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Industrie 4.0 – An empirical and literature-based study how product development is influenced by the digital transformation

Monika Klippert*, Florian Marthaler, Markus Spadinger, Albert Albers

Karlsruhe Institute of Technology (KIT) – IPEK – Institute of Product Engineering, Kaiserstr. 10, 76131 Karlsruhe, Germany

*Corresponding author. Tel.: +49-721-608-47066; fax: +49-721-608-46051. E-mail address: monika.klippert@kit.edu

Abstract

The fourth industrial revolution, referred to as Industrie 4.0 in the German high-tech strategy, is in most cases associated with the industrialization of production, but the term is increasingly broadly understood. Industrie 4.0 means the networking of all areas involved in the value creation process. In areas such as production and politics, visions are already being driven forward, but in the development of products and product-related services it is often unclear how engineering needs to change to realize the potentials of Industrie 4.0. Several research projects are already dealing with the development of new processes, methods and tools to enable these potentials. However, studies show that companies do not have the resources or strategies to implement such solutions. In many ways, the influence of Industrie 4.0 and its impact on product development is still insufficiently known. Therefore, a literature-based study was conducted to systematically identify context factors that characterize Industrie 4.0. In order to analyze the impact on product development, a second step involved an impact analysis with the context factors of Industrie 4.0 onto the context factors of product development known from the literature. In a third step, strongly influenced fields of product development were identified and their relevance for the realization of the potentials of Industrie 4.0 for product development was evaluated in an online survey. In addition, the current status in these fields was analyzed in interviews with experts from industry. With methods of foresight a portfolio was created, which couples the influence of Industrie 4.0 on the context factors of product development with their future robustness. Comparing the current state of development with the findings from the portfolio, recommendations for future research were formulated.

Keywords: Industrie 4.0; digital transformation; product development; influence

1. Introduction

Industrie 4.0, unlike the previous Industrial Revolutions, is not only connected to production, but also with the digital transformation of products, services, business models and all phases of the value creation [1], which is also known as advanced systems engineering [2]. Against the background of long-term trends such as demographic change, scarcity of raw materials and energy and globalization, existing conventional product development (pd) needs to be rethought [3]. For the purpose of this publication, the term product development is understood as defined in [4, 5], but does not include the production and subsequent phases of the product lifecycle. It is essential to design and transform ways of thinking and acting with the organizational and operational structure on the basis of suitable and need-based pd processes, methods and tools in order to be able to handle the increasing complexity [6, 7]. However, the impact that Industrie 4.0 has, is nowadays insufficiently known in many areas outside of production. Therefore, it is necessary to reduce the uncertainty about the emerging changes especially in pd with suitable methods, such as methods of foresight [8]. By using models to describe development contexts, it is possible to better understand development approaches with regard to future scenarios and to adapt them to their respective context [9, 10]. This publication presents the state of research, the aim of research and the methodology to systematically derive the influence of Industrie 4.0 on pd and its behavior with regard to future scenarios. The

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correlations are presented in a portfolio in section 5. Furthermore, recommendations for future research are formulated by comparing the findings of the portfolio with the current state in pd. Section 6 discusses these results and the publication concludes with a brief outlook.

2. State of Research

2.1 Background to Industrie 4.0

Industrie 4.0 today is mostly associated with the industrialization of production. The term did not emerge until 2011 as a future project within the framework of the German High-Tech Strategy [11]. Similar strategic concepts have also been developed in other regions of the world. Terms such as Integrated Industry, Smart Industry, Smart Manufacturing or the Internet of Things (IoT) are used in this context [12]. There are many definitions in the literature, which vary widely in their direction and scope. A clear, generally accepted description of Industrie 4.0 does not yet exist, since essential parts are often interpreted completely different [13]. Although today Industrie 4.0 is primarily associated with production related topics, the term is increasingly broadly understood [1]. Therefore, the new High-Tech Strategy 2025 systematically considers the entire value chain - from the creative idea to its implementation in new products and services - and thus links all aspects and stakeholders of the innovation process [11].

