International Journal of Computer Integrated Manufacturing

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tcim20

Agile product development process transformation to support advanced one-of-a-kind manufacturing

Mitja Varl, Jože Duhovnik & Jože Tavčar

To cite this article: Mitja Varl, Jože Duhovnik & Jože Tavčar (2020) Agile product development process transformation to support advanced one-of-a-kind manufacturing, International Journal of Computer Integrated Manufacturing, 33:6, 590-608, DOI: 10.1080/0951192X.2020.1775301

To link to this article: https://doi.org/10.1080/0951192X.2020.1775301

Published online: 16 Jun 2020.

INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING
2020, VOL. 33, NO. 6, 590–608
https://doi.org/10.1080/0951192X.2020.1775301

ARTICLE

OPEN ACCESS

Agile product development process transformation to support advanced one-of-a-kind manufacturing

Mitja Varl[a], Jože Duhovnik[b] and Jože Tavčar[b]

[a]Mechanical Design Department, Kolektor ETRA, Ljubljana, Slovenia; [b]Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia

ABSTRACT

Increased competition in the global market has forced companies to diversify their product ranges to meet the customers' changing needs and adopt product development strategies for mass customization or even one-of-a-kind production, which inevitably requires designing modular products. Product modularity is achieved via platform-based systems, in which various combinations of different modules are assembled within a common platform. The smart factories that are already beginning to appear to employ a completely new approach to product creation. In smart industry, dynamic business and engineering processes enable last-minute changes to design and production, delivering the ability to respond flexibly to disruptions and failures on behalf of suppliers. This paper presents a case study of product development and design process renovation according to agile and lean principles in one-of-a-kind industrial environments. It defines how changeability integrates with robust, concurrent and smart design strategies. Introduction of agility to highly individualized production environments is mostly about enhancing the robustness of new product development processes. Product development and manufacturing processes are interconnected therefore they need to be re-engineered together. The presented work aims to deliver a generalized conceptual framework that demonstrates how companies in such specific environments can improve smartness and profitability through the utilization of agility concepts.

ARTICLE HISTORY
Received 24 July 2019
Accepted 17 May 2020

KEYWORDS
Agile principles; one-of-a-kind manufacturing; platform design; lean process; concurrent engineering; smart industry

1. Introduction

Rough competition in the global marketplace demands highly functional products, high-quality service, shorter delivery lead-time and increased environmental friendliness, all with a suitable cost. Although advanced manufacturing technologies can partially address these challenges, advanced design techniques are considered crucial since most design and manufacturing properties of a product are influenced by the design decisions made in the early design stages. There are several initiatives that promote smart industry development, including Advanced Manufacturing Partnership 2.0 (AMP) and Industrial Internet (IIC) in the USA and Industry 4.0 (Kagermann, Wahlster, and Helbig 2013) in Germany. Industry 4.0 is focused on creating smart products, procedures and processes (Filho et al. 2017; Lee, Bagheri, and Kao 2015). By connecting people, things and data, new ways of organizing and conducting industrial processes emerge. Smart factories are able to manufacture goods more efficiently, less prone to disruption and capable of managing complexity.

Agile manufacturing (AM) has gained tremendous recognition and acceptability among the manufacturing engineers since the last decade. AM has evolved as a revolutionary way of manufacturing and assembling the products based on rapidly changing market and customer demands. AM includes both management and technological enablers. Reinertsen (2009) has invited the lean principles from manufacturing into R&D environments and has presented the concepts of product development flow, which to a great extent resemble practices of scrum. Smith (2007) has introduced the concept of flexible product development, which is directly inspired by agile development from software and which has been brought into the domain of product development. Vinodh et al. (2010) claim that CAD and rapid prototyping (RP) technologies are powerful to effect agile product development in traditional organizations. RP technology contributes towards time compression, increased flexibility and cost reduction, which are the main pillars of agile manufacturing. Although alignment among competitive drivers exists, it is difficult for an enterprise to achieve agility because of the lack of an efficient

CONTACT Jože Tavčar joze.tavcar@lecad.fs.uni-lj.si Mechanical Engineering, University of Ljubljana, Ljubljana SI-1000, Slovenia

approach for agile development planning (Potdar and Routroy 2018). The research made by Stare (Stare 2014) showed that many agile practices exist; however, we cannot talk about the systematic agile approach to the development of new products, but about partial approaches that have been established on the basis of best practices from past projects. There exists a need to comprehensively model the agile system with key enablers as well as to find the interdependency that exists between the agile enablers in an unpredictable environment (Aravind et al. 2013).

Staying ahead of the competition requires high responsiveness in terms of supporting late design decisions of a system architecture to narrow down the time gap between design freeze and system delivery. Particularly in small and medium enterprises (SMEs), the agile product development (PD) is of vital importance to maintain product quality with reduced manufacturing costs and remain aligned with the user's needs and wants. However, more than often, PD teams are undersized due to resource constraints, highly dependent on suppliers and required to respond to short development cycles (Chen, Reilly, and Lynn 2012). This context may lead some decision-making to more conventional alternatives because they are perceived as low risk in the short term, but they can undermine the future of the company in the medium and long term. One possible way out of this gridlock is to develop structured methods and optimize them to create value in the PD activities (Leite, Baptista, and Ribeiro 2016).

Due to the complexity, associated cost and general uncertainty of performing the creative design process, significant value exists in reusing the design information developed in previous design efforts. Many complex engineering systems are developed through modifications of existing ones (Jarratt et al. 2011). Many industries, such as the automotive industry, are working on modular designs, with clearly defined interfaces between sub-systems, to make integration easier and to facilitate the reuse of sub-systems across a product range. Since the introduction of adaptable design, continuous efforts have been made to improve the design method. However, there is particularly limited information available regarding business operations that produce a large number of distinctly different part numbers in limited quantities (Qudrat-Ullah, Seong, and Mills 2012). Unlike the automotive or aerospace industries, where the engineering efforts are very intense and the manufacturing processes are clearly defined, in a small-volume, high-variety business, there is minimal time allotted to engineering, and the entire time to market becomes very short.

Agile thinking has been a subject of intensive research in the last decade and it mainly derives from lean thinking, an important global paradigm shift established by Toyota in the late eighties. Lean production encourages the systematic elimination of wastes to produce products and services at the rate of demand (Morgan, and Liker, 2006). Agile production is the capability of a manufacturer to operate profitably in an environment of continually and unpredictably changing customer demand (Ghobakhloo and Azar 2018). Agile production is the next step, after lean production, in the evolution from mass production to mass customization. They are two production strategies that can co-exist in one system. Lean production is the most suitable when the demand is predictable, variety is low and volume is high (Potdar, Routroy, and Behera 2017, Tuli and Shankar, 2015). The agile and lean movements have inspired new approaches, and processes have changed (Turner 2017).

However, new engineering products continue to under-perform with regard to their lead times, cost and quality. There has been comparatively less research done to apply agile to product and process development (PPD). This is rather strange, as PPD has the greatest influence on the profitability of any product (Khan et al. 2013). A lack of application of the lean and agile principles to PD was emphasized also by numerous other authors (Haque and James-Moore 2004; Radeka 2007; Schulze and Störmer 2012). Furuhjelm, Håkan, and Tingström (2011) note that while Toyota's production system – or Lean Production, as it is generally denoted in the West – has been thoroughly researched, the principles and methods applied in Toyota's PD are less understood. Additionally, Baines et al. (2006) argue that this is reflected in the literature on lean product development (LPD), which is not as widespread as the lean production and manufacturing literature. Hoppmann et al. (2011) even argue that there is no consensus on how to precisely define LPD. Al-Ashaab et al. (2016) have presented the development and application of a tool that helps to identify the actual status of the organisation in relation to the lean principles.

Nevertheless, it is obvious that the mechanisms of value creation in the production and PD environment are considerably different.

Based on extensive and systematic research of relevant literature and considerable experience, gained in the real industrial environment producing technically advanced and highly individualized products, this study demonstrates the transformation of a traditional PD environment into a highly efficient process according to agile and lean principles. Based on a real case study, this paper proposes a novel framework of the agile PD process under the demanding conditions of a specific one-of-a-kind industrial environment. In Figure 1, the transition from traditional production (A) to agile production (B) is shown, where robustness, modularity, flexibility and adaptability compound design for changeability, which is, together with parametric structure and smart design rules, a foundation of smart factory and agile business operation. The systematic approach for the complete renewal of PD has resulted in an increased product efficiency and robustness for the overall process. This study sheds light on how to approach such transformation challenges and the presented case study offers valuable insights into how to implement appropriate measurements in a real, highly individualized, PD environment. This field, while well researched, lacks comprehensive coverage of the entire agile implementation process. A generalized form of the proposed framework is the main contribution of this study, as it presents a universal solution for such a specific business environment, thus, filling the mentioned gap in the literature.

