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Towards Product-Production-CoDesign for the Production of the Future

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Abstract

The individualization of customer demand combined with increased customer requirements is leading to more complex and diverse products with an increasing frequency of product development. As a consequence, manufacturing companies must maximize efficiency in the design and planning of products and production systems. Here, Product-Production-CoDesign (PPCD) describes an approach to integrated product and production engineering across generations and life cycles. In today's world of global pandemics, volatile markets and supply chain turbulences as well as a shortage in material supply and skilled workers, global manufacturing must adapt and an integrative PPCD is becoming increasingly important. Against this background, this article aims at contributing to addressing these challenges by describing a production of the future based on the principles of PPCD. To that end, a vision of the production of the future is illustrated as a target state. Then, the tools and methods of PPCD are fleshed out to describe how to achieve this target state and overcome potential obstacles during product and production design. Finally, several case studies are presented to show how aspects of PPCD can be implemented step by step to move real-world manufacturing towards the production of the future.

Keywords: Product-Production-CoDesign; Product Engineering; Production System Planning

1. Introduction

Nowadays, high product variance and shorter product life cycles increase the frequency of product and production system development and planning [23]. In addition, shorter time-to-market and individual products require maximum efficiency of product development and production planning processes. To cope with the increasing system variety and complexity, new methods and tools are necessary. [26] Here, a holistic view and the integration of different domains to manage multidisciplinary engineering processes hold great potential. Thus, Albers et al. propose *Product-Production-CoDesign* (PPCD) as an holistic approach for integrated product and production engineering [3], that extends well beyond existing concepts such as concurrent product development, design for manufacturing or simultaneous engineering in particular by incorporating past and future product generations and the entire life cycle of both the product and production. This article further develops this concept focusing on how PPCD enables the production of the future and presents relevant case studies that can help guiding future research in PPCD. Sec. 2 provides an overview of relevant fields of action and literature. A process model covering key aspects of PPCD is proposed in Sec. 3. Sec. 4 gives a detailed vision of the production of the future and Sec. 5 guides moving towards this vision with several case studies. Sec. 6 includes a summary and outlook.

2. Fields of Action

There are existing approaches that deal with the integration of product and production engineering. One sub-area of those deal with integrated product and production systems engineering. For example, VDI 2206 [32] describes the necessity of an integrated view of product and production system development, whereby boundary conditions from the production system are taken into account in the development of new products. A further area is formed by approaches for synchronous and interdisciplinary collaboration. This includes concepts such as simultaneous engineering or concurrent engineering [25], with the idea to simultaneously design and plan processes as well as collaborating in cross-functional teams from an early phase in product development. In addition, there are description models for actual product development, such as the model of Product Gen-

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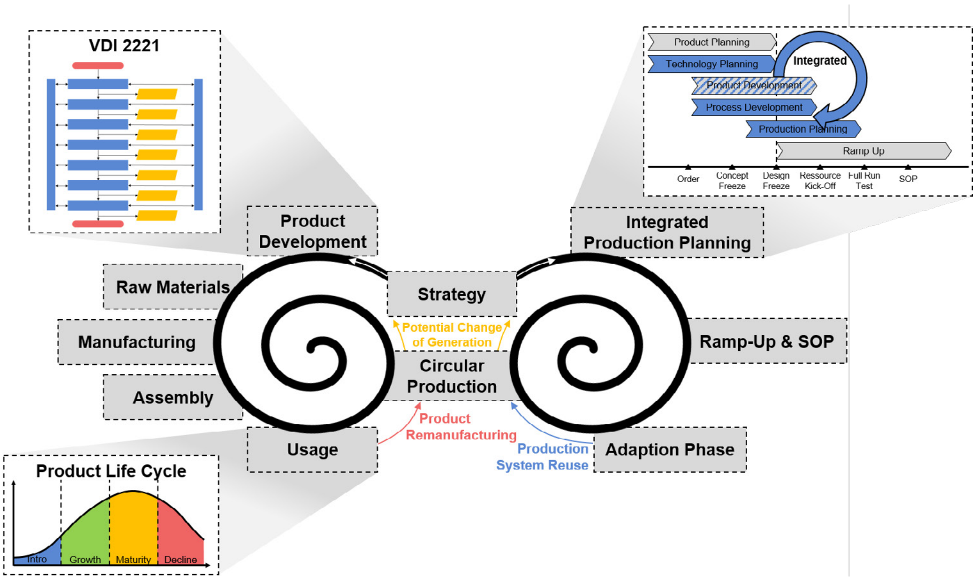

