18 Agile Product Development for Cyber-Physical Products

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Contents

Abstract

The manufacturing industry, especially in high-wage countries, faces new challenges in recent times. The environment of development projects gets more dynamic and uncertain and is characterized by fast-paced changes of technological and economical aspects as well as heterogeneous customer requirements and

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volatile markets. In combination with an increasing complexity of cyber-physical products, the challenges within product development are constantly growing. Furthermore, companies need to be more flexible and be able to adjust to changing conditions (Schuh & Dölle 2021, S. 11). To increase flexibility, enablers (i.e., advanced manufacturing technologies) and tools (i.e., data-based automated design tools) are presented, whose further development and integration into the product development process reduce development times. Agile product development for cyber-physical products has become a significant research focus in order to meet the challenges described and to ensure the future competitiveness of manufacturing companies. The following paper and respective sections will describe the vision and main research activities within the Cluster of Excellence "Internet of Production" (IoP) in the context of agile product development for cyber-physical products.

18.1 Introduction and Research Objective

The Cluster Research Domain C (CRD-C) "Agile Product Development" focuses on the determination of processes, structures, as well as enablers and tools for agile product development for cyber-physical products. In this context, the Internet of Production allows stakeholder integration for an effective development and eliminates latencies for radically reducing development lead time. Multiperspective and persistent datasets within the IoP are an absolute precondition for the implementation of agile product development in manufacturing companies as an opportunity to confront today's volatile market conditions.

Conventional plan-oriented development approaches are reaching their limits in terms of dealing with the radical reduction of development times (Kantelberg 2018). Particularly in the context of cyber-physical systems, the fulfillment of functions by sub-functions of the various domains of mechanics, electronics, and software leads to major challenges in development (Drossel et al. 2018). Thereby, the linking of physical and data processing virtual objects results in a significantly more complex product and its development process. Over the past years, research focused on the acceleration of the pace of adaption and the improvement of agility within product development (Cooper & Sommer 2016). Whereas agile procedure models are popular within the software industry, a systematic transmission of the advantages of these models on the development of cyber-physical products is still pending.

This is due in particular to changed restrictions in the software industry compared to cyber-physical products within the manufacturing industry (Cooper & Sommer 2016). In addition to existing organizational hierarchies and the willingness of employees to change, the significantly increased effort required to implement prototypes should be mentioned in particular in this context (Schuh et al. 2017a). Furthermore, there is a need for synchronization and coordination of the development streams with regard to required information from and for the various disciplines in order to enable rapid and flawless development. Therefore, the CRD-C "Agile Product Development" addresses the following main objective:

To enable agile product development for cyber-physical products in terms of radical reduction of lead time while at the same time enhancing customer satisfaction.

The reduction of lead time and enhancing of customer satisfaction can be achieved by changing the conventional and plan-driven development approach toward an agile process. Therefore, the IoP supports the databased determination of product concepts as well as the related constraints and offers a possibility to deal with unpredictable environmental changes. Accepting and handling uncertainties during the product development process means overcoming the typical completeness paranoia, which describes today's demand of full specifications prior to a development activity. Databased tools as well as advanced manufacturing technologies allow a new way of stakeholder integration resulting in exceeding customer and user expectations. The direct integration of stakeholder feedback in terms of rapid engineering change requests also allows the derivation of even more suitable products. In order to answer this question, the research domain is subdivided into the two focus areas and respective workstreams "Processes and Structures" and "Enablers and Tools" for agile product development, which are introduced in the following sections.

18.2 Processes and Structures for Agile Product Development

The first research area focuses on processes and structures for agile product development. In terms of processes, the market development, engineering and production of prototypes must be evaluated. Furthermore, the necessary structures in terms of organization and data structures for an agile product development in the context of the IoP are derived. Thus, the following research questions structure the research in this field:

1. How should agile processes and methods be designed to support market development, engineering and production of prototypes?
2. How should agile organizational structures be designed and how can an agile culture be implemented?
3. What are the data structures needed to eliminate semantical conflicts and latencies?