2. Literature review

2.1 Agility as a foundation of productivity

Term 'Agile' was introduced in the Agile manifesto in 2001 (Beck et al. 2001). The manifesto was written from the perspective of software development; however, agile is essentially an approach for maximizing success when doing complex projects. Agility enables the industry to deliver customized, equitably priced and superior-quality product in an efficient and time-bound manner by streamlining the internal and external disturbances that arise due to uncertain market conditions. Agile development is a group of development methods based on iterative and incremental development, where requirements and solutions evolve through collaboration between self-organizing, cross-functional teams. It promotes adaptive planning, evolutionary development and

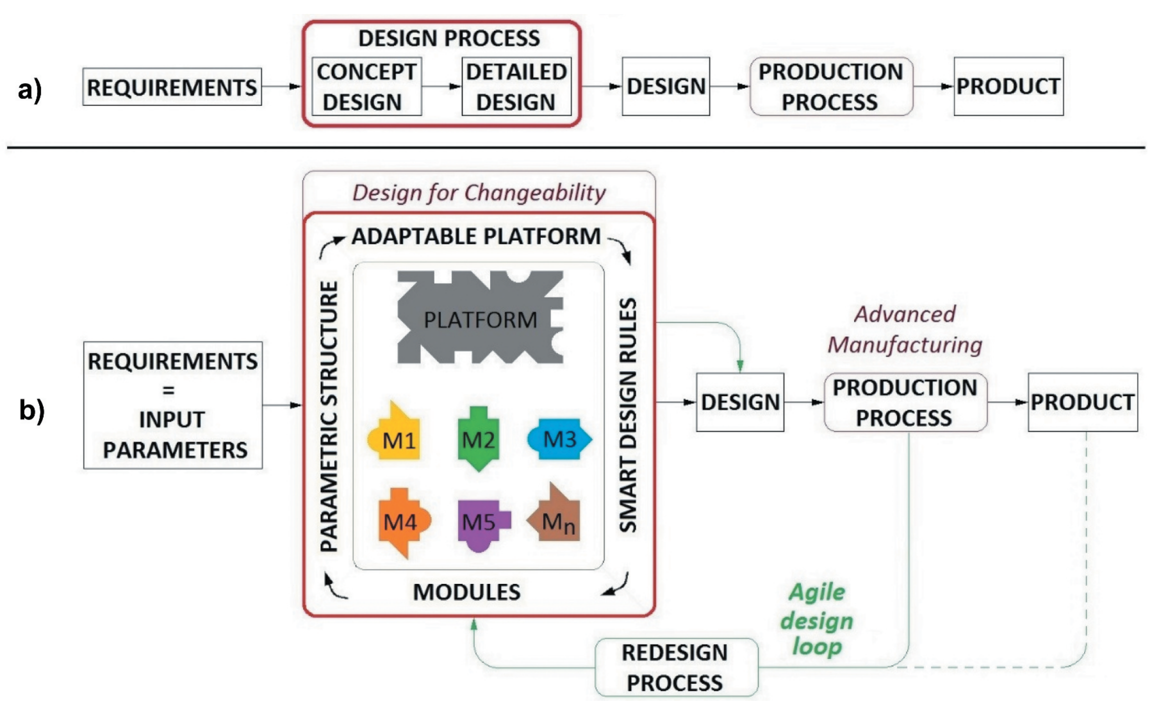

Figure 1. Transition from traditional production to agile production.

delivery, and a time-boxed iterative approach, and encourages rapid and flexible response to change (Leite and Braz 2016; Potdar, Routroy, and Behera 2017). Scrum is an elementary agile method, it is a process framework for managing work on complex products. Scrum makes product management and work techniques efficient and enables continuous improvement of the product, the team and the working environment (Schwaber and Sutherland 2017). Ovesen claims that scrum can be successfully implemented in an integrated product development environment (Ovesen 2012).

Linear product development processes, including the traditional Stage-Gate process, cannot support the iterative cycles and external collaboration that characterize today's product development efforts. Hybrid processes combining elements of Agile and Stage-Gate models offer a more flexible alternative to conventional systems (Sommer et al. 2015). In a complex product development context, some change iterations are unavoidable, and may even be crucial for a successful outcome; thus, the aim should be not to eliminate iterations but rather to induce them at the most productive points of the development process (Leon, Farris, and Letens 2013). When applying agile techniques to the development of complex technical systems, however, existing frameworks known from the software industry not adequately consider the complexity caused by strong interdependencies between and within the system elements (Riesener et al. 2019). Through the early use of simulation software, a simulation-driven development process is aimed at which designers and engineers create a basis for joint developments and thus a basis for discussion, suggestions and new ideas (Enkler and Sporleder 2019). Agile principles in the product development domain require: (i) Collaboration and problem-solving are more important than following a specific procedure. Self-organized teams should be empowered to pursue and resolve issues. (ii) Working prototypes, both physical and digital, are more important than comprehensive documentation. The focus should be on satisfying the requirements for performance. (iii) A customer or equivalent internal representative needs to be involved in the development process. (iv) The organization should be able to respond to issues in an agile and flexible manner (Jackson 2020).

2.2 Background on adaptable design

Adaptable design (Gu, Hashemian, and Nee 2004; Gu, Xue, and Nee 2009) is a relatively new design paradigm that aims to create designs and products that can be easily adapted for different requirements. It is a promising methodology for increasing the potential for the reuse of design information. The methodology encourages a configuration etiquette that makes products generally more adaptable via modularization, platforming and adaptable interfaces (connections between modules and platforms) and increases the corresponding relationships among physical, functional and lifecycle structures while maintaining functional independence. Adaptable design can generally be divided into design adaptability and product adaptability (Gu, Hashemian, and Nee 2004). The process of adapting an existing design, versus producing new designs, usually results in savings in development time and design and production costs. Hanafy and ElMaraghy (2015) have introduced the Modular Product Multi-Platform model to co-design optimal product platforms along with the best number and combinations of corresponding product family members. To discover more about the background on adaptable design, sources Eckert, Clarkson, and Zanker (2004), Fricke and Schulz (2005), Fletcher and Gu (2005), Tavčar and Duhovnik (2005) and Liu, Wong, and Lee (2010) offer valuable insight in this field.

2.3 Design adaptability, product adaptability

Design adaptability is effective in the design process when a population of designs and their realizations (products) exist (Gu, Xue, and Nee 2009). Producers are generally concerned with design adaptability because the benefits of adaptability result from the fact that one adaptable design can be used to create new products for different customers, eliminating the redundancy in the complete re-creation of similar new designs. Thus, the same basic design, existing common parts and assemblies, process plans, production setups, inventories and supply networks, and expertise can be used in several production scenarios, resulting in reduced costs and development time and increased efficiency (Gu, Hashemian, and Nee 2004).

Product adaptability is the capability of a physical product to be adapted to satisfy the changed requirements. It is usually achieved by modifying the existing product, such as adding new components and/or modules, replacing or upgrading the existing components/modules with new ones, and reconfiguring the existing components/modules. The user can benefit from product adaptability by reusing most components/modules of the existing product rather than having to purchase a new product. The common features among large projects, such as power transformers, are substantial cost, time and complexity in design, manufacturing and construction. The design of such large systems is an exceptional case in adaptable design because both design and product adaptabilities are relevant to both the user and the producer (Gu, Hashemian, and Nee 2004).

Product Line Engineering (PLE) is a disciplined approach to constructing a family of products that have commonality in terms of their engineering data. The goal of PLE is to produce product lines with a high degree of reuse of all appropriate engineering data. PLE is a key element of agile product development because the structured approach to modularity and reuse of it promotes and helps to support agile's dynamic refactoring, reprioritization and responsiveness to change (Chard and Douglass 2015).

2.4 Correlation between agile and smart manufacturing

Smart Industry focuses on creating smart products, procedures and processes. Wang et al. (2016) focus on a vertical integration that enables a highly flexible and reconfigurable smart factory. The physical artefacts form a self-organized and autonomous manufacturing system based on big data, an industrial network and an intelligent negotiation mechanism. In the context of intelligent manufacturing, there is a promising predictive diagnosis based on industrial big data (Xu and Hua, 2017; Wan et al. 2017). Nowadays 95.1% of the publications related to Industry 4.0 present a kind of laboratory experiment, while only 4.9% of them present an industrial application (Liao et al. 2017). However, the number of contributions is steadily rising (Thoben, Wiesner, and Wuest 2017; Wang, Törngren, and Onori 2015). Wang et al. (2016), for example, argue that the smart factory framework consists of four layers: 'physical resource', 'industrial network', 'cloud' and 'supervisory control layers'. Big data are collected in the cloud from the smart things in the physical layer and interacts with people through supervisory control. Existing legacy manufacturing systems have limited awareness of the Cyber-Physical System (CPS) requirements and revolutionary design approaches are necessary to achieve the overall system objectives (Gunes et al. 2014).

In serial production, smart manufacturing focuses primarily on shop-floor level and less on development and other supportive processes (Liao et al. 2017). An analogy exists between applying agile methods and smart principles as recognized in Industry 4.0. In both cases, a goal is eliminating unnecessary activities and increasing process robustness. In the one-of-kind production, agile methods have bigger potential for improvements in the development process, because specific technical documentation needs to be created for each manufactured product. Integration of smartness into individualised design processes makes routine work faster and less dependent on human errors. It was a challenge, which took several years, to integrate myriad of designing rules and constraints into a semi-automated product design process. Smart manufacturing principles will be applied, as the next step, to the shop-floor level. Authors argue that the development process re-engineering, according to smart factory principles, has a better return on the investment in one-of-kind production and, therefore, needs to be done first. Based on extensive and systematic literature review approximate framework for the realization of the author's later case study can be formed, Figure 2.

