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Studying Technologies of Industry 4.0 with Influence on Product Development using Factor Analysis

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Abstract

Technological changes in the context of Industry 4.0 affect industrial processes on a large scale. Whereas Industry 4.0 has become a common topic in production-oriented research areas, the influence on product development has not been thoroughly analysed yet. The progressing digitisation in industrial and everyday life causes an increase of networking and of data exchange. Newly developed abilities of collection, exchange, storage and analysis of mass data open up new possibilities and lead to harsher settings in international competition at the same time. Globalisation and technological progress like the miniaturisation of hardware and software components result in more complex products. These events caused a shift from mechanical to electrical and software engineering as the main focus regarding the involved disciplines in product development. This is considered as an ongoing trend because products are continuously getting smarter and more autonomous. However, the systems and technologies currently being used for an interdisciplinary and parallel product development do not match up to the resulting challenges. New technologies from Industry 4.0 are expected to meet these challenges. They operate as support systems and foster product development by enhancing data exchange and consistency.

This paper offers a methodical approach to study influences from new technologies arising from the developments in the context of Industry 4.0 on product development. At first, the required technologies are extracted from relevant related research. Since there is no standardised and generally accepted form and definition for trends and technologies that are developed in Industry 4.0, they are subsequently systematised using an appropriate framework. To validate this framework and the comprised technologies, a qualitative Factor Analysis is performed in two stages. In each stage hypotheses are proposed and tested using a null hypothesis and an alternative hypothesis. The hypotheses of the first stage only address the elements of the framework. In the second stage, the assignment of each technology to a field within the framework is validated by determining the acceptance or rejection of each null hypothesis. Finally, the identified technologies are defined with generic descriptions.
The knowledge about the influence of technologies on product development supports technology selection and implementation as well as spotting future technologies. With the help of the developed framework, practitioners are enabled to deduce and analyse influences of technologies on product development.

Keywords: Industry 4.0, Factor Analysis, Technological Influences, Product Development

1 Introduction

Customers' continuous demands for more individual and complex products with a high degree of integration that are made in ever shorter cycles (Vietor & Stechert, 2013) challenge companies regarding their product development. These challenges are particularly relevant in the product development of mechatronic products and will lead to changes in the collaboration of the involved disciplines (Gausemeier, Ebbesmeyer, & Kallmeyer, 2001). Connected services and cognitive elements form the basis for autonomous and intelligent products (Lindemann, 2016). These new products with integrated electronic and information technology require a product development with intense interdisciplinary collaboration as well as parallel and interdisciplinary processes (Sendler, 2016). This collaboration is in contrast to the discipline-specific procedural methods, perspectives on the product and IT-systems, which are used in manufacturing industry today. As a result, isolated solutions occur as well as lacks of interoperability of processes and systems and insufficient data consistency in the interdisciplinary development process (Baum, 2013b). Although, most of the product-related expenses are determined in the product development, it has the lowest IT-penetration (Eigner & Stelzer, 2009). Existing methods and tools turn out to not sufficiently support the increased number of dependencies in processes, products and systems caused by interdisciplinarity (Eigner & Stelzer, 2009). Thus, productivity in interdisciplinary product development is hindered (Spath & Dangelmaier, 2016b).
New developments in the context of Industry 4.0 intensify the networking of digital systems. Enhanced methods for data collection and analysis support the management of more complex processes (Fallenbeck & Eckert, 2017). However, the focus of the introduction of new technologies in current research is on production so far (Eigner, 2016). However, the implementation of new IT-systems in product development has the potential to bring a change in working methods (Feldhusen & Grote, 2013). Technological innovations from Industry 4.0 are expected to shape new forms of collaboration with regard to communication, coordination and cooperation by help of new software tools for data exchange (Eigner, 2016).
This potential has been identified and described by previous research contributions (Anderl et al., 2016). However, there is still a lack of transparency regarding the immediate benefits, which is a major obstacle for the introduction of Industry 4.0 technologies (Schuh, Anderl,

Gausemeier, Hompel, & Wahlster, 2017). Therefore, technologies in the context of Industry 4.0 influencing product development are identified and analysed in this paper.

2 Related research

2.1 Anticipated role and impact of new technologies

Various frameworks and target pictures were formulated regarding the role and impact of the technologies of Industry 4.0. They contain trends, technologies and their function with varying elements, focus and granularity as well as different examples for application.

