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DESIGN FOR INDUSTRIE 4.0

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1. Introduction

In todays competitive market environment companies face the challenges of short product lifecycles, a need for individualized products in small market segments [Schuh et al. 2014c,d] and the customers' demand for an integration of software in hardware products due to a higher customer benefit [ElMaraghy et al. 2013], [Porter et al. 2014]. In order to stay competitive in the market, companies need to shorten their time to market, be able to offer highly customized products and integrate the customer in the development process [Schuh et al. 2015]. Additionally, Industrie 4.0 (the German word for the Fourth Industrial Revolution, also known as Industry 4.0 or Industrial Internet) is one of the most famous trends in recent years addressing the interconnection of machines, people and products. Schuh et al. pursue the vision that the core characteristics of Industrie 4.0 is a raise in collaboration productivity [Schuh et al. 2013], [Schuh et al. 2014a], [Schuh et al. 2014b]. They provide a reference system with underlying mechanisms for a higher collaboration productivity. This reference system consists of the two indicators “return on engineering” and “return on production”. In the following paper the focus lies on the part of "return on engineering".

As the title shows, this paper introduces a new design approach, namely Design for Industrie 4.0. Intelligent products require a whole set of new design principles [Porter et al. 2014]. Therefore, product development must be adapted fundamentally in the context of Industrie 4.0.

Today Industrie 4.0 mainly focuses on production, but a greater effect can be reached by an implementation of Industrie 4.0-specific design guidelines. Based on the well-known cost curve of Ehrlenspiel, after which the later costs of products may be affected especially in the early phase [Ehrlenspiel 2014], Industry 4.0 must be integrated as early as possible in the product lifecycle to achieve significant benefits (cf. Figure 1). This does not mean, however, that the progress of Industry 4.0 in production is not beneficial, but that the integration must also be employed in the early stages of product development.

Today there is no holistic approach that considers the challenges in product development concerning the integration of Industrie 4.0, namely the consideration of software and the development of smart products. Changes on product and process side have to be made in order to address these challenges.

The remaining paper is organized as follows. In the second chapter related work concerning Design for X and Industrie 4.0 is presented. The third chapter deals with the challenges of product development in the context of Industrie 4.0. In the fourth chapter a framework for Design for Industrie 4.0 is developed. The fifth chapter elaborates the key elements of the framework and the paper closes with a short conclusion in chapter six.

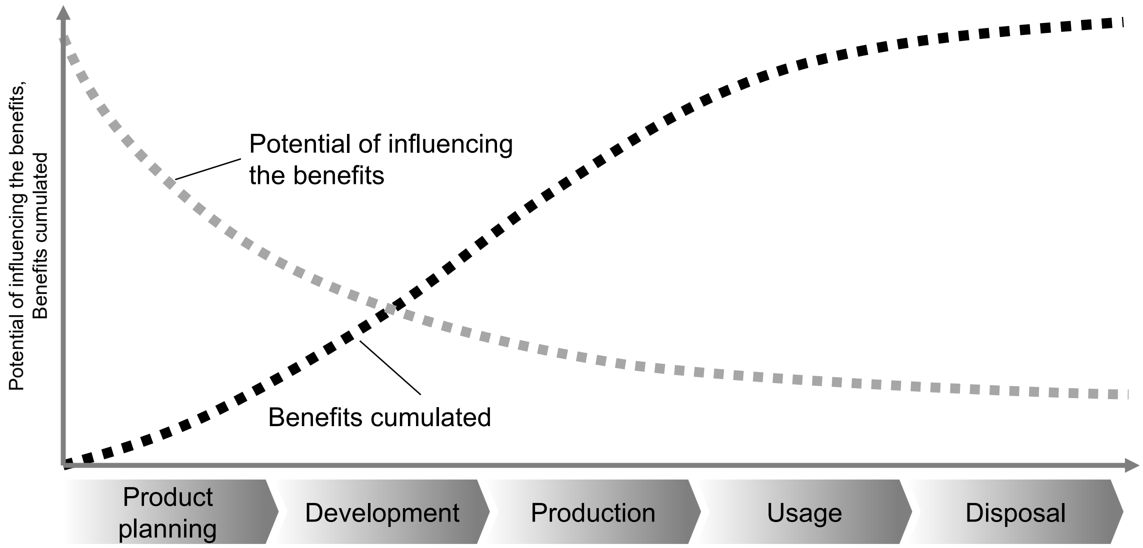


Figure 1. Influencing benefits and cumulated benefits along the product lifecycle (based on [Ehrlenspiel 2014])

2. Related work

As the title of the paper shows the paper deals especially with two topics, Design for X and Industrie 4.0. In the following sections the main related work concerning these topics is introduced shortly.

