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Planning, Evaluation and Optimization of Product Design and Manufacturing Technology Chains for New Product and Production Technologies on the Example of Additive Manufacturing

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Abstract

New emerging technologies challenge companies to adapt their product design and production processes constantly. This paper presents an approach that enables companies to manage new technologies by optimizing interdependent product design parameters and manufacturing technology chains. A product is modularized and modelled via parameter sets. Manufacturing technologies are described in a similar model. Possible manufacturing technologies for this product are identified and combined to technology chains. Based on a multi-criteria evaluation, critical product and manufacturing technology parameters are identified and the impact of adapting these parameters is quantified, thus enabling recursive optimization of product and manufacturing technology chain. Thereby, companies can manage new product and manufacturing technologies by assessing their implications and future potential.

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Keywords: Production Planning, Product Development, Additive Manufacturing, Product and Technology Chain Architecture

1. Introduction

Through globalization and mega-trends, like sustainability, individualization and knowledge in product and processes, companies are in a global field of tension to be innovative in products and manufacturing processes [1,2]. Products increase in complexity, with higher variety but smaller batch size [3]. Processes must fulfil the production requirements of these product portfolios in a cost efficient and flexible way. To meet customer needs and stakeholders' requirements, companies have to challenge this environment [1] by constantly maintaining and extending their competitive position [4].

Part of the competitive position is a constant and increasing change and development of new technologies [2,4,5]. One field of new technologies, which is disrupting the status quo, is additive manufacturing (AM). Through AM, a product is created layer by layer [6,7], which enables the designer to construct complex structures and rethink products. Additive technologies are established in prototyping and tooling. They have a high potential regarding advantages as near-shape manufacturing, optimal force flow and light-weight [6,9–11]. Yet, additive manufacturing processes are slow and have not reached their highest technology readiness levels [12].

Since technologies are subject to a lifecycle and impact a company's competitiveness increasingly [13], an effective technology management gains in importance [5]. Hence, this paper presents a technology management approach, which includes new technologies, uncertainty and enables the user through recursive iterations, to optimize alternative manufacturing technology chains and product designs.

2. Literature overview

In the last years, there has been an increase in discussion about technology assessment approaches and how to meet challenges in management of new technologies. One field of technology management is the planning of technology chains, which are sequentially linked production technologies. In

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contrast, the term 'process chain' includes defined operational equipment (e.g. machines, resource). [14]

In the field of organizational structure for handling new product and production technologies, Simultaneous Engineering (SE) tries to overcome the problem of independent and long development processes. It merges the timeline of different development steps, which influence each other, and creates an information exchange platform. Thus, SE offers shorter development processes and better outcomes [15]. Furthermore, one tries to adapt successful planning methods from the software-development and IT-field, to make product- and production-system planning more efficient and agile. Characteristics are short feedback cycles and fast testing to achieve an incremental progress [16]. Still, the production environment needs a quantifiable planning base and a deeper integration of the stakeholders [17], for example technology chain planning is not integrated in SE.

To support the development of new products, computer aided process planning is developed (CAPP), as a link between design (CAD) and manufacturing (CAM). The system automatically analyses the designed part, compares it to machine data and suggests processes, which are currently limited to few manufacturing technologies because of its complexity [18]. Current research implements additional machine learning methods for specific problems [19].

As SE and other approaches challenge the organizational structure and the support from information technology (IT), they go along with an early assessment of products and production systems, to identify interdependencies and avoid future inconsistency [20]. But especially at the beginning, there is incomplete knowledge and database about new technologies and their implications [21]. Technology management offers methods to handle interdependencies, uncertainty and the evaluation of technology application by technical and economic aspects [22,23]. An approach by Ashby [24] focuses on firstly determining conditions for material, form and process properties. In further steps non-fitting processes get eliminated and remaining process chains get finally evaluated. In addition to the method, Ashby [25] developed a software tool and a database for materials and processes, to support planning and decision making. Eversheim [26] outlines a similar way, determining tasks, a rough selection of processes, detailing product groups and refining process chains for the defined product groups and conditions. This method underlines dependencies between different products

Klocke et al. [27] suggest a two-step process, by first defining needed functions, secondly evaluating technologies and finally elaborating product design and used technologies. Focusing on required functions, Schuh et al. [28] divide products in modules, which fulfil functions, and merge technologies and modules. Goal is a balance of cost efficiency and part variety.

