Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 109 (2022) 167–172

www.elsevier.com/locate/procedia

32nd CIRP Design Conference

Product-Production-CoDesign: An Approach on Integrated Product and Production Engineering Across Generations and Life Cycles

Albert Albers[a], Gisela Lanza[b], Monika Klippert[a]*, Louis Schäfer[b], Alex Frey[b], Fynn Hellweg[a], Philip Müller-Welt[a], Moritz Schöck[a], Carmen Krahe[b], Konstantin Nowoseltschenko[a], Simon Rapp[a]

[a]*IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany*
[b]*wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49-721-608-47066; fax: +49-721-608-46051. *E-mail address:* monika.klippert@kit.edu

Abstract

Shorter product life cycles and high product variance nowadays require efficient engineering of products and production systems. Hereby a further challenge is that costs over the entire life cycle of the product and production system are defined early in the process. Existing approaches in literature and practice such as simultaneous engineering and design for manufacturing incorporate aspects of production into product engineering. However, these approaches leave potential for increasing efficiency unused because knowledge from past generations of products, production systems, and business models is not stored and reused in a formalized way and future generations are not considered in the respective current engineering process. This article proposes an approach for integrated product and production engineering across generations and life cycles of products and production systems. This includes the consideration of related business models to successfully establish the products on the market as well as the anticipation of future product and production system characteristics. The presented approach can reduce both development and manufacturing costs as well as time to market and opens the vast technological potential for product design to achieve additional customer benefits. Three case studies elaborate on aspects of the proposed approach and present its benefits.

Keywords: product engineering; product design; production engineering; life cycle engineering; Product-Production-CoDesign; flexibility

1. Introduction

One of the main challenges in product and production engineering is, that costs over the entire life cycle of the product and production system are defined early in the process [1, 2]. Those processes hereby are being run through more frequently. Firstly, customer-specific, individual products lead to a high product variance and shorter product life cycles [3, 4]. In addition, increasing global competition is creating enormous cost and time pressure [5]. This requires efficient development and planning processes relying on agility and standardization as well as flexible and versatile production systems. Secondly, each iteration of the engineering process gets more complex due to the rising variety of systems [6] and new manufacturing technologies. This requires an integration of different domains and a holistic approach to manage the complexity of multidisciplinary engineering processes as well as method and tool support [7]. Existing approaches in literature and practice describe product and production engineering. However, they leave potential for increasing efficiency unused because knowledge from past generations of products, production systems, and business models is not stored and reused in a formalized way and future generations are not considered in the respective current engineering process. Over the last years,

10.1016/j.procir.2022.05.231

promising progress has been made especially in the domains of data collection via connected sensors, data processing due to available hardware, and data analysis using Artificial Intelligence (AI). This high availability of information leaves the potential for its systematic usage throughout the whole product engineering process. To exploit this potential, the article proposes Product-Production-CoDesign (PPCD) as an approach for integrated product and production engineering across generations and life cycles of products and production systems. This includes the consideration of related business models as well as the anticipation of future product and production system characteristics.

2. Aim of Research and Methodology

As described above there are several motivators for integrated product and production engineering. The aim of this research is to define an overall approach and demonstrate its advantages. This leads to the following research questions:

1. How is the integrated product and production engineering described in the current state of research and what is missing to cope with today's demands? (Sec. 3)
2. How can the integrated product and production engineering across generations and life cycles of products and production systems be defined? (Sec. 4.1)
3. How can aspects of PPCD be realized, and which contribution do they provide in practice? (Sec. 4.2)

To answer these questions, the article's methodology includes a literature study analyzing the current state of research (RQ1), followed by the definition of a target state to synthesize PPCD as an approach to close the observable gap (RQ2). Lastly, three case studies exemplarily show how to cope with some of today's demands and validate certain benefits of PPCD (RQ3). In all three cases, the authors of this paper have direct access to research projects or activities.