2.1 Design for X

Design for X (DfX) attempts to consider equally the usually contradictory product requirements and to find the best possible compromise between them [Hermann et al. 2004]. In the past, many different forms of Design for X have been developed, which touch the whole product lifecycle from development until recycling, for example Design for Quality, Design for Manufacturing and Assembly, Design for Serviceability or Design for Environment. All of these Design for X-approaches do have their place, but all of them only address a section of the requirements for a new product. One of the most famous Design for X-approaches is Design for Manufacturing and Assembly (DFMA) by Boothroyd et al. [2010]. Design for Manufacturing means the design for ease of manufacturing of the collection of parts that will form the product after assembly and Design for Assembly means the design of the product for ease of assembly [Boothroyd et al. 2010]. The approach consists of two elements, namely design guidelines concerning the product itself (for example designing a part that has the maximum possible symmetry about axis of insertion) and recommendations concerning the development process (for example an early integration of production into the development process). Based on the example of DFMA it can be seen that a holistic Design for X-approach needs to consider both product and process aspects.

2.2 Industrie 4.0

Having dealt with Design for X in the first section, the second section deals with the second part of the paper title, Industrie 4.0. The German word Industrie 4.0 stands for the fourth Industrial Revolution, focusing on collaboration based on the Internet of Things [Kagermann et al. 2014]. Words used in a similar context are Industry 4.0 and Industrial Internet. The core of every industrial revolution is an increase in productivity [Schuh et al. 2014a], [Schuh et al. 2014b]. Previous industrial revolutions had a strong impact on the "Shopfloor"-level and the production processes itself. The impact of the fourth Industrial Revolution, however, is more extensive and, in addition to the production, it affects indirect departments, especially engineering processes [Schuh et al. 2014b]. Literature dealing with the current industrial change differs widely and often addresses highly diverse aspects of Industrie 4.0. Therefore, different definitions of Industrie 4.0 exist. One of the well-known definitions is given by the German

Academy of Science "acatech": At the center of Industry 4.0 is the real-time, intelligent, horizontal and vertical networking of people, machines, objects and ICT systems for a dynamic management of complex systems [Kagermann et al. 2014]. As the definition reveals, the development of connected devices is one of the main enablers for Industrie 4.0. Figure 2 shows that in the past ten years the number of connected devices have increased heavily from about 1 billion objects to 18.2 billion objects in 2015 [The Connectivist 2015]. The slope of the graph will be even steeper in the future, so Industry 4.0 is located at the so called Tipping Point of the development. The term Tipping Point refers to a point or moment at which a previously straight and clear development abruptly breaks, changes direction or is greatly accelerated [Gladwell 2006].

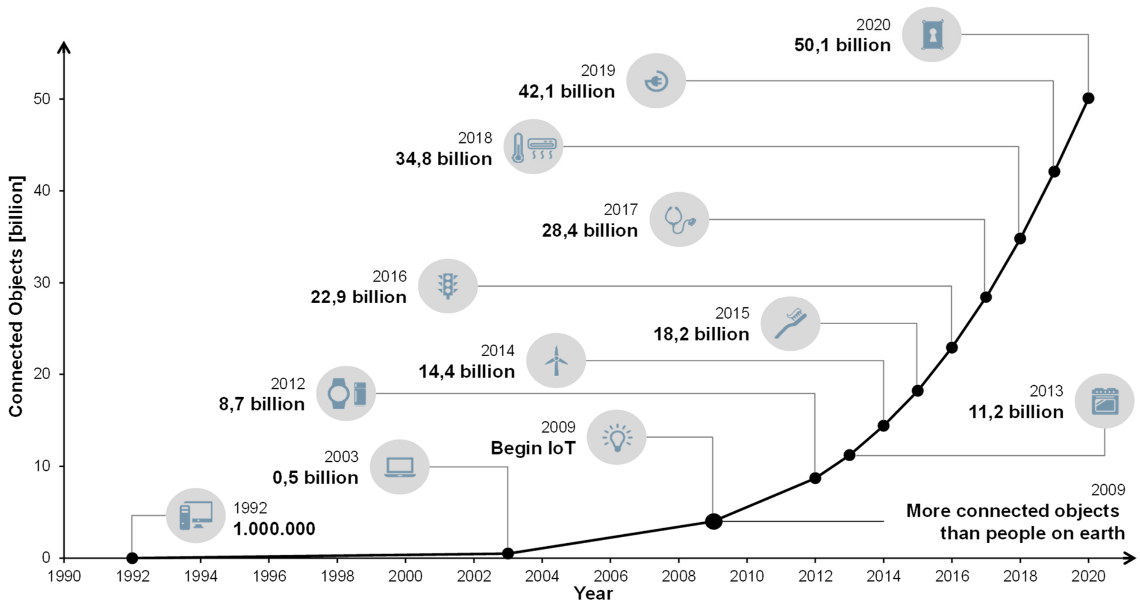


Figure 2. Development of Internet of things [The Connectivist 2015]