2.2 Industrie 4.0 in product development

The increasing digitalization and connection of the real world with the digital world is changing people's everyday lives, markets, business relationships and value chains. This represents a major challenge for companies, because in order to sustainably secure or expand their competitiveness, organizations must adapt quickly and react to the impending changes. In particular, the processes of developing and producing products and services will change significantly. [14]

Abramovici et al. list a large number of studies about Industrie 4.0 that have already been published in the last years that address these challenges [1]. The studies show that engineering has a central and increasing importance to realize the potential of Industrie 4.0, because Industrie 4.0 not only means making production smarter, more efficient, faster and more economical, but also concentrating on engineering and the exceptional capabilities of engineers in the development of innovative products and production systems [15]. The influence of Industrie 4.0 on pd processes has not been systematically analyzed yet [16] but it represents a completely new challenge with a multitude of open questions [1].

2.3 Challenges in product development to realize the potentials of Industrie 4.0

Reducing the expenditure and increasing efficiency of engineering processes as well as higher innovative power are examples of potentials that can be realized through Industrie 4.0. However, pd faces various challenges. Automation and optimization of business processes are major challenges [17]. In particular, connecting all stakeholders involved in value creation is a difficulty. To enable this integration, one of the potentials lies in the use of data [18]. Even if all data is integrated, the main challenge is to make it available to people in a suitable form. At this point in most areas, applications isolated from each other are used in static infrastructures, resulting in data silos that hinder access to and transfer of information [19]. With the generation and aggregation of large amounts of data and sensitive user information, there are a variety of security and privacy issues coming up [20]. On the other hand, the use of data enables the development of new product-related business models that can lead to a higher customer satisfaction and create access to new markets [21]. These are only some of the many examples that describe the challenges in pd to realize the potentials of Industrie 4.0. In order to cope with these challenges, new approaches are needed, because the constantly growing complexity of products and services, such as the processes required for their development, cannot be managed permanently with conventional processes, methods, and tools [15].

2.4 Scenarios for product development

Due to the changes caused by digital change, it is necessary to consider future requirements in pd [22]. Therefore, forecasting methods enable the estimation and management of future developments, with which entrepreneurial decisions can be made under uncertainty [23]. Marthaler et al. provide a methodically derived and expertly validated basis for the targeted research and development of robust methods for the future [24]. This systematic approach combines activities of foresight with the activities of pd and uses the description model of PGE – product generation engineering as a basis [25]. The approach is based on seven consecutive steps that contains three different variants which are carried out according to the development goal:

1. Determining the version of the system depending on the planning horizon (short-, mid-, long-term)
2. Analysis of the reference product by evaluating its relevance on a five-tier scale (--, -, 0, +, ++)
3. Analysis of the potential of the environment (derivation of technology or market environment scenarios as well as identification of relevant trends and forecasts)
4. Derivation of the innovation potentials (development of product scenarios)
5. Evaluation of the potentials (gathering knowledge about the future development and relevance of the object of investigation)
6. Potential identification (identification and evaluation of search fields with particularly high innovation potential)
7. Potential implementation (derivation of a development roadmap)

Many forecasts exist for technological and societal changes, most of them address production related changes but

the practical implications of engineering design are usually not articulated sufficiently [26]. Therefore, Marthaler et al. present four possible scenarios for the application of methods. The future-robust orientation of methodological research is addressed in the scenarios “Flexible, dispersed and virtual!”, “Finding instead of searching”, “Show me don’t tell me!” and “Law and Order!” on the basis of the changes resulting from the digital transformation. [27]

2.5 Context of product development

In order to enable the scenarios mentioned in 2.4, processes, methods, and tools need to be changed to fulfill future requirements. However, first of all it is necessary to understand the development context. Therefore, Gericke et al. consolidate 239 context factors that have an influence on design projects based on a comprehensive literature study. The authors understand the context of pd as the sum of the context factors that influence the course of design projects and the application of processes, methods and tools. [10]

Particularly in view of continuously changing design situations, it is of great importance to be able to adapt and apply development processes, methods and tools to suit the current situation and requirements. In addition to the approach of Gericke et al. Wilmsen et al. present a usable context-model to characterize current design contexts and situations, which are described as time-dependent sections of context factors. [11]

Using these models and schemas, developers are supported to understand development approaches and the context of their applications better [10]. Furthermore, they are able to adapt the used processes, methods and tools to their current development situation [11].