3. State of Research

3.1. Approaches to Integrated Product and Production Systems Engineering

In literature, several approaches describe the development of products, production systems and their connections. For example, VDI2206 [8] describes the necessity of an integration of product and production system development. This approach shows how products and production systems can be developed simultaneously, while restrictions of the production system are considered in the development of new products. The approach of Integrated Product Development [7] goes beyond this and takes a consistent view of the entire product life cycle. This leads to an increased consideration of the interaction between product and process. This implies that the product developer must have internalized a holistic way of thinking, through which he is not only fixed on the product to be created, but also pays attention to the processes required for its creation, maintenance, and destruction. The goal is to create the best possible product while ensuring the best possible production, use, and disposal [1]. To enable this integrated view, interdisciplinary cooperation and simultaneous work of product, production, and sales development are required for the entire product life cycle [1, 3]. Approaches such as simultaneous or concurrent engineering and co-design describe this type of collaboration and are therefore considered more in detail in the following Sec. 3.2.

3.2. Approaches of Parallelized and Interdisciplinary Collaboration

The concepts of simultaneous engineering and concurrent engineering, developed in the 1980s, are conceptually closely related [9] and aim to achieve cost savings and market advantages, through a shorter development time of products [10]. Principles of simultaneous engineering as well as concurrent engineering are the simultaneity of design and planning processes and collaboration in cross-functional teams from the early phase of the product development process [9]. They have a high penetration level in the industry, however, the concepts themselves are to be understood as a way of thinking and not as a holistic method [10]. For example one method to integrate product and production engineering is the approach of Jacob et al. [11]. Herein, the parametrized requirements of a product are compared with the abilities of potential manufacturing technologies. An optimal match is determined by iteratively adapting products and manufacturing technologies and utilizing the degrees of freedom on both sides. Further methods used for concurrent engineering are e.g. set-based concurrent engineering [12] and the design structure matrix method [13] to name only a few. A comprehensive review was done by Addo-Tenkorang [14]. Even though those approaches describe the integrated development of products and production systems, they do not consider this integration across generations and life cycles of products and production systems. The following section, therefore, addresses generation-based product engineering.

3.3. PGE – Product Generation Engineering

Products are developed in generations, which has already been shown in several studies [15, 16]. Knowledge, which is gained from previous engineering projects, is reused to develop new products or at least serves as a starting point for the further development of existing products [17]. This is described in the model of PGE – Product Generation Engineering according to Albers [17], which serves as a basis to develop suitable methods, processes, and tools for the development of product generations. The model of PGE is based on two basic hypotheses [17].

1) Every product development is based on already existing subsystem solutions or concepts. These can be, for example,

the company's predecessor generations, products from other product lines, products of competitors, or technical systems, which are created based on research projects [15, 1]. These subsystem solutions or concepts are described as elements of a reference system [19].

2) The synthesis of a new product generation is based on reference system elements (RSE) and takes place via three variation operators [17, 20]. The *Carryover Variation* (CV) describes the transfer of existing solutions from RSE system elements to the new product generation. Adaptations at the interfaces are made according to the requirements of the system integration. The *Attribute Variation* (AV) describes the development of functional units by changing the function-determining attributes maintaining the solution principle (compared to the RSE). The *Principle Variation* (PV) describes the development of specific functional units using a new solution principle (compared to the RSE).

They make it possible to steer the development process purposefully and to take over only those references, which represent a suitable basis for the development of a new product generation. Both the variation type and characteristics of the RSE used, e.g., its organizational origin, have an influence on costs and risks in the development of a new subsystem [18].