For example, Eigner describes the implementation of a service-oriented business model. In such a business model, sensor and actuator technology is used to collect and submit information. This information is stored in a cloud, processed with business analytics and afterwards visualized. (Eigner, 2016) Kenn describes a framework for the internet of things. He introduces the *thing* as a construct, which creates a data flow and sends it to a decision-making panel. A reverse data flow from the decision-making panel to the thing contains instructions regarding the behaviour of the thing. Kenn describes the required process steps for transportation, repository and analysis of data as well as planning, saving, and transportation of the instructions and the corresponding technology. (Kenn, 2016) Mattern and Flörkemeier introduce a model based on smart objects that serve as mediators between objects, humans and the internet of computers. These smart objects send and receive data and facilitate interaction between the stakeholders. (Mattern & Flörkemeier, 2010)

The heterogeneity of the three described models shows that the current understanding of the role and impact of new technologies widely differs depending on the perspective of the authors and the focus they set. This paper aims at integrating various frameworks and derive a holistic framework for trends and technologies, which influence product development in manufacturing industries.

2.2 Differentiation of new technologies

Another stream of scientific literature addresses the demarcation of technologies that are relevant for Industry 4.0. The technologies are defined and differentiated. The approaches of this stream list the defined technologies or structure them in a framework. In this section selected examples for sources of this literature stream are respented.

According to Eigner, the technologies that constitute Industry 4.0 are model based semantic networks (MSN), in-memory databases (IMDB) as well as grid computing, cloud computing, big data security/safety and usability (Eigner, 2016). Baum considers mobile computing, social media, internet of things, big data as well as analysis, optimization and forecast as technologies for Industry 4.0 (Baum, 2013a). In addition to that, Bauer, Schlund and Marrenbach define a criterion to identify relevant technologies of Industry 4.0: the capability of building a network of humans or objects. Based on this criterion they identify IT security, embedded systems, CPS, smart factory, robust net and cloud computing as relevant fields of technology, where first prototypes already exist. (Bauer, Schlund, & Marrenbach, 2014) Further authors enumerate single technologies like e.g. smart objects without an overall systematised understanding regarding the characteristics of the technologies (Ehrlenspiel, 2009; Spath & Dangelmaier, 2016a).

In summary, it can be stated that there is no common understanding of the relevant technologies and their nomenclature as well as no mutually exclusive definitions and differentiations of the technologies, which are applicable for more than one specific field of application. In this paper, generic descriptions of technological trends of Industry 4.0 are described as part of an overall framework.

2.3 Technological influence on product development

Most research contributions regarding the new technologies in context of Industry 4.0 focus on production (Eigner, 2016). Many technologies are discussed with regard to the concept of a smart factory (Bauer et al., 2014). The influences on product development in general and the collaboration of different disciplines in particular are addressed to a small extend only. Ehrlenspiel discusses the influence of technologies on interdisciplinary product development and emphasises the opportunity to overcome data inconsistency between disciplines (Ehrlenspiel, 2009). In addition to that, Gausemeier et al. note that intelligent systems will influence the overall behaviour of general systems in terms of communication and cooperation (Gausemeier et al., 2001). Leimeister contributes a classification of technologies that are used for collaboration in general but does not focus on the specifics of product development (Leimeister, 2014). Schuh identifies a potential for increase of collaboration productivity based on technologies of Industry 4.0 but does not specifiy the potential and analyse the influence on product development (Schuh, Potente, Varandani, Hausberg, & Fränken, 2014; Schuh, Potente, Wesch-Potente, Weber, & Prote, 2014). Roubanov describes specific technologies like product models and simulation methods and their relevance to product development (Roubanov, 2014). However, current literature does not offer an overall analysis of influences that new technologies in the context of Industry 4.0 may have on product development. The framework presented in this paper focuses on technologies, which have an influence on product development. It is structured according to the specifics of product development. The framework and the generic descriptions of the technologies provide a basis for further investigation of the influence these technologies have on product development regarding processes and collaboration.

3 Derivation of a framework

3.1 Methodical approach

In this paper, an approach to derive a holistic framework including systematically identified and classified trends and technologies of Industry 4.0 is presented and applied. As the discussion of related research in the previous section shows, there is a lack of a generic and systematically determined framework. In order to overcome this deficit, the approach presented in this paper is based on the general systems theory according to Ropohl (Ropohl, 1979) and factor analysis according to Überla (Überla, 1977). In a first step, relevant topics of information and communication technologies related to Industry 4.0 are systematised and a framework is derived. Relevant technologies are identified based on an extensive literature research. Then, the framework is validated and the identified technologies are allocated in the framework using a two-stage factor analysis. The framework is enriched with subordinate elements and generic technologies. Finally, the technologies are defined with generic descriptions, which help to demarcate them against each other.