3. Aim of research and methodology

According to the current state of research, there are various definitions of the term Industrie 4.0, which is why there is no clear description of the impact that Industrie 4.0 has on pd. Therefore, this paper is intended to characterize Industrie 4.0 to systematically evaluate its influence on pd and deduce recommendations for future research by analyzing the current state of development regarding Industrie 4.0 and future scenarios. The following research questions arise from this objective:

- How can Industrie 4.0 be characterized?
- How can the influence of Industrie 4.0 on product development be systematically evaluated?
- How can the correlations between the context factors of Industrie 4.0 and product development be described with regard to their relevance for future scenarios?
- How can recommendations be deduced in order to realize the digital transformation in product development?

In order to address these questions, the procedure shown in Fig. 1 was developed.

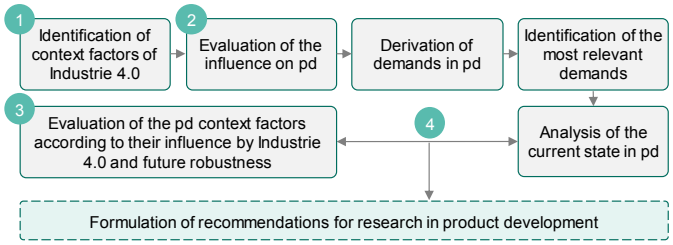

Fig. 1. Approach to answer the research questions

To answer the first research questions, a systematic literature analysis was carried out as a method of qualitative research to identify factors that characterize Industrie 4.0. Firstly, search terms were defined, which were applied to several databases (e.g. Google Scholar, Research Gate, Springerlink). From the totality of all search results obtained, 62 publications were considered relevant after examination of the title and the abstract. 34 of these publications were further analyzed. After a comprehensive collection of information, a total of 32 context factors of Industrie 4.0 were derived. The second research question was answered by evaluating the influence of these context factors on the context factors of pd in an influence matrix. Of a total of 209 context factors of pd, 89 are strongly influenced by Industrie 4.0. Based on these context factors, demands for pd were formulated with knowledge of the state of research. The relevance of these demands for the realization of Industrie 4.0 in pd was evaluated in an online survey. In interviews with experts from industry, the current state in these fields of pd as well as challenges of the digital transformation were analyzed. In order to gain insights into future robustness against the influence of Industrie 4.0 on the context factors of pd, methods of foresight were used to answer the third research question. The context factors of Industrie 4.0 and the four scenarios described in section 2.4 are considered. Their correlations are presented in a portfolio. By comparing the current state of development with the results of the portfolio, recommendations for future research in pd can be formulated to answer the last research question.

4. Literature-based and empirical study of the influence of Industrie 4.0 on product development

4.1 Context factors of Industrie 4.0

In order to analyze the influence of Industrie 4.0 on pd, it is first necessary to characterize Industrie 4.0 with the help of context factors. A literature-based study was conducted to extract relevant information that describe Industrie 4.0. Search terms were defined, which are focusing on Industrie 4.0, pd as well as challenges and potentials. Examples of search terms are "Industry 4.0 AND challenges AND (product engineering OR product development)" or "Industry 4.0 AND potentials". Synonyms of these search terms have been used as well both in German and in English. The search results were first pre-sorted by checking the titles and abstracts for relevant information and reducing them to selected contributions. With the help of an additional forward and backward search, further literature could be identified. In total, 62 studies, conference paper and other research contributions have been identified from which

34 from the years 2001 to 2019 have been further analyzed. The analyzed literature does not provide any specific context factors for Industrie 4.0. Therefore, 425 possible factors were identified in the first step, which were reduced to 32 context factors after eliminating irrelevant information and duplicates. In this case the term context factors are influences in the context (such as connectivity) that may have an impact on the topic under observation. Table 1 shows an extract of the context factors (complete list see Appendix A). Characteristics of the influencing factors are represented by a description in order to distinguish them from various existing definitions.

Table 1. Extract of the 32 identified context factors of Industrie 4.0

Context factor	Explanation
Automatization	Automatization means transferring an action or process to a self-running system.
Autonomy	Autonomy represents a state of self-determination, independence, self-administration or decision-making freedom.
Collaboration	Collaboration means active, goal-oriented and voluntary working together to achieve a common goal.
Connectivity	Connectivity describes cause-effect relationships as well as the properties of the parts in a system and their mutual connections. These correlations can also be found in organizations.
Decentralization	Decentralization means the division of responsibilities and competences as well as the corresponding (partial) tasks into several positions (e.g. departments or systems).

