Product-Production-CoDesign Thinking for Sustainable Manufacturing

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Abstract. Manufacturing needs to contribute towards a sustainable future for the sake of preserving and enriching humanity on planet earth. This goal is enshrined in the Sustainable Development Goals (SGD) set forth by the United Nations. SGD 9 aims at building a resilient, innovative and sustainable industrialization. SGD 12 ensures sustainable consumption and production patterns. Currently, manufacturing falls short of achieving these targets as product design and production engineering operate individually and sustainable practices are not focused. This industrial problem is reflected in the absence of holistic approaches that aim at sustainable production by providing applicable methods. To address this challenge, we propose Product-Production-CoDesign (PPCD) Thinking. With a clear focus on sustainability we delineate PPCD Thinking from Design Thinking and extend the notion towards manufacturing. It encompasses linear manufacturing (SGD 9) and circular production (SGD 12). Four case studies illustrate this software defined production enable PPCD Thinking and its customizability. In a nutshell, Product-Production-CoDesign Thinking, thus, can contribute to moving towards sustainable manufacturing and net zero.

Keywords: sustainability · design thinking · manufacturing

1 Introduction

Sustainable Manufacturing is key to achieve the sustainable development envisioned by the United Nations and hence contribute towards a sustainable future that preserves planet earth [23]. The main contribution of sustainable manufacturing lies in building a resilient infrastructure by promoting a sustainable, innovative industrialization enshrined in Sustainable Development Goal (SGD) 9 and enabling sustainable consumption and production patterns outlined in SGD 12 [23]. While SGD 9 fosters a sustainable industry through linear manufacturing, SGD 12 enhances this notion towards a circular economy. To achieving net zero solutions must encompass product design, business model, production and reverse logistics and remanufacturing. Thus, the future of manufacturing must regard both product development and production engineering in an integrative, holistic manner [2]. In an industrial symbiosis, research must empower a large scale

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industrial shift towards sustainable manufacturing and net zero. Agile approaches constitute such scalable and widely applicable methods [18]. While Design Thinking provides a holistic approach that encompasses product, service and business model design [6], a clear focus on manufacturing and sustainability is missing. However, this lack of coherently regarding product, production and sustainability hinders their application and diminishes their contribution to the SGDs. Novel approaches regard the entire product life-cycle at early stages, such as simultaneous engineering [16], software defined manufacturing [4] or Product Production-CoDesign (PPCD) [2]. To date they are hardly directly applicable to contribute to a transition to sustainable manufacturing. Thus, we introduce Product-Production-CoDesign Thinking as a Design Thinking process that unifies product development and product engineering approaches to achieve sustainable manufacturing and create holistic, net zero contributing solutions.

The paper is structured as follows. Section 2 introduced the fields of action that interplay in PPCD Thinking to enable sustainable manufacturing. In Sect. 3 the research scope and research questions are delineated. Then the general approach of extending Design Thinking towards PPCD is presented in Sect. 4. Enabling sustainable manufacturing through the presented approach is shown and discussed in Sect. 6. Section 7 concludes with a summary and outlook.

2 Fields of Action

2.1 Product-Production-CoDesign

Integrating product development and production engineering is a frequent scope of research. VDI2206 [19] describes the simultaneous development of product and production system and identifies the necessity to perform these concurrently to incorporate production system inflicted restrictions into the product development phase. In a similar vein, the product perspective is clearly illustrated in the integrated Product engineering Model (iPeM) [3] that extends into the starting of production and market opportunities. The initial approach, simultaneous engineering, dreamed of holistically integrating both product and production approach to simplify the complexity [2]. However, these approaches lacked a coherent integration of product generations [2] and production system generation and lifecycles. Hence, Product-Production-CoDesign (PPCD) was introduced in 2022 [2]. PPCD regards the timely paralleling of collaboratively developing, iterative planning and product creation within their systems [2]. This encompasses in particular the life-cycle of products and production systems, while integrating their development over product generations [17]. The latter includes the end of life decommissioning of products and production systems [17] and, hence, incorporates SGDs 9 and 12 for sustainable manufacturing. As sustainable manufacturing encompasses linear sustainability and circular production, PPCD serves as the stepping stone into holistically enabling sustainable manufacturing through both clearly describable approaches such as model based systems engineering [2] and innovative methods such as design thinking [18], that both have attracted research and industry alike.

