment can be used to further detail the planning of the sun gear production.

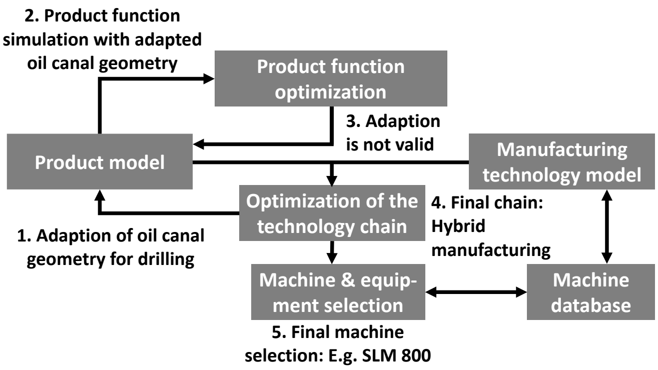

Fig. 6. Overview of the exemplary application.

5. Conclusion

To enhance the competitiveness and the speed of innovation in industrial companies an integration and digitization of product design and production planning is necessary. As shown in this paper, the desired integration of product design optimization, technology planning and machine and equipment selection is currently not applied on a quantitative, automated basis.

To enable this integration, an approach based on product model, manufacturing technology model and machine database is introduced. This is used to optimize the product function as well as the manufacturing technology chain and consecutively the respective machine and equipment. The introduced approach depicts, that this three domains can interact to achieve improved product design and production sequence. An exemplary application regarding a sun gear has been described.

In the future, this approach will be applied further and more detailed results are to be analyzed. Moreover, the integration of CAD and other established design and planning software can be facilitated to increase the industrial use.

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References

[1] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F. Design for additive manufacturing: Trends, opportunities, considerations, and constraints. CIRP Annals 2016;65(2):737–60.

[2] Cunningham CR, Wikshåland S, Xu F, Kemakolam N, Shokrani A, Dhokia V, Newman ST. Cost Modelling and Sensitivity Analysis of Wire and Arc Additive Manufacturing. Procedia Manufacturing 2017;11:650–7.

[3] Gebhardt A, Hötter J-S. Additive manufacturing: 3D printing for prototyping and manufacturing. Munich, Hanser Publishers, Cincinnati: Hanser Publications; 2016.

[4] Zhu Z, Dhokia VG, Nassehi A, Newman ST. A review of hybrid manufacturing processes – state of the art and future perspectives. International Journal of Computer Integrated Manufacturing 2013;26(7):596–615.

[5] Feldmann C, Gorj A. 3D-Druck und Lean Production: Schlanke Produktionssysteme mit additiver Fertigung. Wiesbaden: Springer Gabler; 2017.

[6] Jacob A, Windhuber K, Ranke D, Lanza G. Planning, evaluation and optimization of product design and manufacturing technology chains for new product and production technologies on the example of additive manufacturing. Procedia CIRP 2018;70:108–13.

[7] Wagner R, Haefner B, Lanza G. Function-oriented quality control strategies for high precision products. Procedia CIRP 2018;75:57–62.

[8] Ashby MF, Wanner A, Fleck C, (Eds.). Materials selection in mechanical design: das Original mit Übersetzungshilfen. Heidelberg: Spektrum Akad. Verl.; 2007.

[9] Eversheim W, Schuh G. Integrierte Produkt- und Prozessgestaltung. Berlin: Springer; 2005.

[10] Dantan JY, Qureshi AJ, Antoine JF, Eisenbart B, Blessing L. Management of product characteristics uncertainty based on formal logic and characteristics properties model. CIRP Annals 2013;62(1):147–50.

[11] Oberleiter T, Heling B, Schleich B, Willner K, Wartzack S. Fuzzy sensitivity analysis in the Context of dimensional management. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering 2019;5(1):11008.

[12] Reichler A-K, Gerbers R, Falkenberg P, Türk E, Dietrich F, Vietor T, Dröder K. Incremental Manufacturing: Model-based part design and process planning for Hybrid Manufacturing of multi-material parts. Procedia CIRP 2019;79:107–12.

[13] Schuh G, Klappert S. Technologiemanagement. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011.

[14] Schindler S. Strategische Planung von Technologieketten für die Produktion. München: Utz; 2014.

[15] Stoll J. Bewertung konkurrierender Fertigungsfolgen mittels Kostensimulation und stochastischer Mehrzieloptimierung. Dissertation 2017;Band 202.

[16] Müller J. Integrative Gestaltung von Fertigungsprozess- und Prüffolgen für sicherheitskritische Bauteile. Aachen: Apprimus Wissenschaftsverlag; 2017.

[17] Zaman UKu, Rivette M, Siadat A, Mousavi SM. Integrated product-process design: Material and manufacturing process selection for additive manufacturing using multi-criteria decision making. Robotics and Computer-Integrated Manufacturing 2018;51:169–80.

[18] Kopf R, Gottwald J, Jacob A, Brandt M, Lanza G. Cost-oriented planning of equipment for selective laser melting (SLM) in production lines. CIRP Annals 2018;67(1):471–4.

[19] Thompson MK, Stolfi A, Mischkot M. Process chain modeling and selection in an additive manufacturing context. CIRP Journal of Manufacturing Science and Technology 2016;12:25–34.

[20] Mançanares CG, S. Zancul E de, Cavalcante da Silva J, Cauchick Miguel PA. Additive manufacturing process selection based on parts' selection criteria. The International Journal of Advanced Manufacturing Technology 2015;80(5-8):1007–14.

[21] Roberson DA, Espalin D, Wicker RB. 3D printer selection: A decision-making evaluation and ranking model. Virtual and Physical Prototyping 2013;8(3):201–12.

[22] Schleich B, Anwer N, Mathieu L, Wartzack S. Shaping the digital twin for design and production engineering. CIRP Annals 2017;66(1):141–4.

[23] Kopf R. Kostenorientierte Planung von Fertigungsfolgen additiver Technologien. Düren: Shaker; 2018.