Fig. 1. PPCD Dual Spiral process model covering key aspects of Product-Production-CoDesign.

eration Engineering according to [2]. The basic idea is that the development of a new product generation is based on preceding product generations and therefore existing knowledge and solutions are reused. However, existing approaches leave potentials for increasing efficiency in product and production engineering resulting from digitalisation unused. Furthermore, future generations of products, production systems and business models are not systematically taken into account [3]. For this reason, ALBERS ET AL. introduce the holistic approach of so-called *Product-Production-CoDesign* (PPCD), which can be used to manage the complexity of a multidisciplinary engineering process [3]. The core of this approach is that by using existing knowledge from the past product generations as well as anticipating future products and corresponding production systems, the efficiency of engineering can be increased. Appropriate methods and tools are necessary for its implementation. In [3] six core aspects of PPCD are pointed out, whose realization is illustrated on the basis of exemplary case studies. To implement PPCD on the production side, a flexible and adaptable production system is necessary. However, there is no concretization of the aspects that such a production systems must embody and which methods and tools are necessary for this. In the context of this paper, therefore, the aim is to detail the approach of PPCD introduced in [3] for the production of the future and its entanglement with product design in the context of PPCD.

3. Product-Production-CoDesign

Product-Production-CoDesign (PPCD) describes a high-level approach for the integrated product and production engineering across generations and life cycles of products and production systems [3]. This section aims at further developing this concept by proposing a process model for continuous PPCD consisting of different phases and activities implementing specific aspects of PPCD. Sec. 3.1 visualizes the model and highlights, how key elements of PPCD from [3] are met. Sec. 3.2 gives a more detailed description of the model and its components.

3.1. Holistic Approach

According to [3], the formal definition of PPCD consists of three key elements:

(1) Consideration of past and future product generations and production system evolutions.

(2) Consideration over the entire life cycle of systems.

(3) Consideration of ”the systematic decommissioning of products and production systems”.

By this comprehensive scope, PPCD especially goes beyond concurrent engineering and design for manufacturing as systematically presented in [3].The general process model visualized in Fig. 1 therefore provides a structuring in two spirals, that represent the continuous change of generations and evolution of products and production systems (1). In addition, the left spiral depicts the development process of a product and its entire life cycle (2), while the right spiral covers different phases of the production system and the activities involved in planning. Lastly, the model looks at circular instead of linear value streams and therefore covers the systematic remanufacturing of products and reuse of production systems (3). The PPCD dual spirals of product design and production design are therefore the first to fully implement the formal PPCD approach. The following Sec. 3.2 gives a detailed description of the process model.

3.2. Description of the PPCD Dual Spiral Process Model

Industry relevant trends in the next years evolve around societal trends, e.g. sustainability and multidisciplinary, ways