3.2 Derivation of a framework for trends and technologies

In order to develop a framework for trends and technologies of Industry 4.0, these trends and technologies were analysed and aggregated according to systems theory. Systems theory is applicable to all physical and theoretical objects. Systems in general are examined following the functional, the structural and the hierarchical concept. In the functional concept, a system is considered as a black box with inputs and outputs. The structural concept focuses on the relations between the elements of a system. The hierarchical concept addresses the hierarchies between these elements, called subsystems. In order to describe a system, the elements are demarcated against surrounding elements and their relations are described. (Ropohl, 1979) The trends and technologies are considered as elements from a systems theory perspective. The functional aspect of a system is represented by the task that trends and technologies fulfil. The structural and hierarchical aspects are represented by the relations between them.

For the development of the framework, the existing approaches for structuring trends and technologies as discussed in the section “related research” were analysed and integrated. The contributions of the different authors show overlapping elements of technologies which were aggregated to four fields for the framework presented in this paper. The fields were defined according to the principles of system theory as described above in order to achieve a mutually exclusive and completely exhaustive framework. The field **technical systems** includes all systems that are utilised to collect data from the environment using sensors and actors. The field **infrastructure** describes networks and platforms, which are used for exchange or storage of data. The field **tools** includes systems for the analysis of data and the derivation of instructions and recommendations. The field **interfaces** includes technologies to link systems with each other. Figure 1 shows the four defined fields of the framework and the description of the corresponding content per field.

Field	Content
Technical systems	*Acquisition of data from the environment*
Infrastructure	*Storage and exchange of data*
Tools	*Analysis and processing of data*
Interfaces	*Linkage of systems*

Figure 1. Overview of the framework for trends and technologies

The four fields are subdivided into further subordinate elements. The field technical systems includes intelligent and enhanced mechatronics, which comprise objects with capability for data acquisition and networking based on information and communication technology (ICT). The field infrastructure includes the elements networks and plattforms for data storage and exchange. The field tools is subdivided into the elements analysing systems for modeling and simulation as well as software systems. The field interfaces is further differentiated into the fields human to machine (H2M) interfaces and machine to machine (M2M) interfaces. The framework including the defined elements is shown in Figure 2.

Field	Elements	
Technical systems	Intelligent mechatronics	Enhanced mechatronics
Infrastructure	Networks	Platforms
Tools	Analysing systems	Software systems
Interfaces	H2M interfaces	M2M interfaces

Figure 2. Framework for trends and technologies including subordinate elements

3.3 Identification of relevant trends and technologies

In the next step, corresponding trends and technologies of Industry 4.0 were identified for each of the previously defined fields and subordinate elements in the framework. Two different types of research contributions were included in the analysis: The first type comprises contributions which provide an integral analysis of the topic Industry 4.0 and structure trends and technologies in this field accordingly. Examples for this type are the contributions of Bauer et al., Baum and Eigner (Bauer et al., 2014; Baum, 2013b; Eigner, 2016). The second type comprises contributions regarding specific subtopics. They usually present single trends or technologies and dedicated areas of applications. For the development of the framework, these single trends and technologies were then assigned to one of the fields in the framework. In the following, an overview of the trends and technologies is briefly presented and discussed for each of the fields.

In the field **technical systems**, topics like smart objects (Mattern & Flörkemeier, 2010), CPS or CTS (Broy & Geisberger, 2012; Schuh et al., 2017) are allocated. Relevant topics for the field **infrastructure** and the subcategory networks are Web 2.0, Social Software (Leimeister, 2014) and Enterprise 2.0 (Eigner, 2014). Model based semantic networks and PLM/SysLM as well as team data management (Eigner, 2016) also belong to this field. Examples for platforms are the technology cloud computing and in-memory databases (IMDB) (Zhang, Chen, Ooi, Tan, & Zhang, 2015). In the field **tools**, technologies like big data analysis tools and machine learning algorithms are allocated (Schuh et al., 2017) as well as further tools for analysis and optimisation. Also systems to work with data, which means in virtual product development especially systems for modelling and simulation like CAD, CAM and VR (Eigner, 2014) are allocated to this field. The field **interfaces** includes technologies like mobile computing and multimodal sensoring as well as radio interfaces and Plug & Play or Plug & Produce (Mattern & Flörkemeier, 2010).