3.4. Research Gap

To answer RQ 1, previous sections described existing approaches in the field of integrated product and production engineering. Fig. 1 compares different approaches regarding today's demands coming from e.g., shorter product lifecycles, higher product variance, or increasing system complexity (see Sec. 1). It shows an extract of approaches but does not represent the totality of publications that we considered. Nevertheless, it becomes clear that those approaches only partially fulfill the

Consideration of ...	Product and Production System Development	the entire Product Lifecycle	previous Product Generations and/ or Production Systems	future Product Generations and/ or Production Systems	corresponding Business Models
Concurrent/ Simultaneous Engineering [9]	●	◑	○	○	◑
Iterative product and production optimization [11]	●	○	○	○	○
Integrated Product Development [7]	●	●	○	○	◑
iPeM - integrated Product engineering Model [21]	●	●	●	◑	◑
PGE - Product Generation Engineering [18]	◑	○	●	◑	◑
Three-Cycle-Model [22]	●	○	◑	◑	●
VDI 5200 [23]	○	○	◑	◑	○

● fully considered ◑ partially considered ○ not considered

Fig. 1. Evaluation of related work

criteria given in Fig. 1 and, therefore, leave the potential for increasing efficiency in product and production engineering unused. To deal with all demands equally and holistically, the following section describes a target state which, in the opinion of the authors, cannot yet be observed across the board today.

4. Product-Production-CoDesign

To close the research gap, it is necessary to manage the complexity of multidisciplinary engineering tasks, while at the same time integrating product and production engineering. The effectiveness of product engineering needs to be improved by supporting product and production system engineers to act based on existing knowledge as well as with a particular foresight. Therefore, new methods and tools need to be developed which can be adapted according to the situation and needs. To achieve this target state and to answer RQ2 the PPCD is presented as a new approach:

Product-Production-CoDesign describes the highly collaborative and parallelized activity, i.e., the iterative planning, development, and realization of products and the associated production system up to the efficient and effective operation of production and the development of associated business models as well as the systematic decommissioning of products and production systems. In this context, planning necessarily needs to consider several product generations and the corresponding production system evolutions.

CoDesign hereby referes to collaborative design [9]. PPCD captures the Product, Production System, and Market over successive product generations, the corresponding evolving production system, and customer requirements (see Fig. 2). As products are developed in generations (I) and the evolution of production systems must be considered integrated, adequate methods and tools are needed to support systematic reuse of product and production system-related knowledge and their interdependencies (II) (see Sec. 3.3). Here, the consideration of not only one but all preceding product generations and production systems is crucial. To consequently use this knowledge in engineering activities, it must be adequately formalized. Therefore, it is necessary to formalize explicit knowledge and externalize implicit knowledge during the engineering process (III). At the same time, it is crucial to orient product and production planning towards market requirements and always develop suitable business models (IV). As customer requirements change over time, processes, methods and tools need to support identifying suitable, customer-oriented products and production systems to cope with increasing market volatility (V). By the development of a product and the related production system not only the options to fulfil current but also future customer requirements need to be determined (VI). It is key that flexibility and limitations of products and production systems are defined consistently so that the foreseen adaptations of the product – as far as it is possible – are to be realized by adaptations of the corresponding production system.