3. Real industrial background

3.1 Sample company presentation

A sample company is a renowned producer of large power transformers with a one-of-a-kind business model. The design of each new power transformer (Figure 3) suits an adaptive type of design (Duhovnik and Tavčar 2015). When a new design problem arises, it is solved through the modification of an existing design rather than performing the design process from scratch. Due to the complexity, associated cost and general uncertainty of performing the creative design process, significant value exists in reusing existent design

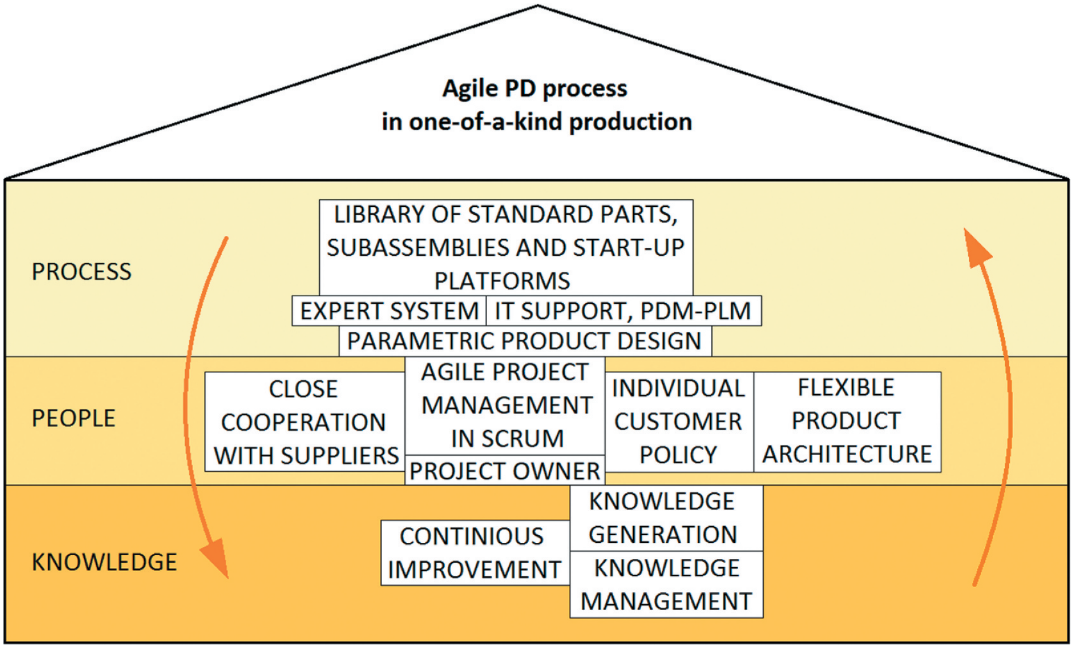

Figure 2. Projection of a house of agile PD Process in one-of-a-kind business environment, based on conducted literature review.

Figure 3. An example of two power transformers, where the same functionality is realized with two very different shape models. Agile PD plays a key role in company competitiveness.

information. Each customer approaches the manufacturer with his or her own set of specific requirements. The basic working principles, as well as the peripheral functional requirements, are fully known, and the design model is well defined. The design begins from the same baseline every time, which is the selection of the appropriate parametric 3D model layout of each respective subassembly. The design and functional characteristics of individual assemblies are generally known in advance. Parametric models consist of parametric subassemblies and parts, the design of which is well considered and based on experience and knowledge of the company, as well as a number of standard components. The essence of the problem for any new design is thus expressed in the search for a new technical shape that would optimally meet the individual requirements of each specific client. Despite a well-structured and content-rich parametric library of start-up assemblies and parts, each new individual contract demands a modification of numerous details, which makes each final product unique. The individualization process includes a parametric change of prepared-in-advance components and sometimes a certain degree of completely new designed components.

4. Research approach

The PD process in the sample company is recognized as the most demanding activity, regarding technical and time-to-market aspects. The biggest part of the company's financial losses is generated through the errors during the PD. Decisions made during the PD process strongly influence all further production activities. A high degree of product individuality has a major impact on the potentially reduced agility of the design process. Authors argue that on a basis of systematic analysis of a design process and product structure, it is possible to establish a smart system of information and methodological support and reorganize the activities in a way that makes a design process and product configuration agile and thus effective.

The next chapter presents in detail a case study and the resultant generalized novel framework of the design process for one-of-a-kind production (OKP) environment. The framework is based on a combination of agile and lean methodology. The demonstrated framework is the result of a 5-year intensive research that led to an extensive transformation of a traditional PD environment into a highly efficient process according to agile principles. Because of clarity and conciseness, authors divided the agile and lean principles into three main groups: Process, People and Knowledge (Figure 4).

As it turned out, the principles under the groups of People and Knowledge may be generalized in a great manner. Furthermore, the principles of the group Process are complex and strongly define any PD process. They have to be attentively tuned with the nature of the respective PD process. Agility cannot be simply introduced into one-of-a-kind business environment, rather it has to be individually altered to optimally accommodate the respective process.

5. Case study and agile methodology specific for one-of-a-kind production

5.1 Process level

The customer is always the starting point of any process. Adding value is defined by the customer's (perceived) value. It is a never-ending journey of waste elimination. Waste is what costs time, money and resources, but does not always add value from the customer's perspective. Value stream mapping (VSM) is an important tool of the lean approach (Dal Forno et al. 2014), which strives to place sequential operations in the correct order to ensure a smooth execution of PD activities. In a case study, PD transformation started with the definition of a strategic action plan, based on the value stream analysis. The company got, in this way, an accurate and broad picture of the current business state. Premature convergence on the wrong solution involves undesired costs throughout the product life cycle. Taking

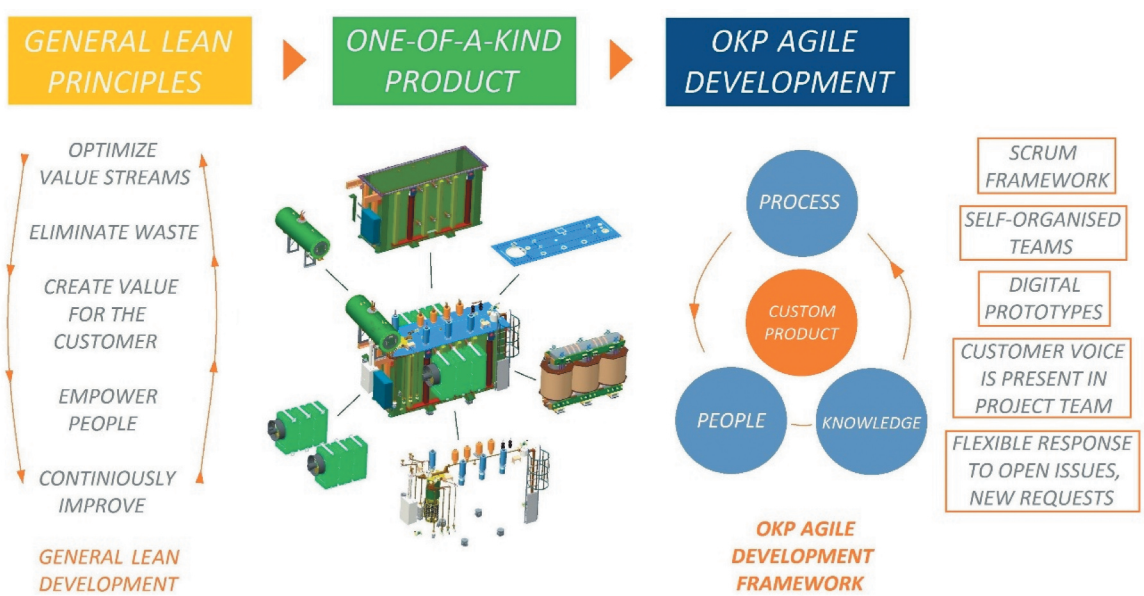

Figure 4. Research approach. General agile and lean principles were altered according to one-of-a-kind production attributes to optimally accommodate the respective process.

time to thoroughly explore alternatives and solve anticipated problems at the root cause has exponential benefits. In the adaptive type of PD process, a new design problem is usually solved through the modification of an existing design solution rather than performing the design process from scratch. Although there is always a certain degree of components which undergo a completely new design, quick and robust adaptation of pre-existing design solutions remains the major part of the discussed one-of-a-kind PD process (to discover more about robust design in OKP domain, see Varl, Duhovnik and Tavčar (2015)). This is the reason why the aspect of reasonable standardization is so important. The challenge is to reduce variation while preserving the creativity that is necessary for the creative process. Standardization enables the creation of highly stable and predictable outcomes with both quality and timing in an unpredictable environment. Table 1 presents applied actions to transform the case study PD process in Process domain.

5.2 People level

Negotiation is the period when the customer and the product manager work out the details of a delivery, with points along the way where the details may be renegotiated. Collaboration is a different creature entirely. With development models such as Waterfall, customers negotiate the requirements for the product, often in great detail, prior to any work starting. This meant the customer was involved in the process of development before development began and after it was completed, but not during the process. The Agile manifesto describes a customer who is engaged and collaborates throughout the development process, making. This makes it far easier for the development to meet the needs of the customer. Agile methods may include the customer at intervals for periodic demos, but a project could just as easily have an end-user as a daily part of the team and attending all meetings, ensuring the product meets the business needs of the customer. Such a philosophy is called Scrum – a lightweight, iterative and incremental framework for managing product development (Figure 5). A key principle of Scrum is the dual recognition that customers will change their minds about what they want or need and that there will be unpredictable challenges – for which a predictive or planned approach is not suited.

One of the important principles of lean philosophy is levelling the flow. It starts with stabilizing the process to be predicted and appropriately planned. This allows product planning to reduce major swings in workload. Another important aspect is the development of a functional design team hierarchy via proper project team formation. The chief engineer is the master architect with the final authority and responsibility for the entire PD process. He is not just a project manager, but a leader and technical system integrator. This unique role

Table 1. Summary of applied actions to transform the PD process in Process domain.

Development phase	Principle, tool, method used	Result, achievement
1.1 Analysis of state – definition of value and separation of waste	• Introduction of applicable lean-based tools: IDEF0, VSM.	• Detailed map of existing process architecture, • Identification of process weak points – confirmed excessive fragmentation of information field.
1.2 Process improvement – IT development, introduction of advanced software solutions	• Implementation of expert system, • Unification of data transfer, • Introduction of effective data management solutions (PDM/PLM system).	• Standardized merging of relevant product data, • Transparent information flow, • Controlled generation, processing and implementation of data, • To some degree automated decision-making (reduced of human factor), • Advanced allocation of rights, • Setup of a change management protocol, • Setup of a functional link between all members of PD personnel, inside scrum team.
1.3 Exploring alternative solutions – working prototypes, both physical and digital, are more important than technical documentation	• Development of advanced, highly modular, start-up assemblies, • Application of parametric modelling and numerical simulations.	• Considerable development and design time savings (approximate average: 3D design: −50%; drawings: −20%; total time: −30%), • Significant increase in the product quality, • Reduced human factor, • Fast and detailed generation of virtual prototypes.
1.5 Enhancing standardization to create flexibility and predictable outcomes	• Development of a highly modular design structure, • Consolidation of design techniques, • Development of a library of standard part subassemblies.	• Facilitated exchange of components among coupled subassemblies, • Enhanced reusability of components and predictability of design.