The first question addresses agile processes and methods. The IoP differentiates between the three areas market development, data and engineering, as well as production of prototypes. Accordingly, underlying procedure models are derived considering multiperspective and persistent datasets. In this context, the systematic transmission of the advantages of agile software methods on cyber-physical products is addressed. The respective organizational structures in combination with an agile culture enable the realization of advantages. Finally, the processes are enhanced as transparent exchange of data along the process erases latencies and semantical conflicts. In order to reflect the relevant literature with respect to processes and structures for agile product development, state of the art is discussed in the following.

18.2.1 State of the Art

The SCRUM approach constitutes an established agile method for the software industry. A key element is the definition of iterative cycles named sprints creating a testable, functional product increment (Schwaber 2004). Smith considers the requirements of manufacturing companies for implementing agile processes (Smith 2007). Klein additionally provides promising approaches toward agile engineering (Klein & Reinhart 2016). Cooper as well as Ahmed-Kristensen and Daalhuizen presented approaches constituting an integrated approach of the conventional Stage-Gate process and agile methods (Cooper & Sommer 2016; Ahmed-Kristensen & Daalhuizen 2015). Conforto defined an iterative development approach integrated into a Stage-Gate process (Conforto & Amaral 2016). The authors' prior work concerned the development of physical products as well as the design of innovation and development processes. The SFB 361 focused methods to increase development effectiveness and efficiency. In addition, several researchers have contributed to the research on agile product development in the context of the manufacturing industry (Schuh et al. 2017a; Rebentisch et al. 2018; Schloesser 2020; Kuhn 2021). Nevertheless, the described approaches do not emphasize the design of agile processes supporting the collaboration of different cross-domain departments in different types of development sprint. In addition, the approaches do not concretize organizational and data structures.

18.2.2 Overview of Research Areas Within "Processes and Structures"

The focus of the research area "Processes and Structures for Agile Product Development" lies on processes and respective methods as well as organizational structures and data structures for agile product development. Therefore, "Processes and Methods" address the derivation of the underlying procedure models. The research field "Organization" discusses working structures as well as the implementation of an agile culture. To build a connection toward the IoP as the main driver for the databased reduction of latencies, the research field "Data" covers the development of a digital shadow for the entire engineering-oriented value chain of the development cycle. Furthermore, this research field comprises the requirements of the tools of the development cycle regarding the IoP (see Fig. 18.1).

In order to radically shorten the development time and increase customer and user satisfaction, the IoP offers several possibilities in terms of stakeholder integration and latency reduction. Within the area of "Processes and Methods,"

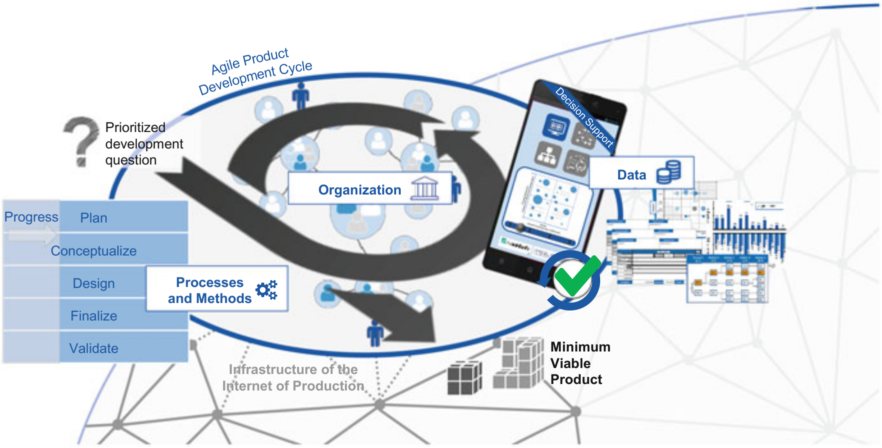

Fig. 18.1 Conceptual overview of processes and structures for agile product development