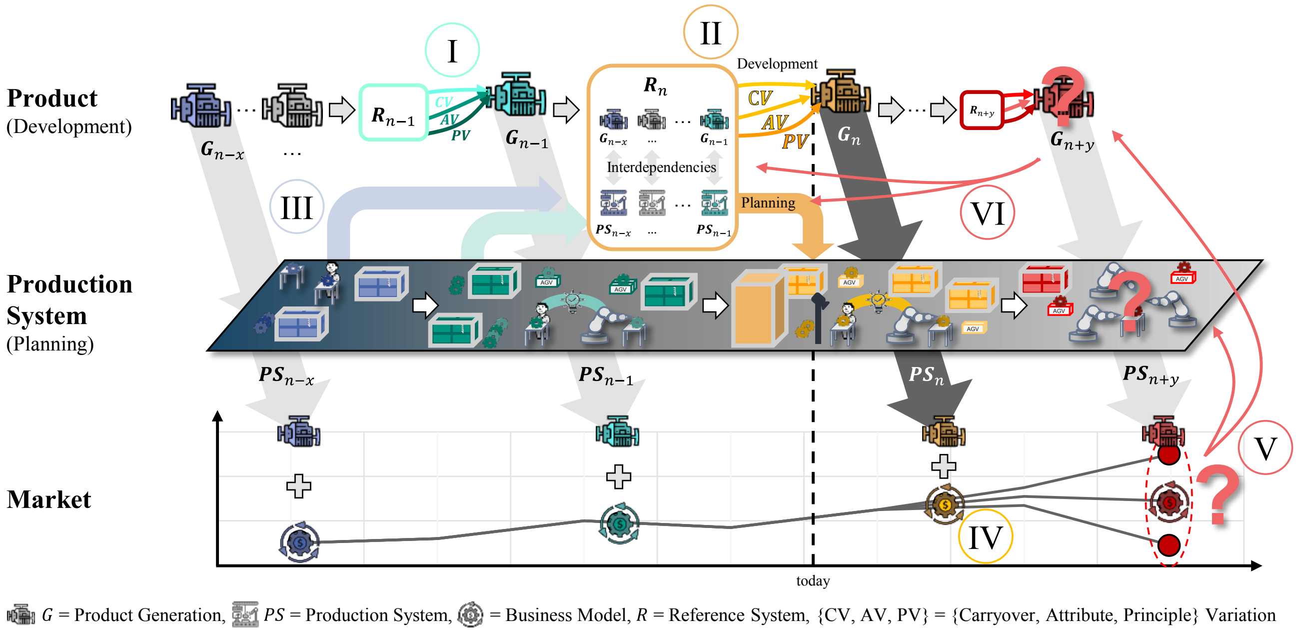

Fig. 2. Visualization of six aspects of Product-Production-CoDesign (PPCD)

5. Case Studies

To answer RQ3, three case studies will be presented in the following subsections to show how aspects of PPCD can be realized, and which contribution they provide in practice. The case studies again emphasize that PPCD is not an applicable step-by-step process but an approach, which describes core aspects of an integrated product and production engineering (I-VI) from Sec. 4.

5.1. Method and Tool Support: Model-Based Systems Engineering

A key aspect of today's engineering is to deal with the increasing system complexity, which demands for the development of new methods and tools for continuous and integrative user support. Especially the interface between product development and production planning presents challenging tasks in the context of complex systems. Here, a shift from document-based to Model-Based Systems Engineering (MBSE) proposes adequate method and tool support in development and planning. Therefore, this case study proposes to derive turnkey production systems based on a product modeled in MBSE. The holistic method consists of three steps: automatic feature extraction from the product to build, turnkey configuration, and builder. A mock-up website shows the interactive approach from uploading product data to the generation and visualization of the corresponding production system prototype including animated production processes [24]. This example emphasizes the importance of modeling interdependencies between product features and the corresponding specifications of the production system (aspect II). Here, MBSE introduces a way to link functions, components, and features of the product as well as manufacturing and assembly processes, machines, and their relations in production [25]. As a result, production system elements can be directly derived from extracted product features [24, 25]. The consistency of modeled information using MBSE helps handle system complexity.

This method supports developers and planners in several other ways, too. A holistic model allows the analysis of changes and their impact on the system as well as the identification of solution patterns [26]. The former provides for the identification of possible changes and their clustering (e.g., external vs. internal changes influencing the considered system). Based on specific changes, holistic, cross-system impact analysis can be executed [25, 26]. The determination of the scope of a change as well as the influence on the corresponding subsystems is of vital importance. The method enables traceability between different elements and the analysis of relevant information in the development of products and production systems [27]. This allows the impact analysis of a process change on features as well as the evaluation of solution alternatives to realize specific product functions. The latter especially tackles shorter product lifecycles and higher product variances, which call for a formalization of implicit solution knowledge for repetitive tasks (aspect III). In this context, the standardized parametric system description with MBSE allows for documenting solution patterns in the development and planning of systems. Here, a solution pattern describes, for example, the relationship between product properties such as shape, form or material and properties of the production system such as layout, technology or capability [26]. Ultimately, a selection and combination of solution patterns can lead to higher efficiency in repetitive development and planning tasks.