2.2 Methods

Different methods and process models—such as the 6-3-5-method or Design Thinking—can be used to increase creativity in the solution finding process. The four phases of a creativity process are discovery, maturation, insight, and elaboration. These can be helpful to integrate creativity into problem solving activities. The whole procedure is accompanied by different emotions, such as fear and euphoria. [14] The necessity to use such methods to consciously promote and use creativity exists, as this allows to concentrate on one's own strengths. In general, creativity methods can be distinguished between intuition and discourse: While intuitive methods focus on the promotion of thought association, discursive methods involve the systematic search for solutions divided into individual logical steps. [5, 20] Examples of intuitive methods are brainstorming, -writing and TRIZ [13], while the morphological construction kit belongs to the discursive methods [8]. SPALTEN is a widely used and fractally structured method for general problem solving developed by [1]. The method is divided into seven different phases, whereby the whole solution process is included. [1]

While SPALTEN is a method to find solutions to problems in a structured way, other methods like *Design Thinking* (DT) are more focused on the implementation of creativity in solution processes. DT can help to accelerate the flow of ideas and, if necessary, to solve existing or emerging mental blocks, while being user-centered. [21] It always includes phases such as empathize, define, ideate, prototype, and test, each with minor adjustments in wording and content. There is a large body of literature on the topic of social innovation where [9] compiles a review of empirical research linking the current state of the art in applying DT in organizations.

2.3 Sustainable Manufacturing

In order to create a holistic environmentally sustainable product, close coordination between production and product systems is essential. Decisions made during the product design phase have a significant impact on the product's environmental footprint throughout its entire lifecycle, including manufacturing, usage, disassembly, reuse, remanufacturing, and recycling, which are largely predetermined [12]. Sustainable design is a vital element in this process, encompassing aspects beyond traditional ecodesign. This includes opportunities for design for Cradle to Cradle and Product-Service Systems (PSS) [7]. Several factors require attention and improvement, such as diagnosability, modularity, and the extension of product lifespan [22]. Achieving these goals necessitates not only proactive planning but also iterative improvement. Traceability plays a vital role, particularly in the success of circular economy practices, specifically in reverse logistics and their management [11]. The evaluation of data, optimization, and adaptation of design, as well as the identification of optimal routes for product and material reuse with minimal waste, are critical. User data collection is important for generating insights and integrating them into subsequent design processes and production improvements. The quantification of system design effectiveness can be facilitated through the utilization of Life Cycle Assessment (LCA) or Life Cycle Sustainability Assessment (LCSA), offering a way to assess its impact. [10] In conclusion, achieving a holistic environmentally sustainable product and manufacturing process necessitates close coordination between production and product systems.

3 Research Scope

The subject of the present research is the interface between product development and the associated production planning and control, as addressed by PPCD presented in Sect. 2.2. Both domains each address specific requirements on the methods and tools used: Activities in product design for example require creativity in finding solutions, whereas activities in production system planning have to deal with uncertain product characteristics. At the same time, digitalization offers new opportunities and possibilities through greater availability of information that can be used throughout the product development process. Here, approaches such as Design-for-X or other concepts are emerging. But the first fundamental question is which methods are suitable for integrated development and planning of product-production systems. For this reason, this article focuses on the following, first research question:

RQ1 Which method is suitable for application at the interface between product development and production system planning, and how can the concept of Product-Production-CoDesign (PPCD) be skillfully supplemented?

This article, thus, proposes a novel concept of Product-Production-CoDesign Thinking. In order to continue the motivation of the SDGs in terms of sustainable manufacturing of sustainable products, this article also investigates how the newly presented method can be applied in the context of sustainability. Thus, the second research question arises as follows:

RQ2 How can the developed methodology be applied to give greater consideration to sustainability in PPCD activities?

4 PPCD-Thinking Based on Design Thinking

To that end, PPCD-Thinking introduces a holistic Design Thinking Framework focusing enabling the interplay between product design and production planning. To address design thinking challenges and answer RQ1, the main stages Discover, Define, Ideate, Prototype, Test and Implement from design [18] are kept.