To find the best process chain, Trommer [29] and Stoll [23] evaluate different sequences of a process chain and the used technologies. Müller [30] extends this approach by focusing on the portfolio of already available technologies in companies.
Putting the product in focus, Kröll [31] evaluates costs, quality, flexibility and the technology readiness level of different alternatives to produce the product. Complexity, uncertainty and dynamic gain in importance hence approaches focus on interdependencies, technology potential and risk [14,23].

All current approaches aim for a smaller range of alternatives and eliminate therefore alternatives, which do not fulfil certain requirements and attributes. Constantly and step-by-step, only technologies and process chains, which fit to the determined requirements and attributes, remain. [14,23]

To evaluate technologies in process chains and display their performance clearly, one uses different indicators. Analytic Hierarchy Process (AHP), TOPSIS or Cost-Utility-Analysis are methods, to structure attributes and define a value. They are enhanced by combining them with other methods like Fuzzy-Logic or statistics [32]. To keep the value and meaning of the indicator on a significant level, one has to keep the indicator in coherence with the analyses [33]. Otherwise an indicator falsifies the chain's evaluation [34]. Furthermore, the created value of such analysis and assessments should be higher than the resulting effort. Thus, an automating is useful [33].

In current approaches, there is a gap in not only including but also holistic optimizing the application of new and developing technologies. Furthermore, there is no or less feedback to the product by constraints and new opportunities. Especially since there is an organisational focus for the product development process on integration and fast feedback, a valid method to receive fast product and production feedback is necessary.

The approach shown in this paper includes iterations between product development and production system assessment by adjusting product or technology chains. The potential of new technologies is optimized through integrating product and production. The iterative process gives a deeper understanding of new technologies, offers advantages in introduction of new technologies and increasing development efficiency, resulting in enhanced competitiveness if applied correctly.

3. Planning method

With respect to the outlined gaps in research, this approach is developed to improve the introduction of new, innovative products and manufacturing technologies. The beginning are modelling of product modules and manufacturing technologies, incorporating uncertainties and interdependencies. Following, the possible technology chains are generated and assessed based on a multi-criteria evaluation. This results in a ranking of alternative technology chains in which an optimal technology chain is determined. The iteration of the optimization process starts with identifying potential on the current product model and the optimal technology chain. Based on this identification the product model and the manufacturing technology model are adapted. By using this adapted models as input data, new technology chains are generated and evaluated. Thus, a new optimal technology chain can be determined, new potential identified and another iteration is started. If a predetermined stop criterion is reached, the optimization stops and a final technology chain is selected. Fig. 1 visualizes the procedure and emphasizes the iterative optimization of product and production technology.

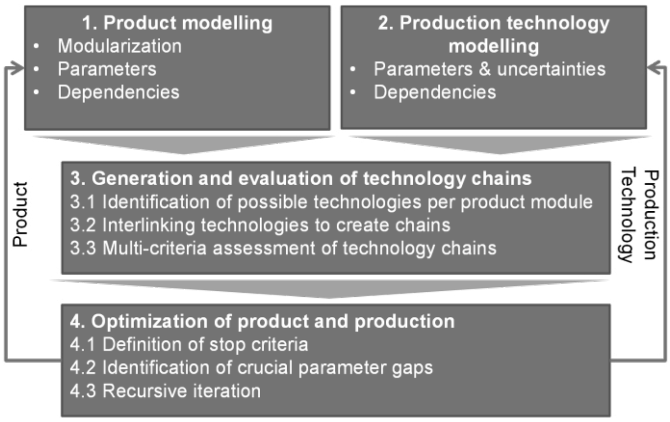

Figure 1: Method overview

The presented approach is limited to product design optimization with fixed product functionality. This is to say: The method only adjusts product model parameters that do not affect the functionality of the product. Instead, it focuses on the optimization of product engineering and manufacturing technologies. Thus, the interdependencies between product design and manufacturing technology are focused on for optimization.

3.1 Product modelling

For modelling the product, a modularization into smaller elements is conducted [29]. This reduction of complexity is necessary to find the best-suited production process [35]. After the decomposition, a description via a characteristic set of parameters, in the following called product module attributes, is carried out based on the production engineering input.