Enablers that will increase the speed of the development significantly are, for example, the lower sensor and the associated automation options. Other reasons are the increasing network connectivity, computer power and storage, the distribution of cloud-based services, and finally the customers that simply expect connected devices. The fourth Industrial Revolution is currently at the tipping point of the development and both companies and researchers need to think about the challenges that come with it in all disciplines of the manufacturing industry. The next section deals with the resulting challenges in product development in the context of Industrie 4.0.

3. Challenges in product development in the context of Industrie 4.0

Having presented the related work concerning Design for X and Industrie 4.0 the next chapter addresses the challenges in the product development that have to be faced in the context of Industrie 4.0. This paper focuses on four main challenges that are further elaborated in the following:

- Orientation
- Data
- Interaction
- Resources

Orientation: Many products, that have been "stupid" in the past, are going to be connected in the future. This means that intelligent products can communicate with each other and can generate significant customer benefits. Compared to a conventional product, the functionality and the possibilities of the business model are larger by a multiple for a connected, smart product. Many established businesses still have to make their way from the non-crosslinked into the connected world. The combination of the different disciplines such as mechanics, software, electronics, and especially the integration of

completely new business model ideas in the product business poses the first challenge for companies in the development in the context of Industrie 4.0. The orientation of what a product should be able to do and the orientation of the necessary product development are often not yet adapted to the new conditions.
Data: On the production side, the transport times, position data, position of the workpieces etc. can be tracked for example by RFID. But which data can be generated and used by product development? There are diverse milestone plans, design data, value stream mapping, but today no high-resolution data, that means very precise information about the product or the development, is available. In indirect areas the digital reality should be included through various data sources as an essential core of Industrie 4.0. Therefore, the second challenge in the context of Industrie 4.0 is that so far there is no systematic approach for the generation and analysis of high-resolution data for products and product development.
Interaction: The third challenge can be explained using the example of the Apollo 8 mission. When the Apollo 8 entered the lunar orbit as the first spacecraft in history on 24 December 1968 NASA Mission Control could only hope that it would come out of the moon's shadow at the right time and at the right speed and would land successfully. The mission was successful, but it would have been much more advantageous if there had been a constant connection to the spaceplane during the entire time. Something similar happens to many businesses today. They stay in contact with the product only until the point of sale and then again, if the device is broken or the customer is complaining. In times of Industrie 4.0 and the associated networking of things this state has to be broken and new mechanisms and ways of interacting must be defined in both the process and product related side.
Resources: One of the basic assumptions of Industrie 4.0 leads to the fourth and final challenge of integrating Industrie 4.0 in the product development: the merging of the physical and virtual world. The resources for this are often insufficiently defined or organized. A recent study of PWC reveals that producing companies usually have more than 100 data-carrying systems [PTC 2014]. Thus, these complex and heterogeneous IT structures prevent the full implementation of the potential benefits. The same goes for the physical side. The resources of 3D printing are still not used or systematically integrated into the development process, either because of relatively high costs or due to the missing of a systematic approach. To put it in a nutshell, there is often a lack of appropriate resources, methods and tools to implement Industrie 4.0 in development.

4. Framework Design for Industrie 4.0

As the previous chapters show there is a need for a holistic approach for the integration of Industrie 4.0 in product development. Designing and developing products for Industrie 4.0 is fundamentally different from principles in the context of system-level design. While system-level design also considers different domains (e.g. mechanics, electronics) it does not take into account the networking between different elements (e.g. products, machines).
Based on the presented basics concerning Design for X and the challenges in the context of Industrie 4.0 the two dimensions of a holistic framework for Design for Industrie 4.0 can be derived. Each of the dimensions of the framework needs to answer different research questions. These questions are defined as follows:
Dimension I: perspectives for Design for X-approaches

- Product: How should a product be designed in the context of Industrie 4.0?
- Process: How should the development process look like in the context of Industrie 4.0?

Dimension II: challenges in product development in the context of Industrie 4.0

- Orientation: How should products and the product development be orientated in the context of industry?
- Data: Which data is available and which role does it play?
- Interaction: How is an Industrie 4.0-specific communication and collaboration defined?
- Resources: Which resources, methods and tools are needed in this context?