4.2 Influence of Industrie 4.0 on product development

By characterizing Industrie 4.0 with only a few factors, it is possible to systematically evaluate the influence on pd. For this purpose, an influence analysis was carried out. A total of 209 context factors of pd from the existing literature [8, 9] were collected (see Appendix B). On a scale from zero (no impact) to three (strong and direct impact) the influence of each of the 32 identified context factors of Industrie 4.0 on the 209 pd context factors was rated (see Appendix C). The sum value formed subsequently indicates the degree of influence by Industrie 4.0 on each of the context factor of pd. From these 209 context factors of pd, 89 factors were rated as strongly influenced. This analysis of the impact has helped to reduce the high number of context factors in pd to the most influenced ones. In order to assess the relevance of these context factors regarding the realization of the potentials of Industrie 4.0, 29 demands in pd were derived considering the state of research. Each of these demands consists of one or more context factors of pd. For example, demand 5 (see Fig. 3) is composed of the context factors "cooperation between departments" (A113), "use of cross-functional teams" (A131), "relationships between teams" (A15) and "experience in dealing with other team members" (A20). Each of the 89 factors were assigned to a single category to avoid duplication and reduce complexity. Afterwards, an online survey was conducted to assess the relevance of these demands on a Likert scale.

A total of 9 participants took part in the survey. Two thirds of the participants are involved in research and pd, the other third in innovation management and strategy. Although the number of participants is very small, the majority of them take up management positions and half of them have more than 5 or 10 years of professional experience.

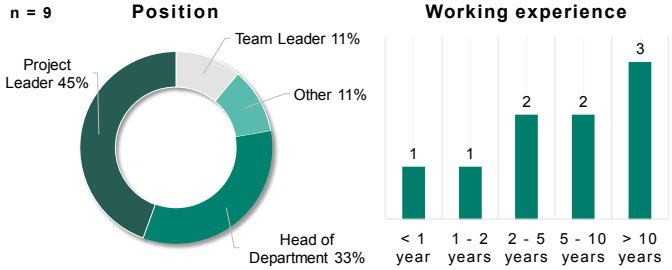

Fig. 2. Position and working experience of the survey participants

Descriptive statistics were used to evaluate the survey results, which are graphically presented using box plots. The results show that 6 out of 29 identified demands in pd have been rated as highly relevant (mean ≥ 4,6) in order to realize the potentials of Industrie 4.0. An extract of the results is illustrated in Fig. 3.