5.2. AI-Assisted Design – Machine Learning for Automated Knowledge Extraction from Existing Product Models

In the course of digitization, many companies already have a large amount of data, e.g. in the form of product models developed in successive product generations (aspect I). This data represents a large knowledge base, most of which is implicit experience of design engineers. Implicit knowledge is understood to mean, e.g., knowledge about the relationship between embodiment design and product functionalities, manufacturability or economic efficiency [28], but also, knowledge about the existence of certain components that can be reused. One reason this knowledge base is not yet systematically used is, that a large part of the knowledge is implicit and therefore difficult to formalize. This problem is an active area of research and offers a promising application of Machine Learning, especially Deep Learning. The goal of this case study is to use existing Deep Learning techniques to extract implicit knowledge in the form of features and patterns from existing product models, to formalize it and thus make it usable (aspect III). The considered use case examines data from CAD models in the area of mechanical engineering. The extracted knowledge is then fed into a design assistant system that indicates the designer to existing, already very similar designs in early phases of engineering.

Therefore, the design assistant guides the design engineer through the design process based on learned design patterns [28] by suggesting proven next design steps in the form of design features. This supports the design engineer in quickly generating a first rough design. For the current design status, similar designs are then indicated based on specific (geometric) properties learned from the training data set. This ensures the sustainable use of existing knowledge from product models in the sense of reuse or only minor adaptation. In addition, production-relevant product properties (e.g., dimensions) from the very similar models can be used to evaluate the current model regarding manufacturability. By incorporating implicit knowledge from previous generations at an early stage, production-relevant aspects are also considered in the early stages of product engineering and thus PPCD is encouraged. By focusing on proven solutions, risks, for example, on functionality and manufacturability, can be reduced and expensive changes can be avoided.

5.3. New and Iterative Product Design Opportunities driven by new Flexibilities in Production Systems

Using current and potential possibilities and knowledge in production to enable new product fdesigns is a key area of research. Therefore, the goal of this case study is to use new concepts of production systems to enable flexibility in production processes independent of standardized or specialized production machines. For example, current production systems for battery cells are not capable of producing different formats on one production line, to satisfy potential design changes in upcoming product generations. They produce standardized cells, which are not specifically adapted to customer requirements. This is only possible with a newly developed flexible production system [29]. This enables new battery system designs by cell geometry adaption or combination of different cells to meet individual product requirements as well as technology changes in the future (aspect V). Machining processes represent another example where the combined use of kinematic robots allows new and flexible processes to be carried out, e.g. with increased process forces or different product-specific sizes and angles, which is not possible with a specialized production machine [30]. Since the view of product engineers is limited to already known production possibilities, production potentials are often not considered in the development of new products and product generations [31].

Given the challenges mentioned above, PPCD provides specific guidance to enable holistic and overarching collaboration between product engineers and production system engineers. Thus, it provides specific benefits for companies and their customers incorporating these values. In this case study, PPCD provided an integrated view on product design and production system culminating in four success factors [31]: Firstly, the increased flexibility of the production system makes it possible to account for future changes in customer specifications with less effort (aspect VI). Secondly, Low-volume production lots driven by the increased flexibility can drive customer-specific designs through the implementation of key PPCD principles. Thirdly, new opportunities in product design are enabled by new possibilities and technologies of the production system. Fourthly, the synergetic potential of agility in product engineering and flexible production systems leveraged by PPCD could enhance the satisfaction of customer needs in terms of shorter time-to-market, faster prototyping, and an iterative approach to product design solutions. Lastly, the degrees of freedom of the product and the production system are utilized to reach a global optimum [11].