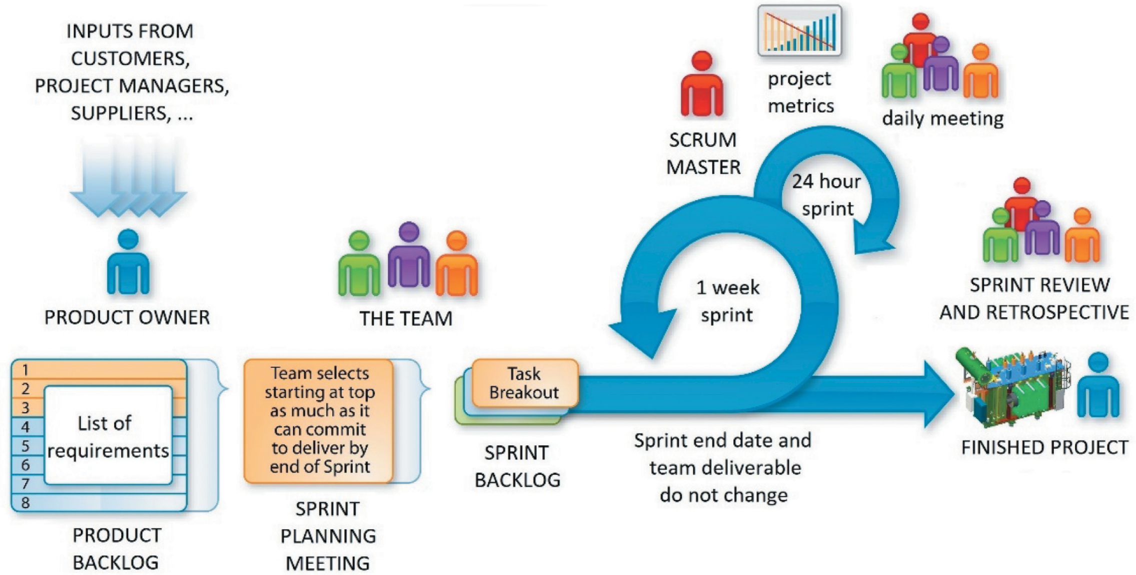

Figure 5. Scrum framework is used for self-organised project team.

Table 2. Summary of applied actions to transform the PD process in People domain.

Development phase	Principle, tool, method used	Result, achievement
2.1 Creating a levelled product development process flow.	• Professional growth of crucial personnel, • Building up engineering knowledge, • Creating a flexible buffer zone with raising skilled, multi-purpose experts.	• Boosting up self-confidence, • Decrease in waste due to staff dependencies and respective excessive waiting times.
2.2 Developing a functional design team hierarchy with product owner and scrum master – collaboration and problem solving are more important than following a specific procedure.	• Formation of project teams and work according to scrum principles, • Setting-up a scrum framework, • Empowered self-organized teams, • Promotion of new project managers and design team leaders.	• Positive changes in individual's attitude, • Increased team awareness, • Higher autonomy of the self-organised design team, • Clear overview over the design and development process, • Improved communication between all the respective parties.
2.3 Integration of suppliers – a customer needs to be involved in the development process.	• In-depth analysis of bilateral production preferences and capabilities, • Product owner has regular contacts with customer.	• Building-up awareness about key value-added properties, • Prompt validation of virtual prototypes.

is the glue that should hold the whole PD system together.

Table 2 presents the applied actions to transform the case study PD process in People domain. Figure 6 shows the transformation process of people during the case study. The transition from a traditional quasi-concurrent to a fully concurrent engineering process with a robust project team structure is shown.

5.3 Knowledge level

Organizational learning is a necessary condition for continuous improvement, which builds on all of the other principles. The ability of a company to learn and improve may well be the most sustainable competitive advantage. Constant interaction with suppliers, enriching engineering knowledge and investing in human resources seem to be the most important aspects of this domain. Toyota's short development lead times are combined with its unparalleled ability to learn, as the organization creates fast and effective learning cycles, which accelerate their continuous improvement engine. The DNA of Toyota is about very strongly held beliefs and values that are shared across managers and working-level engineers. These core beliefs

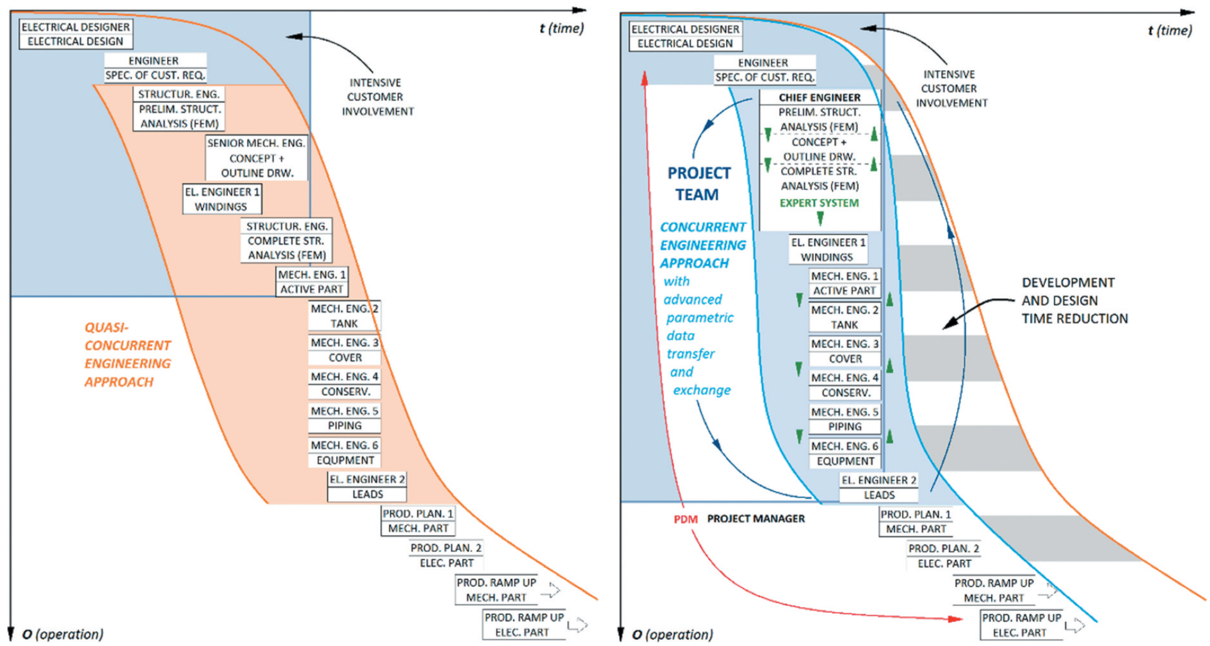

Figure 6. Demonstration of the transformation process of people during the case study. Transition from traditional quasi-concurrent engineering process (left) to fully concurrent engineering process with a robust project team structure (right) resulted in a significant reduction of development and design time, as well as considerable gains in the field of process efficiency.

Table 3. Summary of applied actions to transform the PD process in Knowledge domain.

Development phase	Principle, tool, method used	Result, achievement
3.1 Creating, learning and continuously improving organization – the organization should be able to respond to issues in an agile and flexible manner.	• Constant interaction with suppliers, • Building up engineering knowledge.	• Gained specific production and technology knowledge, • Deepened engineering expertise, • Sustainable PD process on technological feasibility domain, • Sharp decline of rework activities.
3.2 Adapting technology to fit people and process.	• Optimization of software tools, • Standardization of PD process tasks, • Persisting in mutual agreements and applied business strategy.	• Consolidated PD process architecture, • Reliable, transparent and predicted process flow, • Enabled a long-term process perspective.

compel the organization to work harmoniously toward common goals. The presented case study confirmed this assertion. Technology must be customized and always subordinated to the people and process. Adding technology to a fundamentally flawed PD system will do little to help performance, and may even retard it, especially for the short term. Optimization of software tools, combined with a standardization process, is therefore of great importance whereas the retention of applied decisions, over the longer period, is also crucial. Table 3 presents the applied actions to transform the case study PD process in Knowledge domain.

5.4 Product level – modularity, platforming and product family design

An aspect that greatly influences adaptability, flexibility and agility is the concept of modularity. The underlying principle of a segregated architecture is to prevent changes in some parts of the product from propagating to the rest of it. A segregated architecture encourages the development of self-contained and relatively independent (or loosely connected) assemblies or modules that can be detached, modified, relocated and replaced easily. Products with a segregated architecture are usually modularized, and modifications are performed via replacement or local changes of these modules. In this context, a ‘module’ refers to any sub-assembly that can be relatively easily and non-destructively detached from the rest of the product (Gu, Hashemian, and Nee 2004). Modular design aims to develop a product architecture consisting of physically detachable units (modules) (Gershenson, Prasad, and Zhang 2004; Jose and Tollenaere 2005). Because the modules in a modular product are relatively independent, these modules can be designed and manufactured separately. There are numerous advantages to modular products. For example, by carefully modularizing a product, the designs for the earlier models can be used in a new model without any changes.