The two dimensions span a framework consisting of eight fields (Figure 3). These fields are further elaborated in the next chapter. Each field addresses either the increase of effectiveness (focussing on the product) or the increase of efficiency (focussing on the process) and delivers core recommendations for the development in the context of Industrie 4.0.

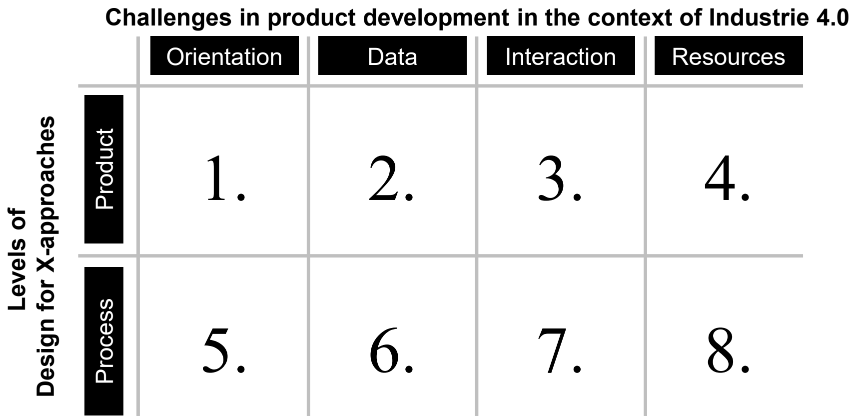


Figure 3. Framework Design for Industrie 4.0

5. Detailled description of key elements of the framework

In this chapter the different fields of the framework will be elaborated and considered in detail. According to Figure 3 the product oriented fields will be presented at first. Afterwards the process oriented fields will be introduced.

5.1 Expansion of existing design guidelines to Industrie 4.0-specific design guidelines

As described before there are several Design for X-approaches in literature and practical work [Hermann et al. 2004]. These approaches remain relevant in the future, however, need to be supplemented by different aspects. An overview of proposals for adjustments that need to be addressed in the context of Industry 4.0 are listed in Figure 4. For example, today's products need to be able to communicate, they need to include cyber-security in addition to a functional safety, they should create insights into products and should be maintained from a distance. Therefore, the different Design for X-approaches need to be examined in detail with respect to the inclusion of the specifics of Industrie 4.0. Companies and researchers need to understand that existing design guidelines for products are no longer completely relevant. Figure 4 delivers some of the main additional aspects that need to be included along the value chain for product optimization.