the three research fields "Market Development," "Engineering," and "Production of Prototypes" concentrate on the systematic transmission of the advantages of agile software methods to the development of cyber-physical products and therefore contribute to realize the potentials of agile product development for cyber-physical products. In order to define an underlying procedure model for agile development, the sprint targets (e.g., market teaser, feasibility, functional prototype, etc.) are taken into account. In addition, the definition of target-dependent sprint lengths as well as necessary IoP-based tools to address the identified latency drivers is required. The definition of the sprint types also shows a strong connection to the definition of working structures within the research field "Organization" as roles and team composition depend on the sprint type. Synchronization of the different sprints is important to ensure the effectiveness and efficiency of cross-domain product development. Multiple agile sprints are combined into one overarching development cycle. This development cycle can vary in length and has the primary goal of answering a set of central development questions and reducing uncertainty in the development project. Development questions are derived from the core requirements that are expected to achieve high customer satisfaction. The focus on a few significant development questions, instead of a complete specification list, represents a paradigm shift in product development and supports the rejection of the so-called completeness paranoia. The validation of the development questions is achieved with the involvement of different stakeholders and the generation of minimum viable products (MVP). MVP are (virtual or physical) "extracts" from a product. Based on a generated minimum viable product, different stakeholders can provide feedback regarding selected development questions so that the next development cycle can be pursued. The early uncertainty reduction and knowledge generation with the help of the iterative generation of minimum viable prototypes or product increments is a crucial characteristic within agile product development

(Riesener et al. 2019). In addition to the previously described processes and methods, respective structures need to be acquired. The research field “Organization” focuses on agile working structures and teams as well as the implementation of an agile culture. First, the necessary members within an agile development team have to be defined. The so-called voice of the product exists, for example, in the form of a group of project managers who hold overall responsibility. As another example, cross-functional team members participate depending on sprint target, process type, and targeted viability of the sprint outcome. In conclusion, the combination of hierarchical organization with lateral working structures can be a solution, as it supports direct communication (lateral structure) as well as instant decision-making (hierarchical organization). Moreover, culture and acceptance are important for the transformation toward agile product development. Management principles, values, and working environment present some of the main factors, whose adaption becomes necessary in the context of agile processes. In addition, the analysis of behavioral patterns provides further information about the acceptance of agile product development. Due to the networked and cross-company collaboration in today’s development projects, it is not sufficient to focus the design of the company organization, but the scaling of agile product development in development networks must also be organized. The last field of research addresses data structures, thus depicting an important part for the connection of agile product development and the IoP. To support the agile development processes, a transparent, legible, and plausible exchange of data is necessary. Such a structure allows the provision of data aggregated according to the requirements of the operator, without semantical errors. Furthermore, the data structure supports system orientation. Whereas nowadays, experts work domain oriented (e.g., mechanics), the aggregation of data without semantical errors allows the consideration of different domains by each expert (Mauerhoefer et al. 2017). In this regard, the approach of model-based systems engineering (MBSE) becomes crucial for the realization of agile product development.

In summary, the described structure of the “Processes and Structures” and the included research fields form the basis for the realization of agile product development in the context of the Internet of Production. The tools to be developed in this context take into account the implementation of development cycles based on development questions for the generation of minimum viable products. With focus on the definition of agile processes, the collaboration in different process types can be improved in all areas in the IoP. By concretizing an agile organization for the own company and also across companies in the network, cross-domain teams including the required roles and responsibilities are defined as a required part of agile product development. Semantic conflicts and latencies can be eliminated by identifying the required data structures. The IoP also improves stakeholder integration and helps to increase customer and user satisfaction and acceptance.

18.3 Enablers and Tools for Agile Product Development

The present chapter, in general, focuses on the determination of structures, processes, and methods as well as enablers and tools for agile product development for cyber-physical products. The following second part of the chapter focuses on the research of enablers (i.e., advanced manufacturing technologies) and tools (i.e., data-based automated design tools) and their sufficient integration in agile product development processes. The following research questions structure the research in this field:

1. How can advanced manufacturing technologies and data acquired from corresponding prototypes be used and integrated to enable agile product development?
2. How can relevant data from production and material be used to determine the minimum viability of a product increment as well as to select, adapt, and improve the corresponding prototyping technologies?
3. How can relevant data provided by the IoP be integrated into automated and interactive design tools to support continuous stakeholder integration as well as latency elimination and thereby enable agile product development?