Figure 7 presents the synergy of physical and parametric modularity, which was, during this research, found to be crucial for the transformation of a traditional development and design process into a highly efficient operation of almost unlimited design flexibility and short time-to-market performance. On the first level (configuration design/physical modularity), a general product architecture is defined via selection of an appropriate platform for each product subassembly. The level-1 smart loop enables an efficient configuration design process because all platforms are interchangeable due to the unified connecting interfaces. The level-2 smart loop enables an exchange of parameters between the first

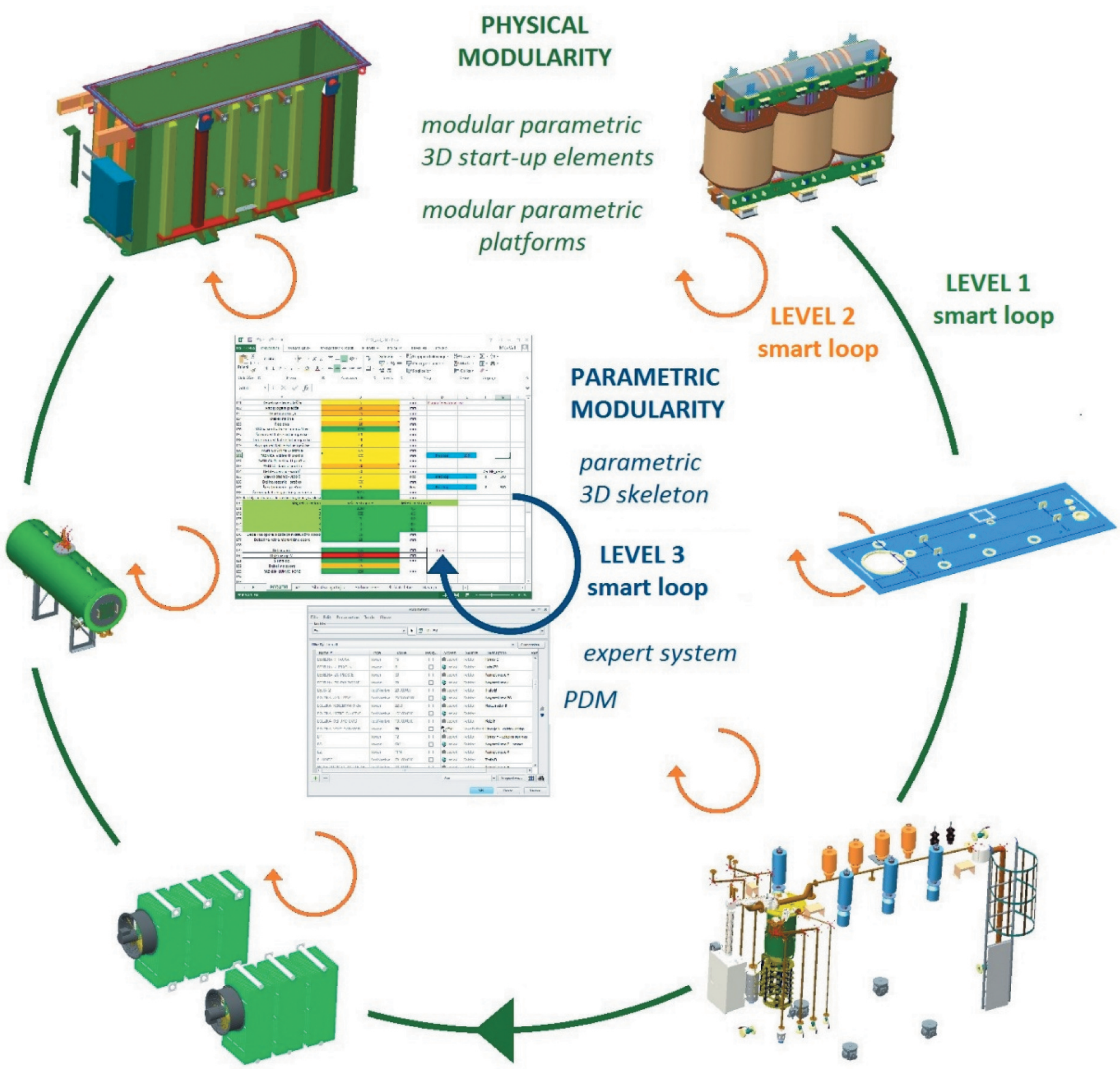

Figure 7. Synergy of physical and parametric modularity in a highly individualized business environment with smart loops on different levels. Subsystems have been mutually linked with a substantial number of self-aware components. Typical major subassemblies of a power transformer (from the upper left, clockwise): tank, active part, cover, equipment, cooling system and conservator.

and third levels. On the third level (detailed design/ parametric modularity), the detailed product architecture is set via the flow of parameters, where parametric modularity enables effective design iterations in the case of late design changes.

Further on, product platforming focuses mainly on offering high product variety to customers while reducing development and manufacturing costs. In platform design, the common components for a number of products are grouped as the platform to be shared by these products (Jiao, Simpson, and Siddique 2007; Simpson, Siddique, and Jiao 2007). The products sharing the same platform usually form a family of products. Simpson, Maier, and Mistree (2001) identified three categories of platforms. *General Platform* design generally entails the identification of common attributes within a series of products, otherwise referred to as a product family. Generally, a platform is any set of standardized parameters, which are maintained within a group of products for compatibility.

Component Standard Platforms unify manufacturing issues in multiple products by using common components whenever possible. *Modular Platforms* use modules from more than one product so that common parts are used whenever possible. Following another classification, product platforms can be classified into two categories: modular and scalable platforms (Simpson, Siddique, and Jiao 2007). During this research, a scale-based platform approach for creating variants with different performance requirements by 'stretching' or 'shrinking' the platforming elements has been proved to be an efficient tool for custom or small-scale PD. Figure 8 shows an example of a fully parametric 3D platform, which, when developed and launched, achieved substantial design time savings, up to 40% in comparison to the former, step-by-step design process.

6. Generalized model of agile one-of-a-kind product development process transformation

The presented case study is the result of several years of systematic academic research and intensive collaboration with a real industrial production environment dealing with specific, highly individualized production. Focus has been put on the development and design process of a complex one-of-a-kind product. On the basis of previously described principles, merged into the master engineering paradigm – Agility – the transformation of a usual PD and design process into highly efficient business operation was performed. Figure 9 presents a generalized framework of such PD process transformation.

As Figure 9 indicates, the transformation process has been divided into three consecutive main phases: the preparation process, classification process and redesign process. The deliberately executed preparation process is of particular importance, while careful product decomposition into relatively independent subassemblies is crucial for a subsequent successful

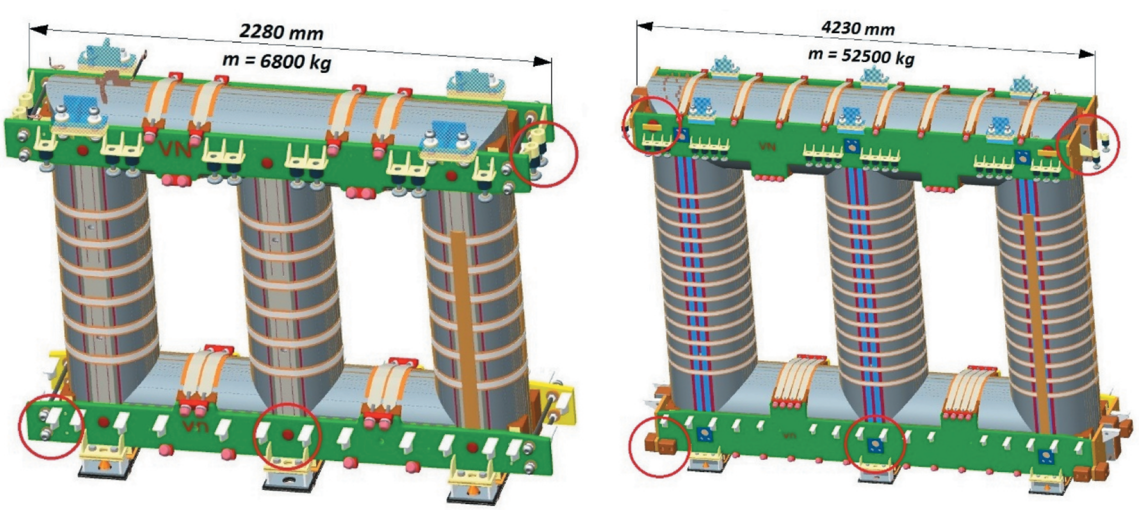

Figure 8. Fully parametric 3D platform of a magnetic circuit. The scalable platform with built-in modular attributes (marked with red circles) enables the model to be customized and adjusted according to new design parameters and customer specifications in a considerably short amount of time. The efficient iterative process enables late design decisions.