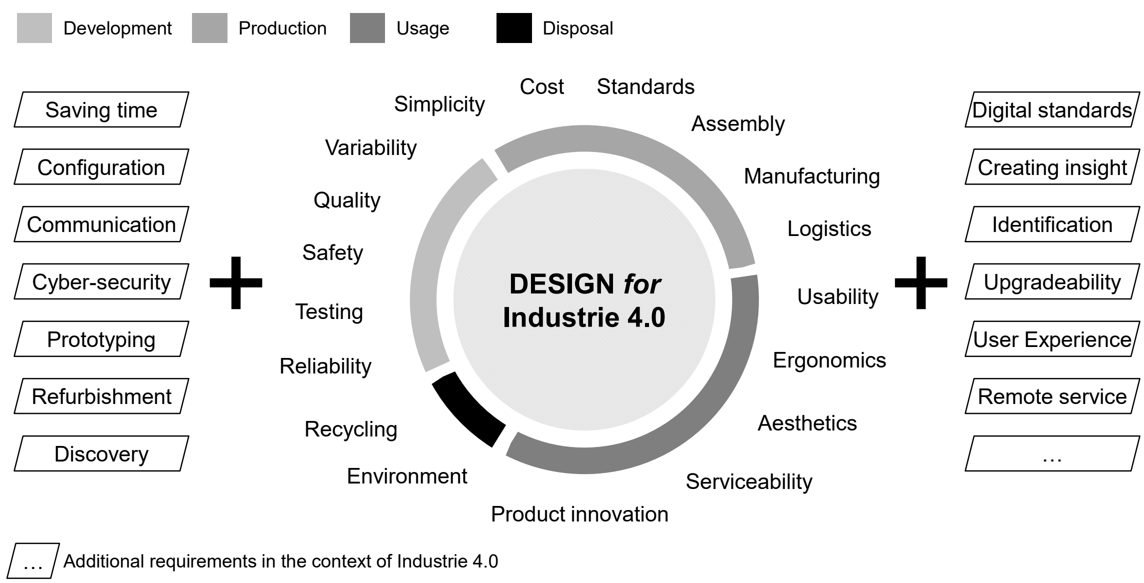


Figure 4. Design for X-approaches in the context of Industrie 4.0

5.2 Usage of high-resolution data by increasing the use of cost-effective active sensors

The second field addresses the usage of high-resolution data for product optimization. On the one hand, product data is very important for customer value creation by smart, connected products in the context of Industrie 4.0, but, on the other hand, collecting data requires sensors, which add cost to the product [Porter et al. 2014]. Sensors require the transmission, the storage, the securing and the analysis of this data. In order to determine which types of data delivered by sensors (e.g. altitude, proximity, accelerometer, moisture, gravity) provide sufficient value relative to cost, companies need to consider questions like the following: How do the different types of data create tangible value for functionality or efficiency in the value chain? Will the data help the firm to improve how the product system is performing and how it could be improved? Figure 5 shows this relationship between the number of sensors and the impact on costs and benefit.

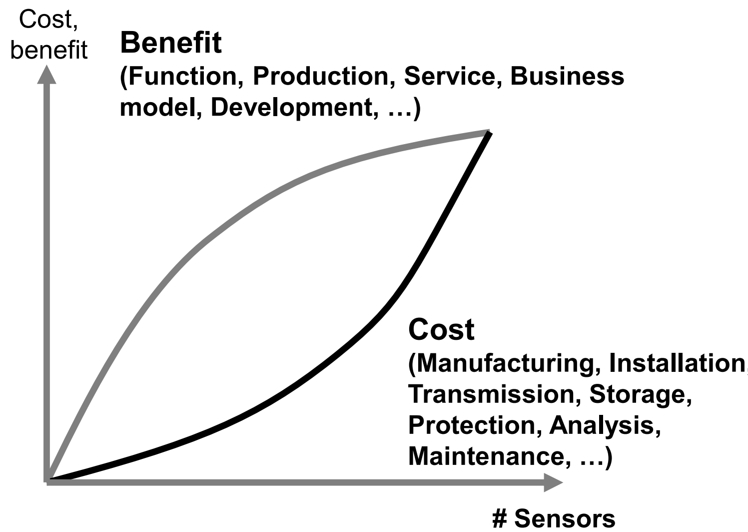
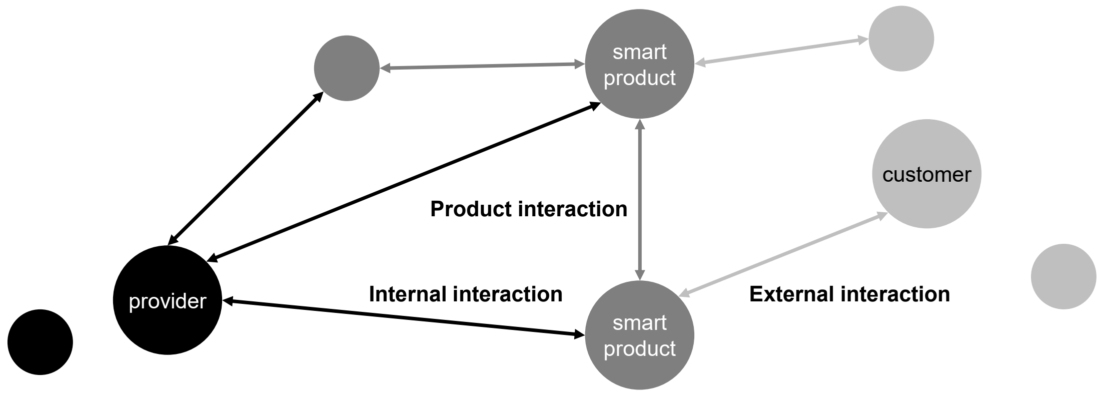


Figure 5. Costs and benefit curve for the integration of sensors into products

5.3 Usage of intelligent products as an information carrier and communication medium

Especially in the early phase of product development data on the usage of the product reveal important information on the usefullness of different functions or design elements. Collecting customer and product information in the testing and usage phase of products enables a 360 degree customers view. Building a "digital shadow" of every product in the field (in some literature also known as "digital twin" with a slightly different meaning) is a first step towards the data driven product optimization. Comparable to a black box in the aviation industry the digital shadow includes all data that can be obtained independently whether they are analyzed today or not. The digital shadow makes it possible to analyse the complete data pool retrospectively in order to identify patterns that can be used for the prediction of future product functionality. For this reason different types of interaction need to be defined (cf. Figure 6). The product itself serves as an information carrier and means of transportation of data [Anderl 2014]. The communication between the company (provider) and the intelligent product is defined as internal interaction and it facilitates regular product updates, maintenance and service and the analysis of usage data. Furthermore, different smart products interact with each other in order to identify themselves, to explore their services and to exchange data with other intelligent products. The third connection, called external interaction, is the networking of the intelligent product with the customer. This enables continuous access to the state of the product, networking with other products and first-level support. The digital shadow of a product makes it possible to communicate with the product about the customer - and not vice versa.