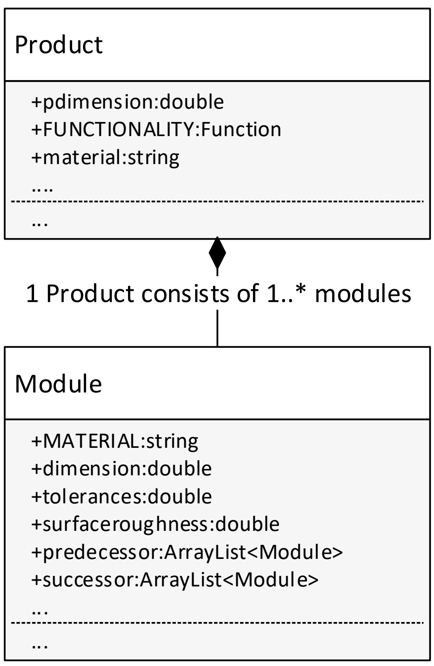

Figure 2: Product and module modelling in UML

When modularizing a product into its modules, the relations between the modules become visible. Dependencies between modules set the frame for planning technology chains. In order to assess the impact of changes, a detailed knowledge of the dependencies is crucial. The components, their relationships and parameters are depicted based on object-oriented programming as shown in figure 2.

The complexity of a parameter modification can be analysed. Büscher et al. 2016 [37] calculate an indicator for evaluating the amount of direct dependencies of a parameter and display them in a correlation matrix. Another important dependency to analyse is the possible order of production which can be analysed in form of binary matrices [14]. This interdependencies are modelled here as a product module specific list of pre- and successor. This implies restrictions to the final process chain, as some product modules need to be processed before or after others.

3.2 Production technology modelling

The increasing amount of manufacturing technologies leads to difficulties when deciding on the best technology for each product element. The expansion through new technologies, such as additive manufacturing, additionally increases complexity and uncertainty. Therefore, similar to the description of products, manufacturing technologies are modelled and characterized via parameter sets, in the following called technology attributes. These include information on, for example, possible materials, achievable geometries and tolerances and process duration estimations. Figure 3 shows an object oriented modelling of technologies.

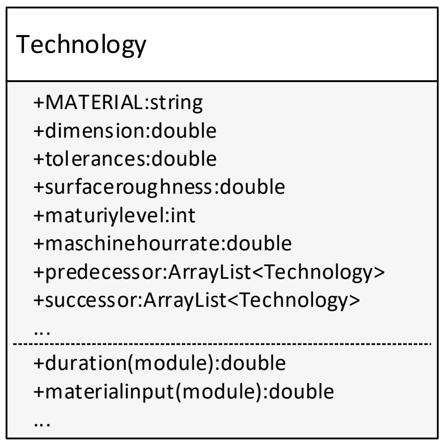

Figure 3: Technology modelling in UML

As the model focuses on the planning in early stages with innovative products and new emerging technologies some of the parameters cannot be known precisely. The model is therefore designed to deal with uncertainties. In cases where a specific range of value is known, a parameter can be described as an interval. Stochastic uncertainties can be modelled via probability distributions [23]. The data acquisition then originates from simulations or measurement of values during production. Unprecise parameters that cannot be quantified directly via a data set, can be transformed to numerical values using fuzzy logic [32].

In a manufacturing process, several technologies are connected and therefore – to a certain degree - interdependent. A particular technology might for example require or eliminate another technology. This knowledge is crucial to select possible process chains. Binary technology relation matrices are used to visualize this kind of interdependencies [14]. This is modelled as technology specific lists of pre- and successors.

3.3 Generation and evaluation of technology chains

With information on the product modules as well as the manufacturing technologies, it is now possible to identify the appropriate technologies. Building on these technologies, technology chains can be generated and evaluated, as presented in [14, 23].

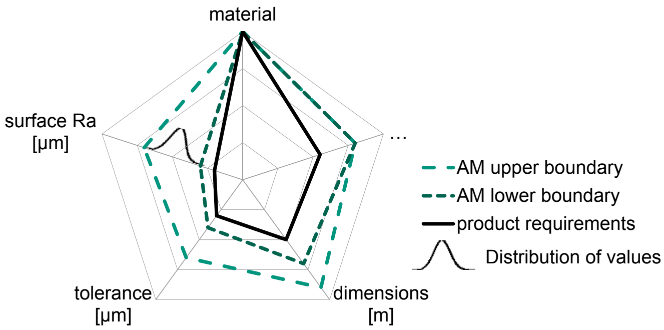

Figure 4: Analysis of product and manufacturing technologies

Figure 4 shows an example of how to assess whether a technology fulfils the requirements of a product module or not. For each required attribute of the product module, the different manufacturing technologies are analysed regarding their requirement fulfilment. Uncertainties about parameters are included into the evaluation in the form of upper and lower boundaries as well as probability distributions. In the example displayed in figure 4, AM fulfils all product requirements.