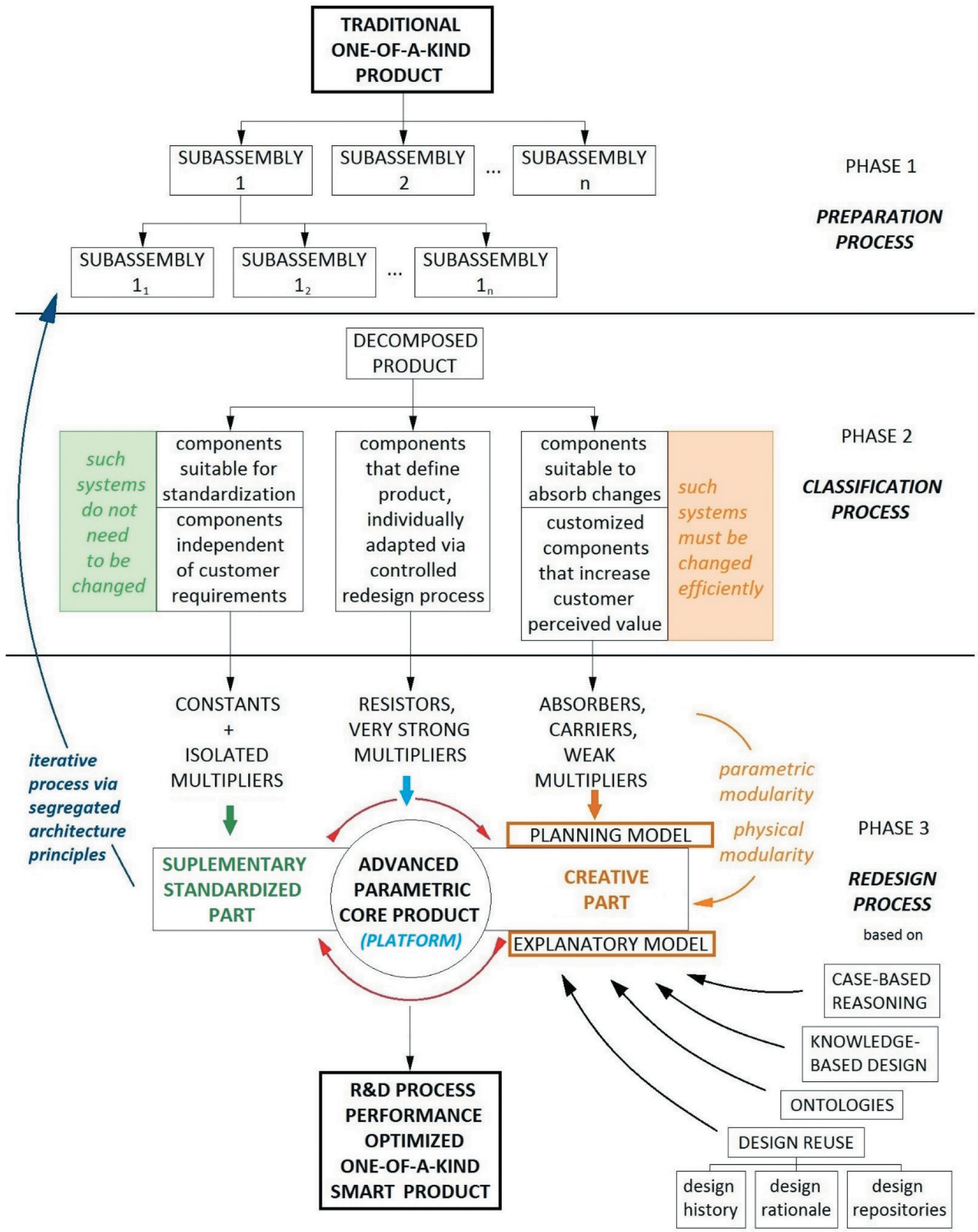

Figure 9. Proposed generalized framework of a highly efficient one-of-a-kind PD process transformation according to the principles of agility.

classification process. Decomposition has to yield three main groups of components. The core group comprises characteristic components that define the product. They are individually adapted to certain project requirements via controlled process re-engineering.

This means that any modification is done with special concern, as any changes to those components usually mean almost certain accommodations to adjacent, usually subordinated subsystems. In another group, components suitable for standardization are classified. Those components are usually very important for the agility of the entire process. Although they are usually not of great importance to customers, they simplify the structure of the product in means of standardized solutions, especially in detailed design. With their help, any individual project gets a certain degree of large-scale product characteristics. The last group of components contains components suitable for the absorption of changes. Such components are typical for one-of-a-kind production since they increase customer-perceived value. Their numerousness generally dictates the market success of a product.

In the third, the process re-engineering phase, numerous tools are encouraged to be used: case-based reasoning, knowledge-based design, ontologies, design reuse and others. Authors have noticed that certain barriers and limitations nevertheless exist. One of the main issues in the described transformation process is finding an optimum degree to which design reuse should be limited. Exaggeration in this domain can make the development and design process less creative, which leads to design fixation and cursory exploration of possible design alternatives. The research indicates that an optimum degree of standardization combined with design reuse may be different for any specific production environment. In the future, research activities will be focused on the further development of proposed framework with its introduction into other applicable one-of-a-kind production environments. In the case of large power transformers, product knowledge was integrated into product development tools such as standard parts, parametric models and platform design. Additional research will be conducted in the field of knowledge management (KM) and how generalised KM can be integrated into PDP.

7. Discussion and assessment

The Toyota Product Development System has been a widely studied and researched engineering paradigm in the past two decades as it represents a fundamental and universal engineering approach to an efficient PD process in serial production environments. In mass industry, even a tiny optimization can, over time and via numerous repetitions result in significant savings. Lean development of individualized products pursues other objectives. Successful management of never-ending engineering changes seems to be the most important aspect of this field. Accordingly, introducing lean into a highly individualized production environment is mostly about enhancing the robustness of the new PD process, which leads to minimization of rework activities, reinforced reputation on the market and overall excellence of a company. This work aims at delivering a generalized framework of lean philosophy introduction into OKP environment. It demonstrates how companies in such specific business environment can improve their profitability through the utilization of LPD concepts.

The principles of modularity, platforming and product family design have been known for quite some time and have proven themselves even before paradigms of lean and agile industry started to redevelop modern industrial guidelines. On top of that, industry is currently turning an important chapter with the outbreak of smart industrial practices, joined under the meaningfully designated term Industry 4.0. Our research team has seen this fact as a significant opportunity to link known optimization principles together with the latest trends in the field of digitally developing processes. The idea to completely break off a custom end-product with a purpose of its redesign with the platform as its core, standardized components on one side and individualized components on the other side, linked with carefully designed interfaces that enable the modular and effective design of product families, has proven itself as a key to restructuring the business operation and ensuring long-term competitiveness. Alternately, it is believed that these effects can even be multiplied when all of these principles are upgraded with a smart digital background in means of parametric flow management, introduction of a PDM/PLM system and introduction of an expert system, which represents product digital core and incorporate self-deciding and learning algorithms.

In the previous chapter, an in-depth analysis of PD process renovation, according to agile philosophy in OKP production environment, indisputably

Table 4. Complete list of savings, resulting in agile PD process renovation according to agile philosophy.

Item	Number of inputs	Number of input sources	Number of outputs	Number of output sources	T_{PREP} [min]	T_{3D} [hrs]	T_{DRW} [hrs]	T_{TOTAL} [hrs]	Project rate [/year]	EC rate [%]
Before implementation	12	9	8	7	60	16	24	40	45	5
After implementation	4	4	4	4	10	5	18	23	78	1
Performance improvement	8	5	4	3	50	11	6	17	33	4
	67%	56%	50%	43%	83%	69%	25%	43%	73%	80 %

Table 5. Proposed generalized framework of a robust, agile process in one-of-a-kind PD environment.

Principle		Crucial aspects, goals	Tools, methods, activities
PROCESS DOMAIN	1.0 Individualized customer policy.	Unlimited individualization possibilities represent a key value-added attribute in customer perceived product value.	Standardize the product architecture instead of a set of available components to ensure modular design structure with unlimited interchangeability of components.
	2.0 Standardized design approach.	Turn the development and design departments into efficient and easy manageable environments with predictable outcomes.	Establish a library of standard parts, subassemblies and start-up platforms. Consolidate the design approach and standardize the design techniques.
	3.0 Extensive data management with advanced IT support.	Transparent overview over relevant project data and its appropriate management gets difficult as the complexity of a product increases. Established overall data management is a key feature of robust PD process.	Minimize fault generation, automate and accelerate the design process with IT development. Introduce expert system, establish parametric data flow and apply PDM/PLM systems.
PEOPLE DOMAIN	4.0 Involvement of suppliers.	Timely definition of feasible product regions reduces PD time and enhances product and process efficiency.	Establish long-term partnerships. Develop professional competences (generate new knowledge) with mutual exploration of new design possibilities.
	5.0 Scrum team structure.	Concurrent cooperation of independent experts results in maximum time performance with advanced and deepened special knowledge and skills acquired by individuals.	Establish a clear project team hierarchy in scrum. Promote a project owner, a competent link between customers, suppliers and production, and convert the design team to suit a conveyor belt philosophy.
KNOWLEDGE DOMAIN	6.0 Knowledge generation.	Constant investments into development of products enhances multiple aspects: creativity, productivity and the competitive position of a company.	Establish research and development team(s), responsible for the generation of a new knowledge. Research activities run in parallel with current work. They are tested on concrete projects, predefined milestones and are brought to production after positive, technical and economic validation.
	7.0 Knowledge management.	Preserving and mastering knowledge gained from previous projects is essential for competent and efficient new PD process. Experience shows that almost any 'new' solution has once already been discovered.	Establish a knowledge database system. Promote mentoring between senior engineers and new associates. Transform into a continuous-learning organization.
	8.0 Company's culture transformation to agile.	Every successful change begins with a change in mind-set. A company has to strive for continuous improvement of its processes.	Persist in introduced changes. Taking shortcuts usually return the process to its starting point.

showed that lean principles, known from mass industry, could generally be introduced in such a specific business environment. However, several adjustments are inevitable, as both business models differ substantially in some crucial aspects. Table 4 shows a detailed list of savings, which were recognized as a direct consequence of implied renovation. The values in this table were obtained via the performance analysis of conducted projects of a sample subassembly (in this case magnetic core) during a one-year test period. Although results for different subassemblies may vary, a similar general trend was noticed. Significant savings were recorded despite varying the specifics of each individual subassembly. In Table 5, a generalized framework of a robust, LPD process for one-of-a-kind PD is proposed.

T_{PREP} = time for preparation. All necessary data for an uninterrupted design process are gained during this time.

T_{3D} = time necessary for the completion of a 3D design of the featured assembly (magnetic core).

T_{DRW} = time necessary for the completion of a corresponding technical documentation.

T_{TOTAL} = total design time (T_{3D} + T_{DRW})

Project rate = number of realized projects per year (per person).

EC rate = percentage of realized projects where engineering change was necessary (rework).