Overall, the usage of intelligent products as an information carrier and communication medium needs to be further detailled by researchers and introduced into practice by companies in order to stay competitive in the markets.



Internal interaction	Product interaction	External interaction
▪ Regular product updates ▪ Maintenance and Service ▪ Analysis of usage data ▪ Product Intelligence	▪ Automatic identification ▪ Exploration services ▪ Independent networking ▪ Exchange of data with other intelligent products	▪ Continuous access to the state of the product by the customer ▪ Networking with other products ▪ First-level support

Figure 6. Types of interaction between provider, smart products and customers

5.4 Complete, redundancy-free data storage in a single source of truth

Finally, the recorded and analysed data need to be stored in one single source of truth. Today, data is collected in many different IT systems, causing redundant or incomplete information. This IT system landscape arises if different supportive IT solutions are used for individual corporate functions. In addition, these solutions are mostly not cross-linked to themselves. In this context, the approach of Product Lifecycle Management (PLM) is an important lever for increasing productivity and reducing costs, both in product development, as well as in all other areas along the value chain. In the future, the PLM system needs to work as a data backbone which is accessed by all other data-carrying systems. An integrated PLM prevents the occurrence of redundancies and inconsistencies in the data so that targeted and efficient work is possible. Therefore, PLM is an essential prerequisite towards a single source of truth. PLM provides concepts for the comprehensive management of product data and for the integration of processes and a system of rights for users across the entire product lifecycle. Thus, data and information on products and their development processes can always be provided free of redundancy and in real time to the relevant people in companies. In the context of Industrie 4.0, where all objects are connected to the Internet of Things, an online access to all relevant product data is a relevant driver for product optimization.

5.5 Simultaneous, horizontally and vertically integrated product and business model development

In the past, many companies only focussed on product innovation, neglecting the chances of business model innovation. In the context of Industrie 4.0 and connected devices more and more business model innovations, often delivered by start-ups, gain significant market success. Therefore, traditional companies need a change in development capacity per discipline, as shown in Figure 7. The mechanical part needs to be reduced according to the share of functions, mechanical parts will take on in the future. Furthermore, developing networks can be helpful for the necessary integration of the vertical value chain across the suppliers and customers. Finally, interdisciplinary project teams lead to an integration of the horizontal value chain and to a better communication and collaboration without thinking and acting in silos. Especially business model development needs to integrate employees from all hierarchy levels in order to integrate the different perspectives on the product specifications.

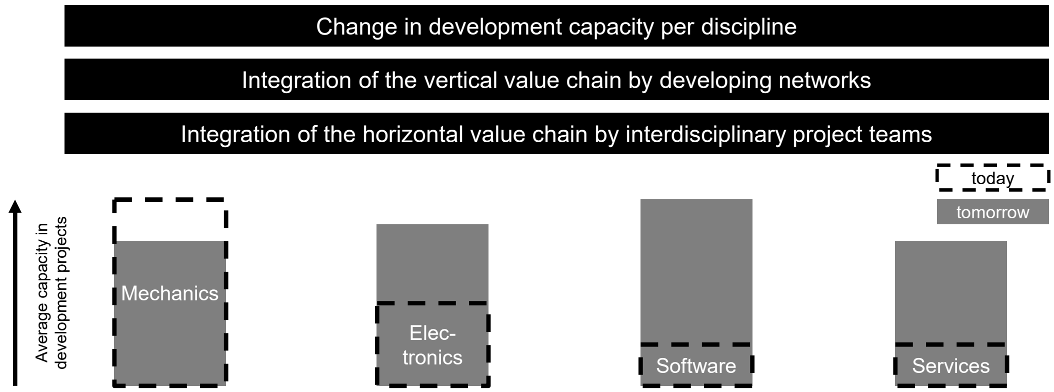


Figure 7. Implications on product and business model development in the context of Industrie 4.0