After identifying all possible manufacturing technologies, they are analysed regarding restrictions due to technology dependencies and production order. The resulting technology chains present all technologically possible process alternatives. An exemplary generation of technology chains is depicted in figure 5.

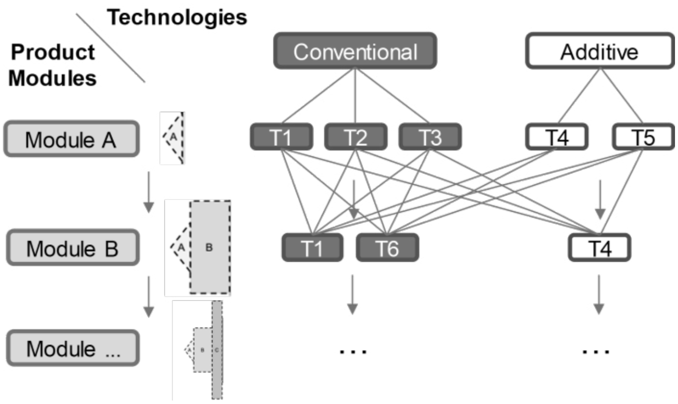

Figure 5. Exemplary generation of technology chains

In the following, the alternatives are evaluated according to predefined criteria. In the case of immature products and production technologies, the manufacturing costs, the technology maturity level and the contained risks are assessed. The manufacturing costs per unit consist of the hourly expenditure of a technology ($MHR_{technology}$), the costs for the personnel ($C_{personnel}$)and the material input (m) [14]. This is shown in formulae (1).

$$C_{unit} = MHR_{technology} \times d_{process} + C_{personnel} \times d_{process} + m \times C_{material} \quad (1)$$

For the calculation, it is necessary to know the duration of a process ($d_{process}$), which is estimated via process time estimation models [14]. The technology readiness level is closely related to the future potential as well as the uncertainties. Peters [38] provides quantifiable indicators for assessing the maturity of a technology, taking into account quality and flexibility.

The assessment yields a justified decision for the best technology chain available as well as a rankling of all alternatives.

3.4 Optimization of product and technology

Based on the selected technology chain, repeated optimizations are carried out in order to further improve product module design, production technologies and technology chains. At this point, a precise definition of the objective is essential. In the present example, the goal is to reduce production costs. Figure 6 depicts the optimization in pseudo code to give a concrete combinatorial approach, based on the overall method presented in figure 1.

In addition, stop criteria and aspiration levels need to be defined in advance (see figure 6, step 4.1). Moreover, the operator can set fixed module or technology attributes, not adjustable in the method, such as product functionality related attributes or material categories. In addition, a company's strategy may implement specific objectives regarding, for example, the introduction of a certain new technology. In case of implementing AM, certain attributes can be set to adjust until an AM technology is included in the technology chain. If an aspiration level is not met, the respective alternative is eliminated from further consideration.

A gap analysis is used to compare the parameters on product side with the related parameters on the technology side, in order to examine which parameter to optimize. For mathematical comparison, all data needs to be transformed to a uniform scale. A ‚zero-one' normalization brings all values to a scale between zero and one and is applicable to deterministic as well as stochastic data [23]. A metric to calculate the parameter gaps can directly be applied to the normalized values. The expected Euclidean distance uses the expected values and is therefore suitable for handling uncertainties. Aspiration levels for parameter gaps can be set. If a predefined gap size is exceeded, the parameter will no longer be considered [23]. The identification of gaps for each module regarding not applicable technologies is conducted in method step 3.1, paralell to the identification of applicable technologies. The respective pseudo code is shown in figure 6.