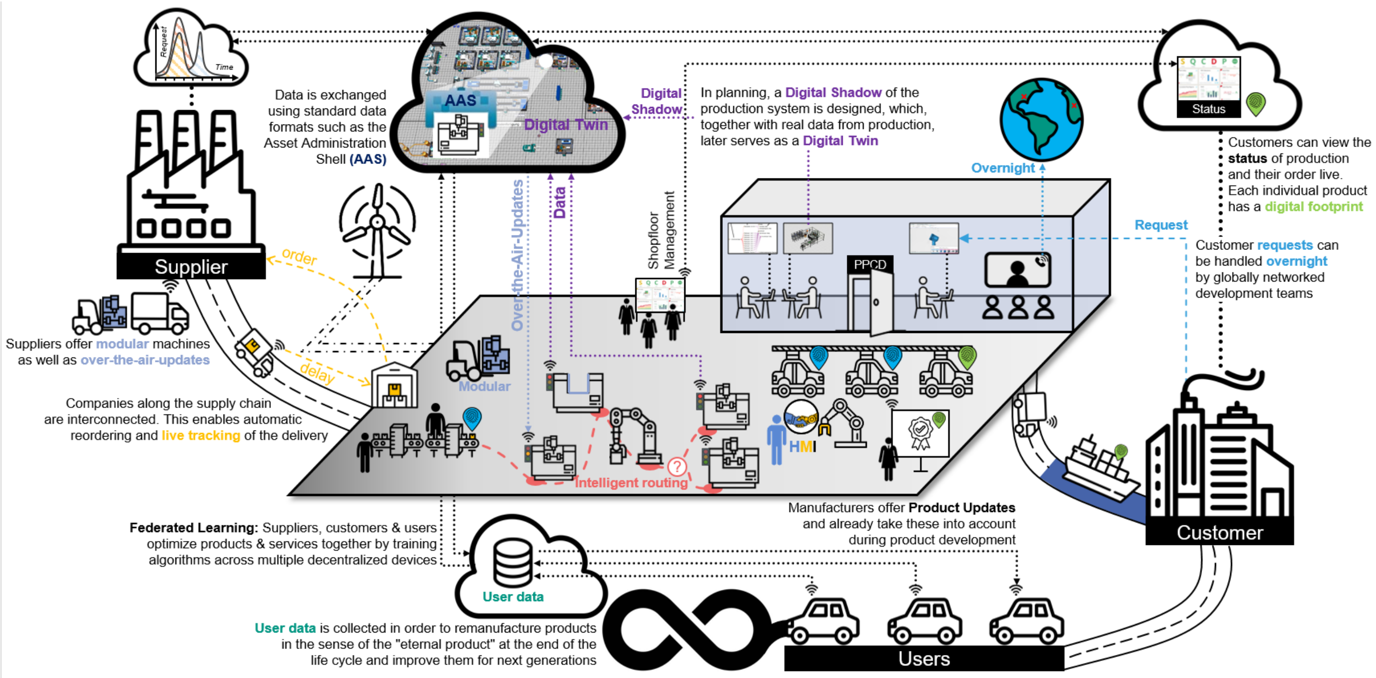

Fig. 2. Production of the future vision enabled by PPCD

of working, e.g. flexibility and collaboration, lifelong learning, e.g. innovation and digital tools, technology, e.g. AI and smart energy or materials, modeling and simulation integration as well as digitalisation [5]. The PPCD Dual Spiral process model aims at covering products and production systems across generations and life cycles by addressing or incorporating these trends. The following gives a step-by-step description of all phases (see Figure 1) that are included, starting with *strategy*. Within *strategy* the production program is to be set. There are many methods regarding a strategic management process, mostly starting with strategic goals, vision and mission statements. Porter's five forces [24] e.g. help analyzing corporate environment. From there on, business models and technology and innovation strategies can be set allowing companies to offer products as first mover, fast follower or late mover [38]. Thus, *strategy* sets off both spirals relating in particular to societal trends from [5].

Within the left spiral that covers the product development process, firstly, products are engineered and designed. Here, Fig. 1 visualizes how the proposed process model includes several reference models. This applies to all phases and not only to the phases where it is implied in Fig. 1. Within product engineering, VDI 2221 [31] can serve as an industry standard. In order to map the product from cradle to cradle, the next phase addresses *raw materials*. If all materials necessary for the production of the product are available (e.g. mined, reused or recycled), the process model distinguishes between *manufacturing* of single parts and their typically consecutive *assembly*. In the following, *usage* serves as a simplification of the product use by the customer, intentionally enabling different business model from ownership to leasing or sharing. However, within this phase, known product life cycle models (such as [17]) can be applied, covering from [5] technology, modeling and simulation integration and digitalisation.

Within the right spiral, *strategy* kicks off *integrated production planning* (IPP). IPP considers activities such as technology planning, process development and production system planning in an integrated way, relating to ways of working and lifelong learning from [5]. Based on the PPCD vision, both spirals are entangled so that product and production development can be concurrently conducted. Afterwards, machinery and equipment need to be commissioned in order to *ramp-up and start [of] production* (SOP), covering both technology and digitalisation from [5]. The following *adaption phase* of the production system includes the entire operation of production with a focus on flexibility and adaptability that was incorporated into the system during the planning phase and enhanced during subsequent production system adaptions.

The two spirals are reunited within the aspect of *circular production*, that stems from [5] societal trends, lifelong learning and technology. At the end of their specific life cycle in order to enable a so-called after-life, products are remanufactured or recycled and production systems are reused. Here, a potential change of system generations might happen. At this point, it shall be noted that the two spirals do not have to be run through simultaneously as there does not need to exist a one-to-one relationship between product and production system.

4. Production of the Future

Based on the challenges [5] as well as basic principles [3] and the process model of the PPCD, a vision for the factory of the future can be created, which is shown in Fig. 2 and described in the following: The factory of the future ...