The allocation of these technologies was conducted by help of a qualitative mapping in order to obtain a first indication on the adequacy and completeness of the framework. A well-grounded and systematic approach was conducted afterwards using factor analysis. This approach is presented in the following section.

3.4 Structuring the trends and technologies using factor analysis

For validation of the framework and the defined elements as well as the allocated trends and technologies in the framework, the factor analysis was applied. The factor analysis is a methodical approach to verify hypotheses. If two variables show a strong correlation and mutual influence, the existence of a hidden factor is assumed. (Überla, 1977) This method is especially used for large amounts of variables, which show overlapping and thus a correlation. To isolate the hidden factor behind the variables, the correlation coefficients of the variables are determined. The variables are then reduced to a single factor based on these correlation coefficients. Thus, factor analysis supports data reduction because the identified hidden factors may be used instead of the original variables. (Backhaus, Plinke, Erichson, & Weiber, 2011) As a result, a few factors cover the whole multitude of variables and help to simplify the framework. When conducting the factor analysis, as many factors are deduced as necessary. They are defined as simple as possible but with sufficient precision. (Ritsert, Stracke, & Heider, 1976)

The correlation coefficient describes the relation between the variables. They obtain values between *-1* and *+1*. The closer the value is to *0* the weaker is the correlation and the closer it is to *-1* or *+1* the stronger is the correlation. The correlation coefficients are visualised in a correlation matrix. A hypothesis is initially set up without further knowledge of the underlying structure. The correlation matrix consists of the variables in the lines and the factors in the columns. If two variables show the same pattern in the correlation matrix, they are overlapping. Figure 3 provides an overview of the factor analysis and the relations between the hidden factors and the measured variables in the correlation matrix.

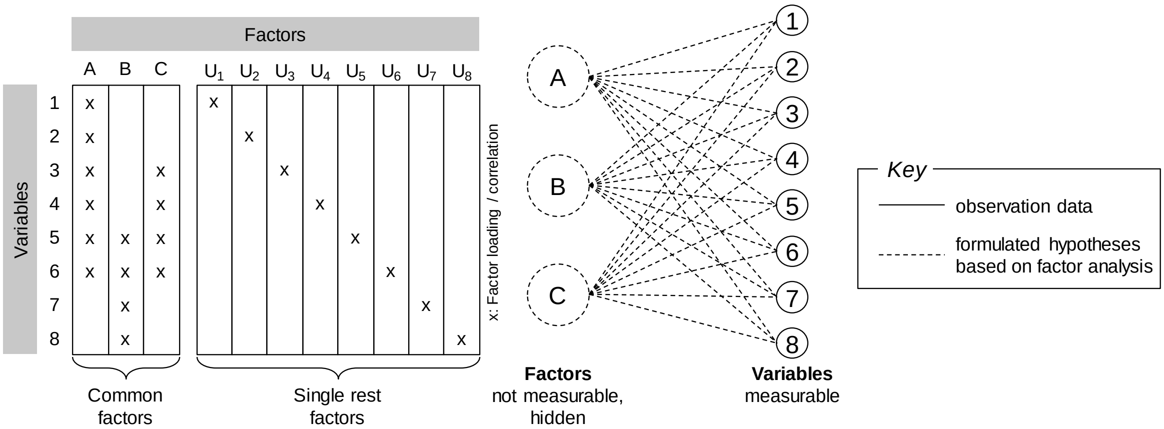

Figure 3. Factor analysis according to Überla

A factor analysis is also applicable for qualitative data with no purely deterministic relations. In this case, a null hypothesis with a corresponding alternate hypothesis is used. (Überla, 1977) The alternatives are formulated as, for example, in the conversion of a gender assignment like *female = 1* and *male = 2*. If experiments are impossible and therefore statistical data is not available, null hypotheses are used as statistical tests. A null hypothesis H_0 in the form of *"there is a deviation"* is compared with an alternate hypothesis H_1 *"there is no deviation"*. One of these possibilities is rated as *"correct"*. Since the hypotheses mutually exclude each other, only one hypothesis is correct, whereas the other one is automatically not applicable. (Überla, 1977) In order to validate the defined elements and the allocated trends and technologies, a qualitative two-stage factor analysis was conducted. For each of the fields and elements, the corresponding hypotheses were proposed. The hypotheses as well as the allocation of the corresponding trends and technologies are shown in Figure 4.