5.6 Smart Engineering by means of data analysis for efficient and effective execution of development tasks

Section 5.3 dealt with the interpretation of collected data for product improvement. Accordingly, this section deals with the analysis and interpretation of data for the efficient execution of development tasks. In this paper it is proposed to use the different steps of the Knowledge Discovery in Databases-process (KDD-process) for the analysis and steering of the development process. In a first step, companies and researchers need to work on the topic of visibility. Data availability needs to be increased by means of descriptive analytics. In the second step (diagnostic analysis), it needs to be understood, why various problems occur in development projects (e.g. delays, interruptions). Therefore, methodologies for the increased interpretability of large data sets need to be developed. The third step, predictive analytics, deals with the forecasting ability by known patterns and realistic models. These tools answer the question of what happens during the development process in the future based on historical data from previous, similar development processes and activities [Rudolf et al. 2015]. Finally, prescriptive analytics address the adaptability to different starting points by means of an autonomous reaction. Decisions can be made automatically based on the interpretation of smart data, e.g. concerning the definition of upcoming activities in the next phase of the development process.

5.7 Iterative development and data-based market inspection through targeted market expeditions in ecosystems

The development of physical or mechatronical products was perceived as a continual process aimed at executing and solving a single complex task. Including cyber-physical connected products, companies need to consider and adapt techniques from other disciplines like software development in order to react to the faster product development cycles and the required shorter time-to-market. Companies need to make use of the "agile" methodology which is widely used by product development teams in software and IT industries [Schwaber 2004]. Agile uses fast, iterative development cycles over the whole course of the project and integrates the customer in very early stages with roughly specified prototypes [Lorenz et al. 2015]. By doing this product development time can be reduced significantly [Lu et al. 2007]. The objective is to develop a so called "minimum viable product" quickly and then to improve it through iterations. This higly iterative approach stands in constrast to traditional development approaches (e.g. Stage-Gate), which aim to define detailled specifications up front to yield the "perfect" product [Lorenz et al. 2015].
Industrie 4.0 facilitates the usage of smart data for better analysis of the tested prototypes and better understanding and prediction of future customer needs. The highly iterative development process is mainly based on the rapid realization of innovations in prototypes and the high frequency optimization in order to achieve an early product maturity. Short cycles and iterative feedback loops enable fast recalibration and a fast course correction ("fail fast"-mentality) during the whole development process.

The real testing of the "minimum viable product" in so called ecosystems leads to an early feedback of the intended market segment. By analyzing "real prototype market data" the course for the further development can be planned and the development teams can apply the lessons to ensure that the development process stays on the path towards the "right" product for the specific market segment [Lorenz et al. 2015].

5.8 Combined use of Virtual Engineering and Rapid Prototyping for fast development of complex technical systems

The presented optimization proposals can only be realized by the systematic integration of new technologies into the development process. As described in the section concerning the highly iterative development process the physical or virtual realization of prototypes is necessary for early feedback loops and the integration of customers into the development process. Therefore, the necessary resources presented in this section include the possibilities for both the physical and virtual realization of conceptional, functional and geometrical prototypes. On the virtual side, Virtual Engineering enables intuitive interaction with the object, it is decision oriented and it works in real time. In comparison to Digital Engineering the people are at the focus in Virtual Engineering. On the physical side, Rapid Prototyping is supported by the latest developments concerning Additive Manufacturing that enable a fast realization of prototypes without a long and expensive tool development. Along the product development process there is the need for either a virtual or a physical prototype. Today there is no systematic approach that combines these possibilities in a defined process.

Overall, the eight presented and elaborated fields of action build a framework for both researchers and practitioners. According to the orientation of the Design for X-approaches both the product side and the process side need to be redesigned. Products must be aligned considerably more interdisciplinary in the future and need to use sensors in order to act as information carriers and means of communication. This can be realized in a redundancy-free data storage, the PLM system. On the process side, in turn, the development team must be put together differently and development processes must be optimized based on smart data. Through a highly iterative development process based on data analyses customer requests can be integrated faster. For this reason, a combination of virtual engineering and rapid prototyping (e.g. by 3D printing) is necessary.