Table 1. Summary of Case studies

Dual Spiral Ph.	Description of Case Study	Aspect
Product Dev. & IPP	**Model-Based Systems Engineering:** *Model-based Systems Engineering* (MBSE) enables continuous, integrated modeling and analysis of information in product, productions system development. [20] Holistic models enable the analysis of propagation and impact of changes across the product-production boundaries [11, 27].	(1)
Product Dev. & IPP	**Model-Based Production Planning:** Model-based production system planning aims to extend MBSE for all tasks of production system planning. A reusable, universally applicable ontology allows to model elements, attributes, and relationships between product and production system. [4, 21] Production system elements can be modeled as easily reusable solution patterns that can be combined when planning production systems [26].	(1)
Product Dev. & IPP	**Overnight Cost Estimation:** Companies are able to calculate costs overnight, especially for individualized, engineer-to-order products. Based on the underlying CAD models, similar, already existing parts are searched by using machine learning methods, e.g. on the basis of geometry and other production-relevant properties. [16]	(1)
Product Dev. & IPP	**Generative Design:** Based on functional models, generative machine learning is used to generate various design alternatives as a function of manufacturing processes [37, 15] or technology chain alternatives [14].	(1)
Product Dev. & IPP	**Product and production architecture for production and remanufacturing:** Modular product and production kits allow the configuration of products and production systems [6]. By considering remanufacturing in this, production systems can be modularily enhanced over time when products are coming back from the field.	(2)
Raw Materials	**Automated notification of delays in delivery:** The increasing shortage of raw materials and supply bottlenecks must be considered in product development when selecting materials, in addition to functional properties, e.g. by showing material availability or alternatives and at the same time suggesting similar designs [16].	(1)
Manufacturing & Assembly	**Intelligent Product-specific Production Control:** Production orders are equipped with identifiers allowing every product to steer itself through production [12]. The process precedence graphs can be derived directly from product data [26]. Optimal routings are calculated based on availability and capability of machinery.	(1)
Manufacturing & Assembly	**Energy efficient Production Control:** Enhancing sustainability asks for lowering energy consumption by controlling machine states with energy-efficient control policies that switch off/on machines. Including product information and machine learning offers great potential to develop such product-specific control strategies. [19]	(1)
Usage & Product Dev.	**Design from Use:** By tracking product data, insights into actual product usage can flow directly back into product development. Product feature can be adapted and corresponding process parameters can be adjusted. [36]	(2)
Integrated Production Planning	**Integrated product and process configuration:** BOM configuration rules are checked for consistency [35]. PPCD creates and checks BOMs and routings holistically, to avoid product-process inconsistencies [9].	(1)
Integrated Production Planning	**Matrix Production:** Rising market complexities require flexible production systems [23] and artificial intelligence based real-time control [30]. Due to machine duplication and decoupled material flow, matrix production offers higher degrees of freedom for the production of diverse variants with different routings. [12]	(1)
Ramp-Up & SOP	**Collaborative Robots:** Collaborative robots (cobots) can increasingly work alongside humans without security fencing. [13] CAD models can be used to teach and simulate cobots to provide feedback to product development.	(2)
Ramp-Up & SOP	**Federated Learning with other factories:** During ramp up, digital twins are used to determine optimal process settings [8]. Different companies' data can jointly enable integrated product and production federated learning.	(2)
Adaption Phase	**Predictive maintenance based on functional models:** Functional models of machines used for predictive maintenance [1] are refined during operation and reused for future generations with natural language processing [22].	(1)
Adaption Phase	**Modular Production Systems:** A modular production architecture considering hardware (OT) and software (IT) enables scalable manufacturing [28]. The production module definition allows to map manufacturing processes to product features. Software-defined manufacturing then adds modular software code by separating software applications and underlying systems from software defined networking [39] to industrial production.	(2)
Adaption Phase	**Product and Production System in Asset Administration Shells:** The Asset Administration Shell (AAS) is a standardized data structure assigning each asset (e.g. equipment, products) on the shopfloor an AAS. This allows e.g. monitoring and matching of product condition via AAS product models with maintainer capacity. [29]	(2)
Circular Production	**Design for Remanufacturing:** There are guidelines available to design for remanufacturing [7]. In PPCD, remanufacturing line information is used to design the next product generation and production system.	(3)
Adaption Phase	**MBSE based definition of flexibility and adjustability:** Process chains can be systematically deducted from product features [14]. If product variants are modeled in MBSE, required process flexibilities can be considered for determining process chains. If information on the predicted development of customer requirements is in the models, it can be used to determine a corridor for the necessary adaptability of the production system.	(1)
Adaption Phase	**Quality-based Control Strategies using Digital Twins of Product and Production System:** Product digital twin based functional testing through the entire product development phase is a highly iterative validation of product generations [18]. With a production system digital twin and product development integration [10] production-related degrees of freedom (e.g. tolerances, materials) for new product manufacturing can be derived [34]. With in-line measurement data, digital twins are used to represent product function models integrated into production control to enable function-oriented decisions (e.g. real time optimized quality control loops). [33]	(1)