The first research question focuses on advanced manufacturing technologies and their qualification for an efficient and rapid realization of market teasers, feasibility studies, and functional prototypes. Beyond the determination of the minimum viable product increment and the corresponding prototyping technologies, the second research question addresses the actual technological limitations of prototyping technologies. In this context, the data gathered during the production process of the product increments supports the continuous process optimization of advanced manufacturing technologies. Finally, the focus of the third research question – the ubiquitously available data, information, models, and knowledge across user, production, and development cycle provided by the IoP – has to be condensed into design-specific digital shadows. The respective tools considering the data from user, production, and development cycle support the developer within the different sprints in terms of easy-to-use applications. In order to reflect the relevant literature with respect to enablers and tools for agile product development, state of the art is discussed in the following.

18.3.1 State of the Art

Concerning manufacturing technologies efficiently transferring digital design data into physical products, additive manufacturing (AM) and more general advanced manufacturing technologies (AMT) are growing fields of international research

(Gu et al. 2021; Poprawe et al. 2018; Behera et al. 2013). In particular, metal AM is of increasing interest, and several international research groups are working on this topic (Baumers et al. 2016; Zaeh & Ott 2011).

Research at the RWTH Aachen University via the Cluster of Excellence (CoE) "Integrative Production Technologies" in the field of AMT focused on direct, mold-less production technologies – especially metal AM (Poprawe & Bültmann 2017), hybrid incremental sheet forming (ISF) processes (Göttmann et al. 2013), efficient 3D-ultrafast laser ablation (Finger et al. 2015), and new advanced weaving technologies (Gloy et al. 2015).

While concentrating on solving the dilemma between scale and scope (i.e., enhancing process efficiency and quality), there has been little research on integrating AMT into agile product development processes (Schuh et al. 2017a). Technical limitations and the systematic deviations between AMT and conventional manufacturing technologies (e.g., spring-back for incremental sheet forming or resulting microstructure for AM) restrict a wider use of AMT for minimum viable products (Schmitz et al. 2020).

AMT typically provides a new "freedom of design" (e.g., lattice structures by AM, functional surface structures by laser ablation, or complex patterns by 3D weaving), resulting in a multiscale problem. To adopt a product or component to specific functional requirements, thousands or millions of lattice or surface structures must be adopted to those requirements. Due to the increased design effort and the according lead time, the potential of such functional adopted multiscale structures could not fully be utilized today. Therefore, current international research focuses on the field of automated or generative design (Wu et al. 2015; Panesar et al. 2018; Hinke 2018).

18.3.2 Overview of Research Areas Within "Enablers and Tools"

As described in the first section, the concept of minimum viable products (MVP) is an auspicious approach to radically reduce development lead time while drastically increasing customer/user satisfaction simultaneously. To answer development questions with the aid of MVP, the respective MVP has to adequately represent the requirements derived from the research questions. In this context, MVP represents not only the product/component geometric or haptic design but all relevant functional and mechanical properties necessary for answering the development question focused on by a sprint (see Fig. 18.2).

The research field "Advanced Manufacturing Technologies" (AMT) focuses on the industrialization of AMT and its integration into agile product development processes. Additive and subtractive Digital Photonic Production (DPP) technologies like additive manufacturing (AM) and ultrafast laser ablation, as well as incremental sheet forming (ISF) or advanced weaving technologies for 4D textiles, enable