Figure 10 shows the number of completed projects in mechanical design department for the studied product segment together with the number of realised engineering changes. The analysis clearly shows a considerable drop in necessarily engineering changes, which are the consequence of non-optimal product design and are usually initiated during the manufacturing process on the basis of encountered product discrepancies. The results are in direct association with the enhanced robustness of the development and design process. The sample company experienced radical changes during the renovation presented by this case study as explained in Table 1–3 in detail. Analysis of state with the definition of value and separation of waste was initiated with the introduction of relevant lean-based tools (i.e. IDEF0, VSM). As relevant data was gained, the core of the PD and design process was taken into consideration. Turning the company towards a smart factory, an expert system was implemented and effective data management solutions (i.e. PDM/PLM system) were introduced. Standardization was enhanced on several levels. Special focus was put on the development of standardized design processes, highly modular design structure, consolidation of design techniques and a library of standard part subassemblies.

Parallel to Process level, progress was made also on people and knowledge level. Project teams with flexible organisation, a project management office that efficiently links the departments of Design, Sales and Procurement, together with building up engineering knowledge through most experienced staff, were recognized to be among the most important measures. Constant interaction with suppliers was confirmed to be essential for the long-term quality assurance. Individualized production turned out to be strongly dependent on specific production, technology knowledge, and reliable, robust and predicted process flow (Varl, Duhovnik, and Tavčar 2016). Based on this, the authors propose a competent-standardized framework of a robust, LPD process in one-of-a-kind PD environment (Table 5).

8. Conclusions

This study presented an extensive transformation of an illustrative example of one-of-a-kind PD process according to agile and lean principles. The focus of comprehensive renovation has been placed on reducing waste and increasing agility and smartness of the design process in a specific, highly individualized production environment, which would create a robust basis for efficient manufacturing process. A valuable contribution of this study is the demonstration of an appropriate action plan of a renovation process. Transfer of optimization principles, techniques and tools into a highly individual type of production is possible and can be efficient and beneficial in a great manner when certain rules and limitations are taken into consideration. The results of the featured research are very promising in multiple aspects and offer various opportunities for further development. The proposed framework (Table 5) is generalized, which makes it directly applicable in similar business environments.

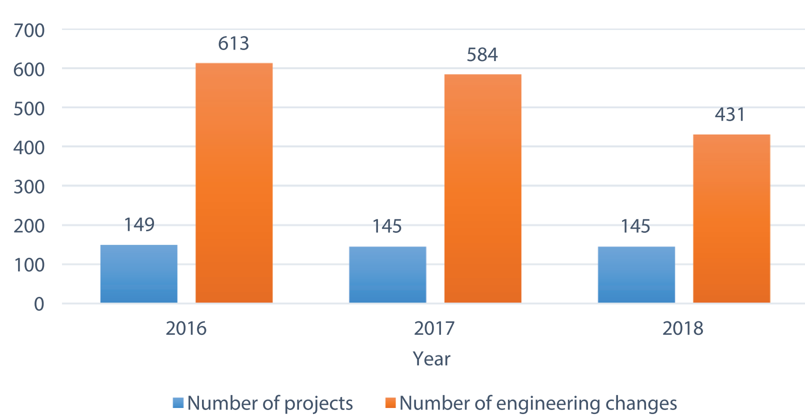

Figure 10. Engineering changes per year in comparison to completed projects.

An important part of agility is designed for changeability. Modularity, platforming and product family design are recognised as strategic principles that enable design reuse. Upgrade opportunities and the ease of customization lead to high attractiveness to customers or stakeholders. Design reuse aims to maximize the value of customization efforts by reusing successful past design information in whole or in part for future designs. More often than not, when a new design problem arises, it is solved through modification of an existing design rather than performing the design process from scratch. Due to the complexity, associated cost and general uncertainty of performing the creative design process, significant value exists in reusing design information. The ultimate aim of design reuse is to assist the designer in the development of high-quality products that meet all customer requirements while expending the least amount of effort and resources. Conducted research demonstrates that the exposed issue is complex; therefore, its professional width requires the cooperation of the entire company. In practice, reduction of waste means finding the most reliable and least time-consuming way to design a product that would fully meet the customer's requirements and preferences. It has been proved that management can set the stage for an effective and long-term agile PD organization by developing holistic solutions and designing standardized systems combined with highly efficient platform designs that consider modularity and scalability coupled with a consideration to reduce indirect costs.

Quantitative analysis (Table 4 and Figure 9) indicates that the proposed approach results in extensive savings in all relevant business aspects. Savings are expressed as a combination of direct savings (reduced development cycle-time, time-to-market, rework, man-hours, etc.) and indirect savings (improved data flow along processes, improved knowledge management, increased company reputation, etc.). The collaborative work and goal-driven team motivation, particularly during the design phase, help to reduce quality issues and a number of changes during later phases. The proposed approach facilitates a mutual knowledge build-up, improves motivation and enhances effectiveness due to the optimized PD process phases according to agile and lean principles, combined with collaborative development, proactive information exchange and unified project data management policy. Despite the specific case presented in this study, the results indicate a possible and reasonable wider application of the proposed approach in the OKP domain. The contribution of this study is the introduction of a modified generalized approach for complete PDP renovation according to agile principles, where several aspects have importantly been adjusted to fit into the OKP business model. Moreover, this study offers a valuable insight into its possible merits. The results and findings will provide valuable managerial and academic insight into the development and design domains for the integration of agile principles, thus helping to establish the best practice guidelines for promoting competitiveness in one-of-a-kind PD process.

Acknowledgments

This work was partly supported by Slovenian Research Agency – ARRS, grant number contract no. P2-0265.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Slovenian research agency – ARRS [contract no. P2-0265].

ORCID

Jože Tavčar http://orcid.org/0000-0001-9046-0913

References

Al-Ashaab, A., M. Golob, U. A. Urrutia, M. Gourdin, C. Petritsch, M. Summers, and A. El-Nounu. 2016. "Development and Application of Lean Product Development Performance Measurement Tool." *International Journal of Computer Integrated Manufacturing* 29 (3): 342–354. doi:10.1080/0951192X.2015.1066858.

Aravind, R. S., A. Sudheer, S. Vinodh, and G. Anand. 2013. "A Mathematical Model to Evaluate the Role of Agility Enablers and Criteria in A Manufacturing Environment." *International Journal of Production Research* 51 (19): 5971–5984. doi:10.1080/00207543.2013.825381.

Baines, T., H. Lightfoot, G. M. Williams, and R. Greenough. 2006. "State-of-the-art in Lean Design Engineering: A Literature

Review on White Collar Lean." *Journal of Engineering Manufacture* 220: 1539–1547. doi:10.1243/09544054JEM613.

Beck, K., M. Beedle, A. van Bennekum, A. Cockburn, W. Cunningham, M. Fowler, and D. Thomas 2001. "Principles behind the Agile Manifesto. Manifesto for Agile Software Development." Accessed 20 January 2020. http://www.agilemanifesto.org/principles.html

Chard, J., and B. P. Douglass. 2015. *Agile Product Development for Dummies*. NJ: John Wiley & Sons.

Chen, J., R. Reilly, and G. Lynn. 2012. "New Product Development Speed: Too Much of a Good Thing?" *Journal of Product Innovation Management* 29 (2): 288–303. doi:10.1111/j.1540-5885.2011.00896.x.

Dal Forno, A. J., F. A. Pereira, F. A. Forcellini, and L. M. Kipper. 2014. "Value Stream Mapping: A Study about the Problems and Challenges Found in the Literature from the past 15 Years about Application of Lean Tools." *International Journal of Advanced Manufacturing Technology* 72: 779–790. doi:10.1007/s00170-014-5712-z.

Duhovnik, J., and J. Tavčar. 2015. "Concurrent Engineering in Machinery, Chapter 22.." In *Concurrent Engineering in the 21st Century: Foundations, Developments and Challenges*, edited by J. Stjepandić, N. Wognum, and W. J. C. Werhagen, Cham [etc.], 639-670. Springer International Publishing Switzerland.

Eckert, C., P. J. Clarkson, and W. Zanker. 2004. "Change and Customisation in Complex Engineering Domains." *Research in Engineering Design* 15 (1): 1–21. doi:10.1007/s00163-003-0031-7.

Enkler, H.-G., and L. Sporleder. 2019. "Agile Product Development—coupling Explorative and Established CAx Methods in Early Stages of Virtual Product Development." *Procedia CIRP* 84: 848–853. doi:10.1016/j.procir.2019.04.221.

Filho, M. F., Y. Liao, E. R. Loures, and O. Canciglieri. 2017. "Self-aware Smart Products: Systematic Literature Review, Conceptual Design and Prototype Implementation." *Procedia Manufacturing* 11: 1471–1480. doi:10.1016/j.promfg.2017.07.278.

Fletcher, D., and P. Gu 2005. "Adaptable Design for Design Reuse." *Second CDEN international conference on design education, innovation, and practice*, Canada.

Fricke, E., and A. P. Schulz. 2005. "Design for Changeability (Dfc): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle." *Systems Engineering* 8 (4): 342–359. doi:10.1002/sys.20039.

Furuhjelm, J., S. Håkan, and J. Tingström. 2011. "Creating Value through Lean Product Development – Applying Lean Principles." *Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design*, Vol. 1: Design Processes, Lyngby/Copenhagen, Denmark.

Gershenson, J. K., G. J. Prasad, and Y. Zhang. 2004. "Product Modularity: Measures and Design Methods." *Journal of Engineering Design* 15 (1): 33–51. doi:10.1080/0954482032000101731.

Ghobakhloo, M., and A. Azar. 2018. "Business Excellence via Advanced Manufacturing Technology and Lean-agile Manufacturing." *Journal of Manufacturing Technology Management* 29 (1): 2–24. doi:10.1108/JMTM-03-2017-0049.

Gu, P., D. Xue, and A. Y. C. Nee. 2009. "Adaptable Design: Concepts, Methods, and Applications." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 223 (11): 1367–1387. doi:10.1243/09544054JEM1387.