The examination of both production system and product is pivotal and illustrated in subsequent Fig. 1 delineating the two levels. After the described steps discover, define, and ideate have been completed, the feasibility on the product level can be assessed and refined through the utilization of virtual or physical prototypes. Further iterations loops, such as acceptability and comprehensibility of the solution, arise through the process of testing. The admissibility of user problems iterates back to the discovery process are also involved to discover new experiences and strategic topics. The examination of the production system levels presents the opportunity for additional iteration loops. Following the creation of the prototype, the implementability of the idea can be evaluated. Through testing, further loops can be enabled, including the iteration of data validity, the ability of the idea to address user concerns, and the assessment and enhancement of consistency with the production strategy. The coherent integration of product generations and production system generations distinguishes PPCD Thinking from other approaches such as life cycle management and simultaneous engineering.

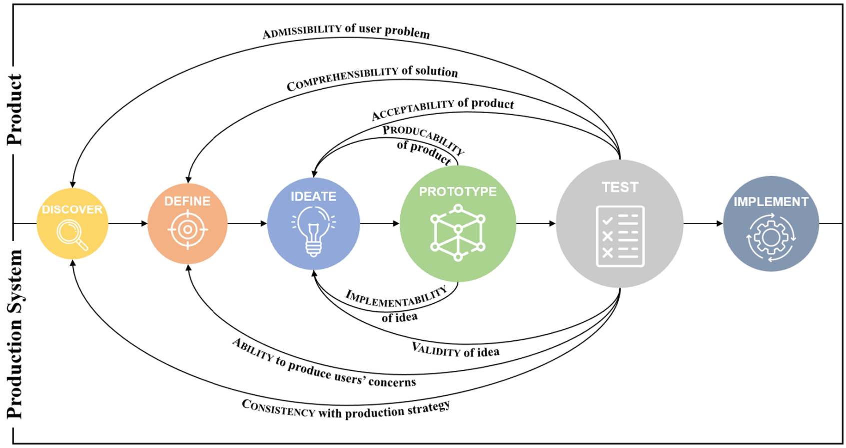

Fig. 1. Product-production-codesign thinking process model

5 Case Studies

The first case study, as highlighted in Fig. 2, highlights the admissability of the user problem. Model based Systems Engineering (MBSE) is a method commonly used in PPCD [17]. In this case MBSE based user requirement analysis structures and links identified user requirements before and during the prototype phase to improve subsequent product changes. The second case study makes use of a MBSE impact analysis, highlighting product producibility by mapping product features with production processes. In the third case study, consistency between production strategy and prototype are regarded. With a strategic fit analysis the effects of producing the prototype with required processes on the abilities and network footprint are assessed. Lastly, again on the production side, the implementability of a prototype production can be validated with a virtual prototype put into event discrete simulations on production system level and virtual commissioning on machine and system level.

6 PPCD-Thinking for Sustainable Manufacturing

A major contribution of PPCD is the extension and applicability to a circular production [2]. With PPCD-Thinking, this aspect should, hence, be in depth regarded as designing and engineering product and production systems [15] without regarding their end of life is still too common [17]. Thus, we couple the PPCD-Thinking process with the life cycle of products to address RQ2. As products are design in generations [3], the PPCD-Thinking process in linear production ends with the successful start of production. Independent of decommissioning being integrated into product and production engineering during this PPCD-Thinking, as soon as used products return to the manufacturer, the coherent PPCD need arises. Sustainable PPCD-Thinking comes into play as the next product generation shall incorporate learnings and potentially subsystems and components of previous product generations as shown in Fig. 3. This vastly increases complexity and