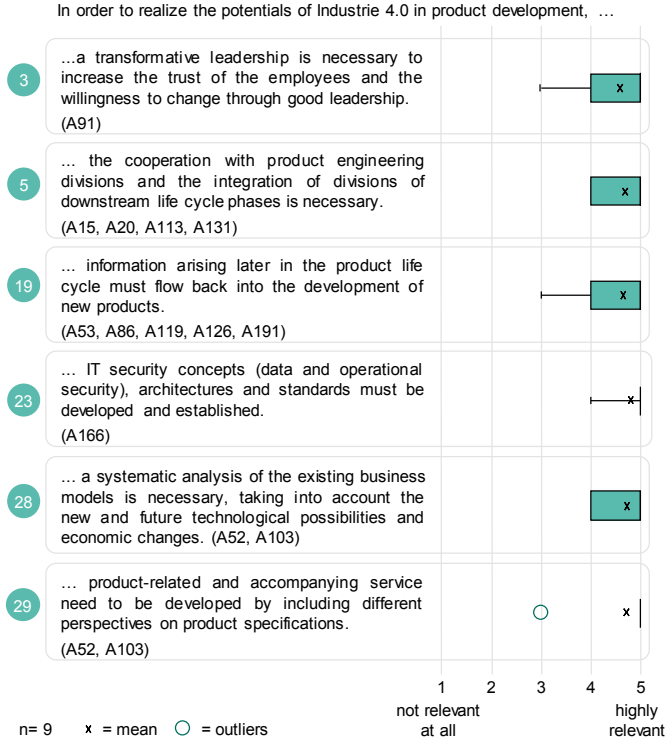

Fig. 3. Extract of the results of the online-survey

5. Analysis of the future robustness of and the influence on product development in relation to Industrie 4.0

To answer the third question, the strategic approach to evaluation of the potentials (step 5) of [24] as described in section 2.4 was applied. Instead of customer-experienceable properties of a product, the context factors of pd are examined. The parameter "degree of influence of Industrie 4.0 on product development" replaces the parameter "need for change", since the need for change in pd is analyzed in section 6. The context factors of pd are evaluated on the basis of this new parameter

and their "future robustness". The context factors of Industrie 4.0 as well as the four scenarios of the development methods [27] are considered in the evaluation. First, the degree of influence on a context factor of product development pd_c indicates how strongly the context factors are influenced by Industrie 4.0 (index i) and takes values between -4 and 4 (see eqn. (1)).

$$\gamma(pd_c) = \frac{1}{n}\sum_{i=1}^{n} pd_{c,i} \quad (1)$$

Subsequently, it is examined to what extent the future scenarios are similar with regard to a context factor of pd. The corresponding formula is represented in equation (2). $\delta(pd_c)$ corresponds to the future robustness of pd_c, which results from the individual characteristics of the scenarios $pd_{c,scy}$ (y indexes the respective scenario). Future robustness assumes values between 0 and 4.

$$\delta(pd_c) = 4 - \left(\max\{pd_{(c,sc1)}, pd_{(c,sc2)}, \dots, pd_{(c,scy)}\} - \min\{pd_{(c,sc1)}, pd_{(c,sc2)}, \dots, pd_{(c,scy)}\}\right) \quad (2)$$

The higher the value, the more robust the context factor is regarding the scenarios. The result is a portfolio (see Fig. 4).

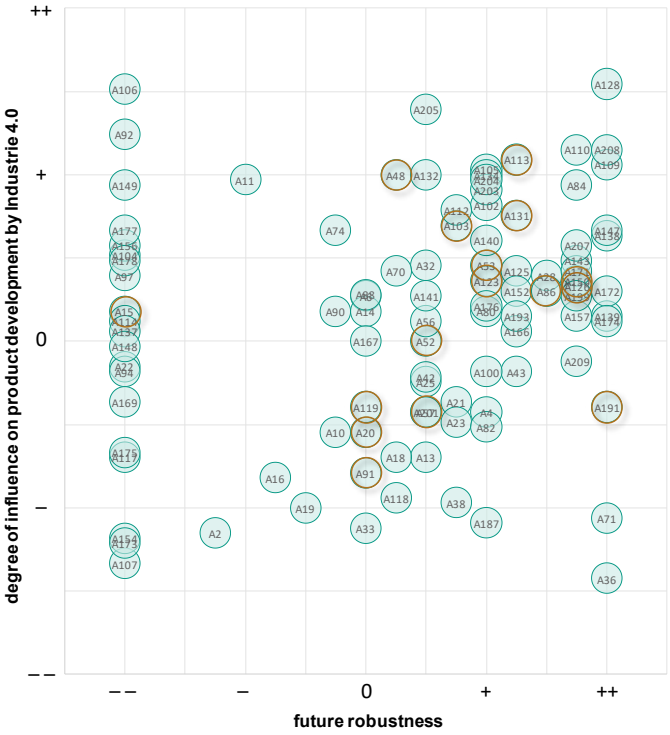

Fig. 4. Portfolio of the product development context factors

In this portfolio the context factors of pd (A1-A209, see Appendix B) are mapped depending on the previous evaluation. It provides information on the correlation between the influence of Industrie 4.0 on the context factors of pd and their robustness with regard to the scenarios. The context factors evaluated in the survey as particularly relevant for the realization of the potentials of Industrie 4.0 are highlighted in brown circles. The result shows that, with one exception, all relevant context factors are assessed as future-robust, which means that they show a low dispersion in the four scenarios. In addition, it is found that more than half of these factors are strongly influenced by Industrie 4.0. This result implies that these context factors in particular have to be examined with regard to their need for change according to the current state of development in order to derive recommendations for future research. In the following sections the demands 5, 19, 23, 28 and 29 are therefore further analyzed.