Gu, P., M. Hashemian, and A. Y. C. Nee. 2004. "Adaptable Design." *Manufacturing Technology* 53 (2): 539–557.

Gunes, V., S. Peter, T. Givargis, and F. Vahid. 2014. "A Survey on Concepts, Applications, and Challenges in Cyber-physical Systems." *KSII Transactions on Internet and Information Systems* 8 (12): 4242–4268.

Hanafy, M., and H. ElMaraghy. 2015. "A Modular Product Multi-platform Configuration Model." *International Journal of Computer Integrated Manufacturing* 28 (9): 999–1014. doi:10.1080/0951192X.2014.941407.

Haque, B., and M. James-Moore. 2004. "Applying Lean Thinking to New Product Introduction." *Journal of Engineering Design* 15: 1–31. doi:10.1080/0954482031000150125.

Hoppmann, J., E. Rebentisch, U. Dombrowski, and T. Zahn. 2011. "A Framework for Organizing Lean Product Development." *Engineering Management Journal* 23 (1): 3–15. doi:10.1080/10429247.2011.11431883.

Jackson, C. 2020. "Agile Product Development Processes." *Internet blog*. Accessed 20 January 2020. https://www.lifecycleinsights.com/tech-guide/agile-product-development-processes/

Jarratt, T. A. W., C. M. Eckert, N. H. M. Caldwell, and P. J. Clarkson. 2011. "Engineering Change: An Overview and Perspective on the Literature." *Research in Engineering Design* 22 (2): 103–124. doi:10.1007/s00163-010-0097-y.

Jiao, J., T. W. Simpson, and Z. Siddique. 2007. "Product Family Design and Platform-based Product Development: A State-of-the-art Review." *Journal of Intelligent Manufacturing* 18 (1): 5–29. doi:10.1007/s10845-007-0003-2.

Jose, A., and M. Tollenaere. 2005. "Modular and Platform Methods for Product Family Design: Literature Analysis." *Journal of Intelligent Manufacturing* 16 (3): 371–390. doi:10.1007/s10845-005-7030-7.

Kagermann, H., W. Wahlster, and J. Helbig. 2013. "Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0." Berlin: Industrie 4.0 Working Group of Acatech.

Khan, M. S., A. Al-Ashab, E. Shehab, B. Haque, P. Ewers, M. Sorli, and A. Sopelana. 2013. "Towards Lean Product and Process Development." *International Journal of Computer Integrated Engineering* 26 (12): 1105–1116. doi:10.1080/0951192X.2011.608723.

Lee, J., B. Bagheri, and H. A. Kao. 2015. "A Cyber-physical Systems Architecture for Industry 4.0-based Manufacturing Systems." *Manufacturing Letters* 3: 18–23. doi:10.1016/j.mfglet.2014.12.001.

Leite, M., A. J. Baptista, and A. M. R. Ribeiro. 2016. "A Road Map for Implementing Lean and Agile Techniques in SMEs Product Development Teams." *International Journal of Product Development* 21 (1): 20–40. doi:10.1504/IJPD.2016.076922.

Leite, M., and V. Braz. 2016. "Agile Manufacturing Practices for New Product Development: Industrial Case Studies." *Journal* of Manufacturing Technology Management 27 (4): 560–576. doi:10.1108/JMTM-09-2015-0073.

Leon, H. C. M., J. A. Farris, and G. Letens. 2013. "Improving Product Development Performance through Iteration Front-loading." *IEEE Transactions on Engineering Management* 60 (3): 552–565. doi:10.1109/TEM.2012.2228205.

Liao, Y., F. Deschamps, E. F. R. Loures, and L. F. P. Ramos. 2017. "Past, Present and Future of Industry 4.0 - A Systematic Literature Review and Research Agenda Proposal." *International Journal of Production Research* 55 (12): 3609–3629. doi:10.1080/00207543.2017.1308576.

Liu, Z., Y. S. Wong, and K. S. Lee. 2010. "Modularity Analysis and Commonality Design: A Framework for the Top-down Platform and Product Family Design." *International Journal of Production Research* 48 (12): 3657–3680. doi:10.1080/00207540902902598.

Morgan, J. M., and J. K. Liker. 2006. *The Toyota Product Development System: Integrating People, Process and Technology*. New York, NY: Productivity Press.

Ovesen, N. 2012. "The Challenges of Becoming Agile: Implementing and Conducting Scrum in Integrated Product Development." PhD diss. Denmark, Aalborg: Department of Architecture & Design, Aalborg University.

Potdar, P. K., and S. Routroy. 2018. "Analysis of Agile Manufacturing Enablers: A Case Study." *Materials Today: Proceedings* 5: 4008–4015.

Potdar, P. K., S. Routroy, and A. Behera. 2017. "Agile Manufacturing: A Systematic Review of Literature and Implications for Future Research." *An International Journal* 24 (7): 2022–2048.

Qudrat-Ullah, H., B. S. Seong, and B. L. Mills. 2012. "Improving High Variable-low Volume Operations: An Exploration into the Lean Product Development." *International Journal of Technology Management* 57 (1–3): 49–70. doi:10.1504/IJTM.2012.043951.

Radeka, K. 2007. "The Toyota Product Development System: Integrating People, Process and Technology – Book Review." *Journal of Product Innovation Management* 24: 274–281. doi:10.1111/j.1540-5885.2007.00250_1.x.

Reinertsen, D. G. 2009. *The Principles of Product Development Flow - Second Generation Lean Product Development*. CA, USA: Celeritas Publishing.

Riesener, M., E. Rebentisch, C. Dölle, S. Schloesser, G. Schuh, J. Radermacher, and G. Schuh. 2019. "A Model for Dependency-oriented Prototyping in the Agile Development of Complex Technical Systems." *Procedia CIRP* 84: 1023–1028. doi:10.1016/j.procir.2019.04.196.

Schulze, A., and T. Störmer. 2012. "Lean Product Development – Enabling Management Factors for Waste Elimination." *International Journal of Technology Management* 57 (1–3): 72–91. doi:10.1504/IJTM.2012.043952.

Schwaber, K., and J. Sutherland. 2017. "The Scrum Guide. The Definitive Guide to Scrum: The Rules of the Game." Accessed 20 January 2020. https://www.scrum.org/Scrum-Guide

Simpson, T. W., J. R. A. Maier, and F. Mistree. 2001. "Product Platform Design: Method and Application." *Research in Engineering Design* 13 (1): 2–22. doi:10.1007/s001630100002.

Simpson, T. W., Z. Siddique, and J. Jiao, Eds. 2007. *Product Platform and Product Family Design, Methods and Applications*. Berlin: Springer.

Smith, P. G. 2007. *Flexible Product Development: Building Agility for Changing Markets*. California: John Wiley & Sons.

Sommer, A. F., C. Hedegaard, I. Dukovska-Popovska, and K. Steger-Jensen. 2015. "Improved Product Development Performance through Agile/stage-gate Hybrids: The Next-generation Stage-gate Process?" *Research-Technology Management* 58 (1): 34–45. doi:10.5437/08956308X5801236.

Stare, A. 2014. "Agile Project Management in Product Development Projects." *Procedia – Social and Behavioral Sciences* 119: 295–304. doi:10.1016/j.sbspro.2014.03.034.

Tavčar, J., and J. Duhovnik. 2005. "Engineering Change Management in Individual and Mass Production." *Robotics and Computer-integrated Manufacturing* 21 (3): 205–215. doi:10.1016/j.rcim.2004.07.017.

Thoben, K. D., S. Wiesner, and T. Wuest. 2017. "Industrie 4.0 And Smart Manufacturing – A Review of Research Issues and Application Examples." *International Journal of Automation Technology* 1: 4–16. doi:10.20965/ijat.2017.p0004.

Tuli, P., and R. Shankar. 2015. "Collaborative and Lean New Product Development Approach: A Case Study in the Automotive Product Design." *International Journal of Production Research* 53 (8): 2457–2471. doi:10.1080/00207543.2014.974849.

Turner, R. 2017. "The Impact of Agile and Lean on Process Improvement." *CrossTalk, the Journal of Defense Software Engineering* 30 (2): 4–7.

Varl, M., J. Duhovnik, and J. Tavčar. 2016. "Towards a Model for Robust Design and Design Process in One-of-a-kind Production of Large Power Transformers." *International Journal of Agile Systems and Management* 9 (1): 67–88. doi:10.1504/IJASM.2016.076578.

Vinodh, S., S. R. Devadasan, S. Maheshkumar, M. Aravindakshan, M. Arumugam, and K. Balakrishnan. 2010. "Agile Product Development through CAD and Rapid Prototyping Technologies: An Examination in a Traditional Pump-manufacturing Company." *International Journal of Advanced Manufacturing Technology* 46 (5–8): 663–679. doi:10.1007/s00170-009-2142-4.

Wan, J., S. Tang, D. Li, S. Wang, C. Liu, H. Abbas, and A. Vasilakos. 2017. "A Manufacturing Big Data Solution for Active Preventive Maintenance." *IEEE Transactions on Industrial Informatics* 13 (4): 2039–2047. doi:10.1109/TII.2017.2670505.

Wang, L., M. Törngren, and M. Onori. 2015. "Current Status and Advancement of Cyber-physical Systems in Manufacturing." *Journal of Manufacturing Systems* 37 (2): 517–527. doi:10.1016/j.jmsy.2015.04.008.

Wang, S., J. Wan, D. Zhang, D. Li, and C. Zhang. 2016. "Towards Smart Factory for Industry 4.0: A Self-organized Multi-agent System with Big Data Based Feedback and Coordination." *Computer Networks* 101: 158–168. doi:10.1016/j.comnet.2015.12.017.

X. Xu and Q. Hua. 2017. "Industrial Big Data Analysis in Smart Factory: Current status and research strategies." *IEEE Access* 5: 17543-17551.