Subsequently to finding applicable technologies per module, technology chains are generated and evaluated (see chapter 3.3).

```
3. Generation and evaluation of technology chains
  3.1 Identification of possible production technologies for each
  product module and of gaps for not possible production
  technologies
for (all modules){
  for (all technologies){
    If (module.attributes=technology.attributes){
      Save current technology in module.possibletechnology;}
    else if (not(module.attributes module.attribute and
    technology.attrib= technology.attributes)) {
      Calculate distance between module.attribute and
      technology.attributes;
      Normalize distance between module.attribute and
      technology.attributes using specific metric;
      Save distance between module.attribute and
      technology.attributes in module.technology.attributegap;}}}
  3.2 Generation of technology chains
  3.3 Evaluation of technology chains and determination of optimal
  chain
4. Optimization of product and production
  4.1 Definition of stop criterion
  4.2 Identification of potential attribute changes on product
  modules and production technologies
for (all technologies in optimal chain){
  Identify technologies with high cost = identifiedtechnologies;
  Identify module processed by technologies with highest cost =
  identifiedmodules;}
for (all technologies) {
  Identify small values in identifiedmodules.technology.attributegap =
  identifiedattributes;}
for (all identifiedattributes){
  if (identifiedmodules.identifiedattributes can be changed){
    Change the respectives attributes in
    identifiedmodules.identifiedattributes;}
  if(identifiedtechnologies.identifiedattributes can be changed){
    Change the respectives attributes in identifiedtechnologies.
    Identifiedattributes;}
  Use changed identifiedmodules.identifiedattributes as input for
  step 4.3;
  Use changed identifiedtechnologies. identifiedattributes as input
  for step 4.3;}
  4.3 Repeat step 3.1, 3.2 and 3.3 with changed attributes from 4.2
  4.4 Repeat step 4.2 and 4.3 until stop criterion is reached
```

Figure 6: Pseudo code of optimization

The optimal process chain of the initial iteration is analyzed and product modules and technologies with high production cost are identified. For example, manufacturing product modules through AM-technologies, like laser beam melting (LBM), usually result in high manufacturing cost. For the identified crucial technologies and modules relaxations of module or technology attributes are conducted (see figure 6, step 4.2). E.g. requirements for surface roughness are lowered on a specific product module or, based on technology scouting, faster LBM-Machines are available, so that the LBM-process duration becomes faster. More elaborate product design changes, for example changing the dimension of a module consisting of a grid structure, can also be modelled.

Based on the adapted module and technology attributes the generation and evaluation of technology chains is conducted again and yields a new optimal technology chain (see figure 6, step 4.3). E.g. based on the relaxation of surface roughness requirements, LBM-specific post processing steps are not necessary anymore, which reduces cycle times and production cost. Similar improvements are possible for faster LBM-process time attributes. The dimension change of a grid structure module also impacts the duration of the respective AM-technology process duration and therefore the overall cost.

This optimization of module attributes and technology attributes is conducted as long as it is possible to improve the objective, e.g. costs, while all aspiration levels are met (see figure 6, step 4.4.). Also, other optimization goals aside from cost are possible through adapting the evaluation method (see chapter 3.3).

Eventually, product module attributes and technology attributes have been adapted to optimize the interdepend architecture of product design and manufacturing technology chains. Thus, from a holistic perspective, engineering related product design, manufacturing technologies and technology chains have been optimized. As stated earlier, the product functionality is unchanged when respective product module attributes stay unchanged.

4. Application

This method is currently being validated within the research project “KitkAdd” on the introduction of new product and production technologies based on additive manufacturing in combination with conventional manufacturing technologies.

For example, GKN Sinter Metals GmbH investigates gear production based on different manufacturing technologies. Targeted technologies are conventional, post-processing and metal additive manufacturing technologies. The gear is divided in multiple components, and matches each component with one or more manufacturing technologies. Hence there are conventional, additive, and hybrid process-chains, plus post-processing. One product component consists of a grid-like structure and offers new product advantages. In further steps, process-chains and product characteristics are analyzed and optimized regarding dependencies between manufacturing technologies and product components.

5. Summary and outlook

This paper introduces a method enabling the simultaneous improvement of product and production. Iterative modifications of product modules and production technologies optimize the production step by step. A decomposition of the product and the assessment of dependencies within product and manufacturing technologies can be modelled and therefore used for optimization. The possibility of handling uncertain data appropriately enables the usage of this method for technologies with low maturity level. Thus, it is of interest for companies who want to reduce the time-to-market of either new products or new production techniques in early stages of development.

However, limitations exist, that demand further investigations in order to improve this method. The modelling of product element interdependencies is highly case specific and must be brought on a generic level. Moreover, the evaluation and iterative optimization is restricted to only a small number of criteria. Including functional models of products to assess not only production driven design adaptions, but also product function implications are required to reach a new assessment dimension: customer value. Also, automation and combination with existing IT-tools would reduce the effort of this approach.

Nonetheless, by applying this method, companies can efficiently manage new products and new manufacturing technologies by assessing their implications methodically and with less effort. Interdependencies between the product module design and the production technologies are analysed for production optimization. Moreover, technological and economical potential of product design and manufacturing technologies can be identified and quantified.

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