6. Conclusion and need for research

Due to shorter product lifecycles, the need for more individualized products and the fast development concerning the realization of functions in products via software, the need for a holistic approach concerning the product development in the context of Industrie 4.0 arises. In this paper, a framework has been presented that addresses both researchers and practitioniers working in the field of product development. On the practitioners' side Design for Industrie 4.0 requires a set of eight key methods or advices. These key methods can be implemented according to the actual status of a specific enterprise. From a researcher's perspective this framework can be used for further detailling of the integration of Industrie 4.0 in product development. Each field can be used as the origin for a specific method. The key takeaways from this paper are as follows:

1. Expansion of existing design guidelines to Industrie 4.0-specific design guidelines
2. Usage of high-resolution data by increasing the use of cost-effective active sensors
3. Usage of intelligent products as an information carrier and communication medium
4. Complete, redundancy-free data storage in a single source of truth
5. Simultaneous, horizontally and vertically integrated product and business model development
6. Smart Engineering by means of data analysis for efficient and effective execution of development tasks
7. Iterative development and data-based market inspection through targeted market expeditions in ecosystems
8. Combined use of Virtual Engineering and Rapid Prototyping for fast development of complex technical systems

Further research should focus on the detailling of the respective fields and on the implementation in practical cases. Furthermore, future development will show if the great expectations concerning the benefits of Industrie 4.0 keep on what they promise or if the limitations of Industrie 4.0 (e.g. data security) outweigh the benefits.

References

Anderl, R., "Industrie 4.0 - Advanced Engineering of Smart Products and Smart Production", Technological Innovations in the Product Development, 19th International Seminar on High Technology, Piracicaba, Brazil, 2014.

Boothroyd, G., Dewhurst, P., Knight, W. A., "Product Design for Manufacture and Assembly - Manufacturing Engineering and Materials Processing", 3rd ed., CRC Press, 2010.

Ehrlenspiel, K., "Kostengünstig Entwickeln und Konstruieren", Berlin, Heidelberg, Springer Berlin Heidelberg, 2014.

ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schönsleben, P., Tseng, M., Bernard, A., "Product Variety Management", CIRP Annals - Manufacturing Technology, Vol.62, No.2, 2013, pp. 629-652.

Gladwell, M., "The Tipping Point – How Little Things Can Make a Big Difference", Little, Brown and Company, 2006.

Herrmann, J. W., Cooper, J., Gupta, S. K., Hayes, C. C., Ishii, K., Kazmer, D., Sandborn, P. A., Wood, W. H., "New Directions in Design for Manufacturing", ASME Conf. Proc., 2004, pp. 853-861.

Kagermann, H., Wahlster, W., Helbig, J., "Recommendations for implementing the strategic initiative Industrie 4.0", Acatech, 2013, pp. 13-78.

Lorenz, M., Jentzsch, A., Andersen, M., Noack, B., Waffenschmidt, L., Schuh, G., Rudolf, S., "The Lean Advantage in Engineering", 2015.

Lu, S. C.-Y., ElMaraghy, W., Schuh, G., Wilhelm, R., "A Scientific Foundation of Collaborative Enginereering", CIRP Annals - Manufacturing Technology, Vol.56, No.2, 2007, pp. 605-634.

Porter, M. E., Heppelmann, J. E., "How smart, connected products are transforming competition", Harvard Business Review, November 2014.

PTC, "Intelligent, connected products", ebook, 2014.

Rudolf, S., Dölle, C., "Increasing the Efficiency of Development Projects applying Predictive Analytics", Proceedings of the 2015 IIE Engineering Lean and Six Sigma Conference, 2015.

Schuh, G., Potente, T., Wesch-Potente, C., Hauptvogel, A., "Sustainable increase of overhead productivity due to cyber-physical-systems", Proceedings of the 11th Global Conference on Sutainable Manufacturing – Innovation Solutions, 2013, pp. 332-335.

Schuh, G., Potente, T., Varandani, R., Hausberg, C., Fränken, B., "Collaboration Moves Productivity To The Next Level", 47th CIRP Conference on Manufacturing Systems, 2014a.

Schuh, G., Potente, T., Wesch-Potente, C., Weber, A. R., Prote, J.-P., "Collaboration Mechanisms to Increase Productivity in the Context of Industrie 4.0", Procedia CIRP, Vol.19, 2014b, pp. 51-56.

Schuh, G., Rudolf, S., Riesener, M., "Similarity-based Product Configuration", Proceedings of the 47th CIRP Conference on Manufacturing Systems, Managing Variety in Manufacturing, Windsor, Canada, 2014c.

Schuh, G., Rudolf, S., Riesener, M., "Identifying preferable product variants using similarity analysis", Proceedings of the 2nd CIRP International Conference on Ramp-Up Management (ICRM 2014), Aachen, Germany, 2014d.

Schuh, G., Rudolf, S., Diels, F., "Highly iterative product development process for engineering projects", WGP conference, 2015.

Schwaber, K., "Agile project management with Scrum", Microsoft Press, 2004.

The Connectivist based on Cisco data, "The Internet of Things – an explosion of connected possibility", Available at: <http://www.i-scoop.eu/internet-of-things/>, 2015, [Accessed 18.10.15].

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