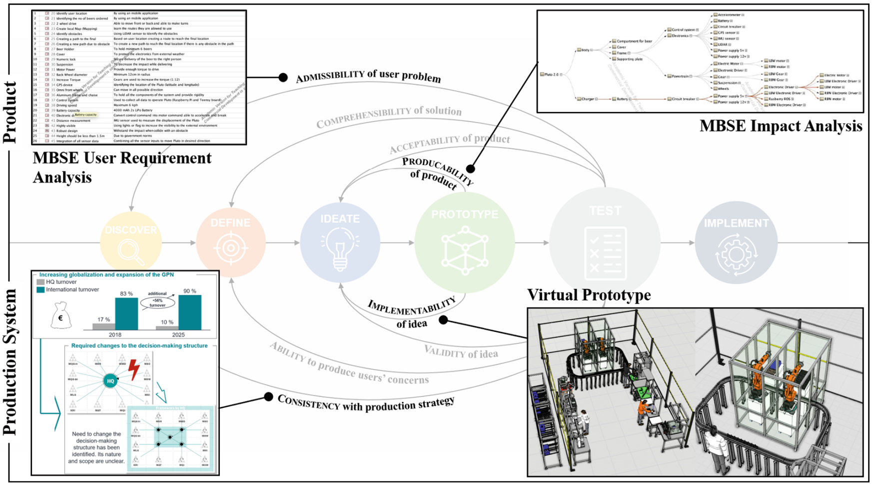

Fig. 2. Exemplary case studies highlighting four selected aspects of PPCD-Thinking: MBSE allows for understanding user req. And tracking these within complex systems and virtual prototypes were used to validate the implementability of generated ideas.

requires the integration of several PPCD-Thinking cycles. Figure 3 introduces major challenges to be solved during the PPCD-Thinking application.

7 Summary and Outlook

In a nutshell, PPDC-Thinking provides a novel design thinking approach highly customized for the realm of producing physical goods. Based on the PPCD approach, product design and production engineering are interlinked and relevant questions are addressed in the framework. The individual tools and solutions used in the framework can be taken from [17] and regularly extended. However, the framework aims at enabling sustainable manufacturing and circular production, so that a longer term validation will be necessary. As with any design thinking approach, educating engineers to properly apply the approach will be necessary during the application.

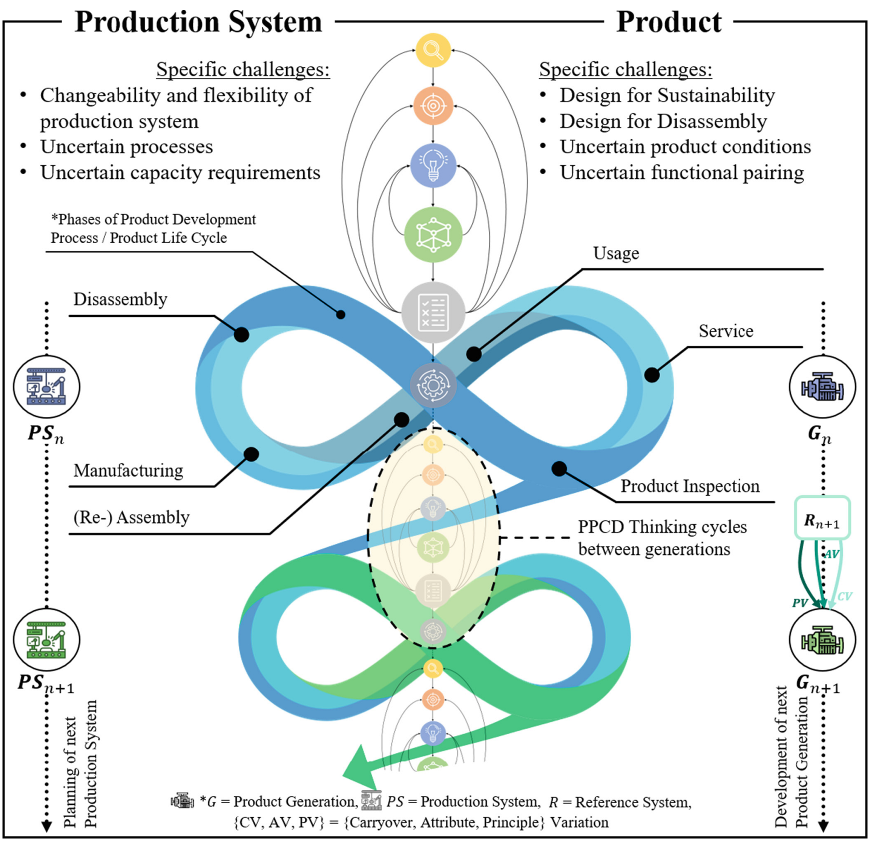

Fig. 3. PPCD-Thinking cycles (yellow) addressing specific circularity challenges within the development of new product and production system generations (vertical axis).

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