6. Recommendations for future research in product development

Interviews with five industry experts were conducted to analyze the current state of pd in their companies. The experts occupy management positions and, with one exception, have worked in their companies for more than 10 to 20 years in research and development as well as production. For the future-relevant demands identified in section 5, the current state in pd and the research demands derived from it are presented in Table 2. Approaches mean processes, methods and tools.

Table 2. Current state in companies and demand for further research

No.	Current state	Research demand
5	There is often no common understanding of objectives, as individual domains operate mostly separately from others. This is often due to a lack of basic understanding of other domains since knowledge bases are separate from each other.	• development of approaches to support collaboration of different domains • development of new forms of collaboration • development of approaches to create a basis of common goals
19	Feedback information from the usage phase of current products as well as information from planning and procurement processes are hardly included and considered in new developments. It is unclear which information needs to be available for other departments and how this information can be processed and shared.	• development of approaches for the individual and collective collection, storage and reuse of information/ knowledge within and outside departments • development of approaches to what data and how this data will flow back into the development of new advanced systems
23	Nowadays many standards are missing in the area of IT. The use of data, the associated security risks, and the danger of cyber-attacks have not yet been sufficiently researched. Experts in these areas are mostly not integrated in development teams.	• development of IT security concepts, architectures and standards • development of approaches to integrate experts into development teams
28	In general, it is important in development to focus on the customer and to orientate on his needs. Companies are often unable to cope with rapidly changing requirements.	• development of approaches to identify and analyze (future) customer requirements in order to integrate them into engineering processes at an early stage • development of approaches for a flexible reaction to changing requirements
29	Due to the increased use of data in engineering processes, the development of new product-related and accompanying services is unknown field for many companies.	• development of approaches to what data and how this data can be used to provide new services

7. Discussion

The present list of context factors is based on a literature study in the area of Industrie 4.0 and pd. As these factors are based solely on the literature, no guarantee can be given for their completeness. Therefore, validation and verification of the identified context factors by experts is essential. The following analyses are very complex due to the evaluation of a large number of factors. In order to reduce the effort of these analyses, a prioritization of relevant factors appears necessary. Thus, it is also possible to focus on specific fields of pd. The evaluation of the demands in pd to realize the potentials of Industrie 4.0 does not provide sufficient data, which is why further empirical studies are necessary to validate and verify the results. The procedure for analyzing the future robustness of the individual context factors of pd already shows first implications of which areas are particularly relevant with regard to Industrie 4.0 and the selected scenarios. However, it should also be noted that some factors (vertical line on the left) cannot be assessed for their future robustness. This is due to the lack of a description of these factors in the scenarios. Therefore, it is necessary to develop further scenarios for Industrie 4.0. Nevertheless, the presented procedure shows that it is possible to systematically analyze the influence of Industrie 4.0 on pd by characterizing Industrie 4.0 and using models to describe pd processes (context factors). Furthermore, it could be shown that foresight methods enable the identification of demands in pd and the formulation of recommendations for further research.

8. Conclusion and Outlook

The digital transformation is increasingly affecting all areas of value creation, not just production-related topics. The relevant literature of this work shows that a systematic approach is necessary to derive the influence of Industrie 4.0 on pd in order to be able to adapt processes, methods and tools as well as organizational structures in order to realize the potentials of Industrie 4.0. This publication presents a way how Industrie 4.0 can be characterized to systematically analyze its influence on pd. So far, no such procedure has been described in the literature. Based on this, it was presented how future-robust context factors of pd with regard to Industrie 4.0 could be identified using methods of foresight to reduce uncertainties in this field. With knowledge of the current state of development in companies and the portfolio, requirements for realizing the potential of Industrie 4.0 in pd were identified and recommendations for further research were derived from this. In a next step, it is possible to focus on specific fields of pd to reduce the complexity for subsequent studies to an acceptable level. Applying the future scenarios and trends-based approach for strategic potential identification of Marthaler et al. [24] concrete development roadmaps can be derived for certain areas of pd.

Appendix A. Context factors of Industrie 4.0

Appendix B. Context factors of product development

Appendix C. Extract from the impact analysis of Industrie 4.0 on product development

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