... is planned in generations: Knowledge from past generations of the production system is documented in a model basis and knowledge base. The user is supported in this by using machine learning to recognize and extract solution patterns in past planning. Requirements of future product generations and potential product updates or upgrades are anticipated and flexibility and adaptability of the production system are designed accordingly, reacting to the societal trends, technology and flexible ways of working. For example, mechanical functions are abstracted and digitally provided so that they can later be developed with software if required and activated by means of over-the-air updates, without the need of physical access and changes.

... is digitally modeled throughout: Via an integrated *Model-based Systems Engineering* (MBSE) model of product and production, customer requirements are translated into components via product properties and these in turn into production modules via production system properties. In this way, production systems are systematically derived from customer requirements and remain accessible for knowledge generation. Digital twins of the product and the production system are created from the MBSE models, which are updated in real time based on shopfloor data via the digital shadow, integrating simulation and modeling.

... is human-centered: Real time data analyses derived from digital twins are provided to the shop floor teams as a basis for shopfloor management meetings where they can autonomously initiate and steer a continuous improvement process with new ways of working.

... is sustainable and integrates linear and circular production: Implementing sustainability in line with a sustainable product life-cycle, the manufacture of products from new components transitions smoothly into (re-)manufacturing and various other circular economy approaches. Wherever possible, production systems are planned to perform both assembly and disassembly operations, allowing them to respond flexibly to an increasing or decreasing number of returns from the field by using modern technology to react to societal trends.

... is real-time capable: Information from product development, such as changes to the product, from the supplier, such as delivery delays, from the customer, such as changes in demand, or from the end customer, such as their usage behavior, is transmitted to the factory in real time through digitalisation. There, this information represents input variables for the integrated digital twin of product and production system on the basis of which optimal reactions can be determined. The statuses of systems and products are recorded in real time and extend a static knowledge base. The digital twin can therefore be used to determine the current status of the production at any time and plan and control with foresight.

... is vertically and horizontally collaborative: Communication with suppliers and customers is automated and in real time covering aspects of lifelong learning. E.g. if low inventory is detected, orders are placed automatically with the supplier considering real time information about goods already on the way to the factory. Through federated learning different knowledge bases and production systems can learn jointly. By combining information from MBSE and the *Manufacturing Execution System* (MES) the current status of an order is transparent for the customer including development and production phase.Likewise user data can improve remanufacturing and the circular approaches by containing information and knowledge.

... is adaptable: Machines can be designed by anticipating changes in product characteristics over product generations and technologies. Whereas the hardware for the related functions is initially provided, the related software is developed and deployed over the air later on when required to achieve a software defined manufacturing.

5. Case Studies

Based on the described aspects of PPCD (respectively in Sec. 3 & Sec. 4) and the vision of the production of the future, this section gives an overview of several case studies which have been conducted (see Table 1). Besides a general description, each case study is linked to the phases of the proposed process model from Sec. 3.2 and highlights the implemented aspect of PPCD according to Sec. 3.1.

6. Summary and Outlook

This article describes the conceptualization of PPCD as the main enabler for the production of the future by addressing the grand challenge in engineering of uniting product design and production, in particular covering all aspects of quality management, production planning and control. A novel methodological approach based on the PPCD Dual Spiral process model is introduced and the notion of the production of the future is derived. Key of this embodiment of Product-Production-CoDesign (PPCD) is the integrative, interconnected and holistic CoDesign of both products and production systems throughout their lifecycles spanning product and production generations. Mutual benefits of PPCD require major efforts for both product design and production, however many aspects of the envisioned production of the future are yet not sufficiently researched. To that end, this paper describes several case studies that set off research in the realm of PPCD and contribute to specific phases of the PPCD Dual Spiral process model. Likewise, the case studies showcase the need to advance individual aspects of PPCD as outlined in the phases and production of the future definition. Thus, future research shall contribute to advancing the individual aspects of PPCD both for product design and production planning. Moreover, the broad concept and vision of a PPCD enabled factory for the production of the future shall be broken down into more tangible target states for individual production environments and concepts to enable future researchers to move the state-of-the-art closer towards a fully implemented PPCD Dual Spiral process model for the production of the future. Additionally, regarding the implications for adjunct business functions and the integration with a circular economy will become increasingly important.

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