6. Summary and Outlook

This article proposes an approach to describe the integrated product and production engineering across generations and life cycles of products and production systems. In doing so, the article emphasizes the analysis of the current state of research concluding several approaches only partially addressing today's demands arising from shorter product lifecycles and high product variance. Based on these findings, the authors define PPCD and visualize the interdependencies of products and their corresponding production systems as well as business models. Then, three case studies exemplary demonstrate the realization of selected aspects of PPCD and their benefits including: firstly, the necessity of method and tool support at the interface between product and production engineering addressed by modelling interdependencies between product features and production processes. Secondly, the shortening of development times using a design assistant, which formalizes knowledge from past product engineering processes. Finally, the flexibilization of a production system and the use of innovative technologies enable new opportunities in product design and production planning while increasing adaptation to current as well as future customer requirements.

In the following research, elements of PPCD will be applied to develop specific recommended actions in product design based on the flexibilization of a production system. Among others, it is necessary to analyze, which knowledge and how this knowledge is transferred between product and production engineering in order to optimize the processes. Since new production technologies result in an increase in the variety of design solutions, it will also be investigated, how knowledge from existing products and production systems can automatically be included in the design of future products and production systems. Additionally, new methods and tools will be developed, which support engineers in the synthesis and evaluation of new product designs. From this, it is also possible to automatically derive operation sequences from product data using interdependencies of past and future product features and manufacturing and assembly machines.

References

[1] Ehrlenspiel K, Meerkamm H. Integrierte Produktentwicklung – Denkabläufe, Methodeneinsatz, Zusammenarbeit. Carl Hanser Verlag; 2017.

[2] VDI 2235: Economical decisions during design engineering process; methods and equipment. Beuth-Verlag, Berlin; 1987.

[3] VDI 2221: Design of technical products and systems – Model of product design. Beuth-Verlag, Düsseldorf; 2019.

[4] Westkämper E, Löffler C. Strategien der Produktion – Technologien, Konzepte und Wege in die Praxis. Springer; 2016.

[5] Fleischer B. Methodisches Konstruieren in Ausbildung und Beruf. Springer, Wiesbaden; 2019.

[6] Albers A, Peglow N, Powelske J, et al. Coping with Complex Systems-of-Systems in the Context of PGE – Product Generation Engineering. Procedia CIRP; 2018.

[7] Lindemann U, Lorenz M. Uncertainty handling in integrated product development. In DS 48: Proceedings DESIGN 2008, the 10th International Design Conference, Dubrovnik, Croatia; 2008. pp. 175-182.

[8] VDI/ VDE 2206: Development of mechatronic and cyber-physical systems. Beuth-Verlag, Düsseldorf; 2021.

[9] Putnik G, Putnik Z. Defining Sequential Engineering (SeqE), Simultaneous engineering (SE), Concurrent Engineering (CE) and Collaborative Engineering (ColE): On similarities and differences. Procedia CIRP; 2019. 84, pp. 68-75.

[10] Stjepandić J, Wognum N, Verhagen W. Concurrent Engineering in the 21st Century– Foundations, Developments and Challenges. Springer; 2015.

[11] Jacob A, Windhuber K, Ranke D, et al. 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, pp. 108-113.

[12] Levandowski C, Raudberget D, Johannesson H. Set-based concurrent engineering for early phases in platform development. In Moving Integrated Product Development to Service Clouds in the Global Economy. IOS Press; 2014. pp. 564-576.

[13] Yassine A, Braha D. Complex concurrent engineering and the design structure matrix method. Concurrent Engineering, 11(3); 2003. pp. 165-176.

[14] Addo-Tenkorang R. Concurrent Engineering (CE): a review literature report. In Proceedings of the World Congress on Engineering and Computer Science Vol. 2; October 2011. pp. 19-21.

[15] Albers A, Bursac N, Rapp S. PGE-Product Generation Engineering-Case-study of the Dual Mass Flywheel. In: DS 84: Proceedings of the DESIGN, 14th International Design Conference; 2016. pp. 791-800.