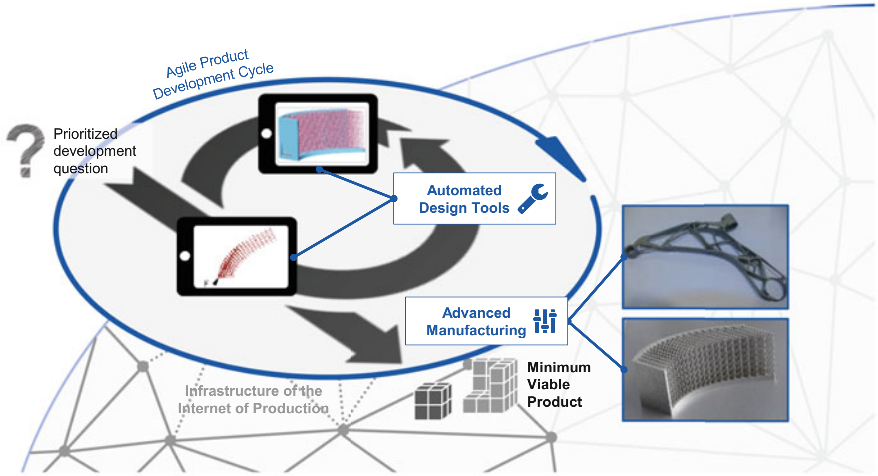

Fig. 18.2 Conceptual overview of automated design tools and advanced manufacturing for agile product development

the efficient and rapid production of small lot sizes and complex geometries. Furthermore, such technologies allow the direct transfer of product ideas into physical MVPs. Thereby, these technologies enable agile product development in two ways:

1. AMT allows for the efficient and rapid realization of market teasers, feasibility studies, and functional prototypes in terms of MVP.
2. AMT enables the efficient series production of small lot sizes, a critical success factor for agile developed products – especially when it comes to the realization of product releases in small numbers.

Based on the digital material shadow and the digital production shadow, the focus is on understanding, managing, and reducing systematic deviations (e.g., microstructure, mechanical properties, or surface quality) of components manufactured with diverse AMT. Based on these findings, it is possible to evaluate different AMT in terms of applicability to develop a question-focused MVP. Due to the modelling and understanding with the aid of gathered data, the optimal AMT for MVP production can be selected considering the development question as well as time and cost. The intended integration of AMT into agile product development is based on the systematic management of deviations of the components by means of model and databased optimization of technology chains and process parameters. Selecting the optimal AMT concerning the development question becomes essential for agile product development. In combination with the respective minimum viability mentioned Sect. 18.2 and the understanding of the AMT processes, it is possible to allow databased selection of the respective technology to be used for producing an MVP. Therefore, evaluation, and selection of the appropriate manufacturing technology an IoP-based, interactive prototyping toolbox is derived, mapping the MVP requirements (e.g., geometric tolerance and mechanical properties of a security-sensitive car body component), the digital shadow of potential AMT from (e.g., geometric tolerance of ISF) and the digital shadow of resulting material behavior from (e.g., achievable microstructure of AM). Although AMT are promising for agile product development, there are still many technological limitations. In order to accomplish the intended industrialization and applicability of AMT the research in this the respective following section on enablers and tools focuses on enhancing the performance of advanced manufacturing processes (e.g., mechanical properties, surface quality, efficiency) and corresponding machine tools. The examples described in Sect. 18.3, are reduced spring-back of ISF components due to model-based CAD-CAM chains or increased flexibility of laser ablation machine tools due to new kinematic approaches based on machine learning. Data from the production process of MVP allows the continuous evaluation and adjustment of parameters for process optimization.

Beyond AMT for the efficient and rapid realization of MVP, another key enabler for agile product development are IoP-based automated, interactive, and networked design tools. These tools are integrated into the different sprint types (market development, engineering, and production of prototypes). Based on reduced models and model-based AI methods, these interactive tools should automatically design product or component geometries, respectively, geometric structures based on the material-specific digital shadow, the process-specific digital shadow, and continuously tracked data from production processes. The examples described in Sect. 18.3 are a design tool for algorithmic generation of lattice structures for AM and an AI-based design tool for Optical Systems Development.

18.4 Conclusion

As described, the Cluster Research Domain C (CRD-C) “Agile Product Development” focuses on the determination of processes, structures, as well as enablers and tools for agile product development for cyber-physical products. According to the current state of research, the previously described structure and the included research questions are elaborated in the following chapters of CRD-C.I and CRD-C.II. Within these chapters, research results and use cases are presented. In future research, the aim is to expand and scale the results obtained to date. Overall, the increasing importance of the topic sustainability will be taken into account for future research. The question of the influence of sustainability on agile product development will be addressed. Longer product life cycles, but more individualized products, are to be expected.

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