[16] Albers A. Wintergerst E. The Contact and Channel Approach (C&C²-A): relating a system's physical structure to its functionality. In: A. Chakrabarti und L.T.M. Blessing. An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Exploration. London: Springer; 2014.

[17] Albers A, Bursac N, Wintergerst E. Product generation development–importance and challenges from a design research perspective. New Developments in Mechanics and Mechanical Engineering: proceedings of the International Conference on Mechanical Engineering; 2015. pp. 16-21.

[18] Albers A, Haug F, Heitger N, et al. Produktgenerationsentwicklung Praxisbedarf und Fallbeispiel in der automobilen Produktentwicklung. In: Symposium für Vorausschau und Technologieplanung (SVT); 2016.

[19] Albers A, Rapp S, Spadinger M, et al. The Reference System in the Model of PGE: Proposing a Generalized Description of Reference Products and their Interrelations. In: Proceedings of the Design Society: International Conference on Engineering Design; 2019. pp. 1693-1702.

[20] Pfaff F, Rapp S, Albers A. Modeling and Visualizing Knowledge on the Reference System and Variations based on the Model of PGE – Product Generation Engineering for Decision Support. Proceedings of the Design Society; 2021. pp. 2167-2176.

[21] Albers A, Reiss N, Bursac N, et al. The integrated Product engineering Model (iPeM) in context of the product generation engineering. CIRP Design Conference; 2016.

[22] Gausemeier J, Plass C. Zukunftsorientierte Unternehmensgestaltung – Strategien, Geschäftsprozesse und IT-Systeme für die Produktion von morgen. Hanser; 2014.

[23] VDI 5200: Fabrikplanung– Planungsvorgehen. Beuth-Verlag, Düsseldorf; 2011.

[24] Gönnheimer P, Kimmig A, Mandel C, et al. Methodical approach for the development of a platform for the configuration and operation of turnkey production systems. Procedia CIRP; 2019. pp. 880-885.

[25] Albers A, Stürmlinger T, Mandel C, et al. Identification of potentials in the context of Design for Industry 4.0 and modelling of interdependencies between product and production processes. Procedia CIRP; 2019. pp. 100-105.

[26] Schäfer L, Burkhardt L, Kuhnle A, et al. Integriertes Produkt-Produktions-Codesign/Integrated product-production codesign. In: wt Werkstattstechnik online 04; 2021. pp. 201-205.

[27] Mandel C, Stürmlinger T, Yue C, et al. Model-Based Systems Engineering Approaches for the integrated development of product and production systems in the context of Industry 4.0. In: IEEE International Systems Conference (SysCon); 2020.

[28] Krahe C, Kalaidov M, Doellken M, et al. AI-Based knowledge extraction for automatic design proposals using design-related patterns. In: Procedia CIRP 100 (3); 2021. pp. 397-402.

[29] Ruhland J, Storz T, Kößler F, et al. Development of a Parallel Product-Production Co-design for an Agile Battery Cell Production System. In: Proceedings of the Changeable, Agile, Reconfigurable and Virtual Production Conference and the World Mass Customization & Personalization Conference; 2021. pp. 96-104.

[30] Mühlbeier E, Oexle F, Gönnheimer P, et al. Wertstromkinematik – Produktionssysteme neu gedacht: Interdisziplinäres Forscherteam arbeitet an der Produktionstechnik der Zukunft (Teil 1). Zeitschrift für wirtschaftlichen Fabrikbetrieb; 2021. 116(11). pp. 847-851.

[31] Schoeck M, Kimmig A, Mühlbeier E, et al. Wertstromkinematik-Produktionssysteme neu gedacht: Interdisziplinäres Forscherteam arbeitet an der Produktionstechnik der Zukunft (Teil 2). Zeitschrift für wirtschaftlichen Fabrikbetrieb; 2021. p. 116 (12).