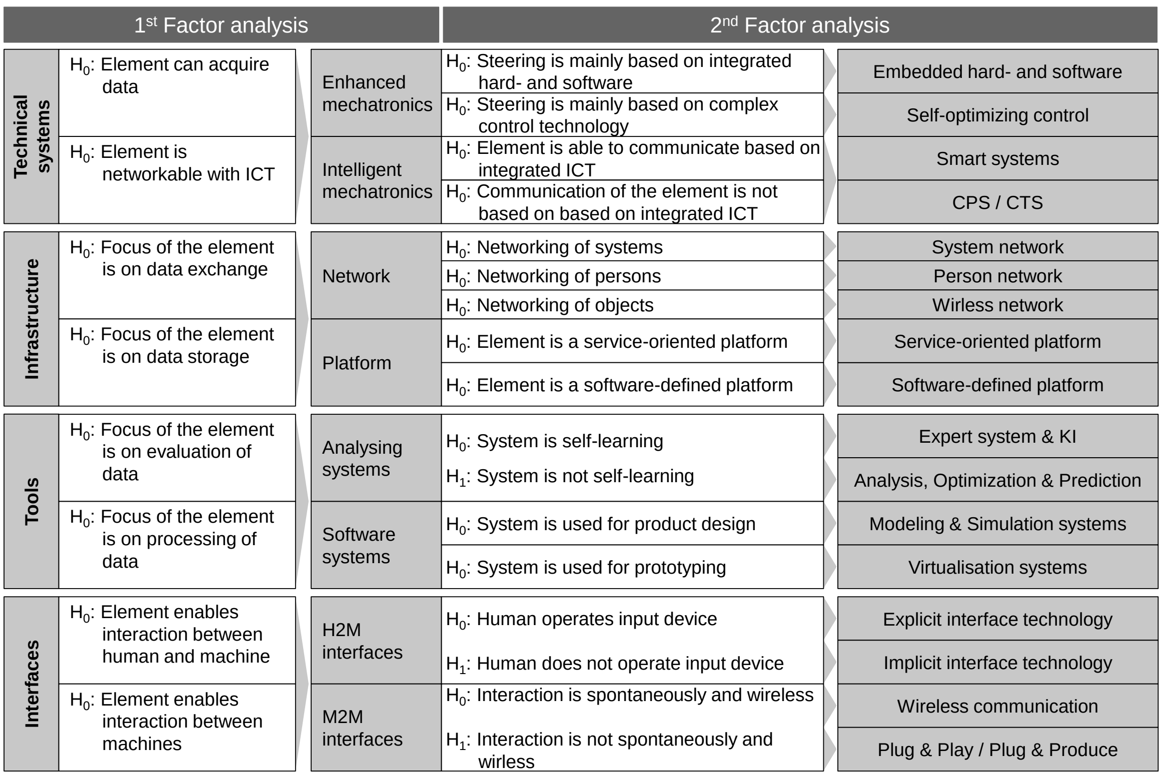

Figure 4. Hypotheses for validation of trend and technology-allocation in the framework

For the technologies identified in the analysis of the related research, no technical or statistical data is available. To validate the framework and the comprised technologies extracted from related research, a qualitative factor analysis was performed in two stages. In each stage hypotheses were proposed and tested using a null hypothesis and an alternative hypothesis.
The hypotheses of the first stage only address the fields of the framework. They aim at fulfilment of the main purpose of a field, e.g. for technical systems *H_0: "Element can acquire data"* and *H_0: "Element is networkable with ICT"*. With the test of the hypotheses regarding technical systems in the factor analysis, two hidden factors are revealed, which lead to two elements. (rating: "*0*" for *"hypothesis not correct"* and "*1*" for *"hypothesis correct"*).
In the second stage, the assignment of each technology to a subordinate element within the framework is validated by determining the acceptance or rejection of each corresponding null hypothesis. In this stage, the hypotheses are formulated to meet the characteristics of subgroups of the technologies. For the example of technical systems, the null hypotheses are *H_0: "Steering is mainly based on integrated hard- and software"*, *H_0: "Steering is mainly based on complex control technology"* and *H_0: "Element is able to communicate based on integrated ICT"*, *H_0: "Communication of the element is not based on the integrated ICT"*. An overview of the two-stage factor analysis is shown in Figure 5.

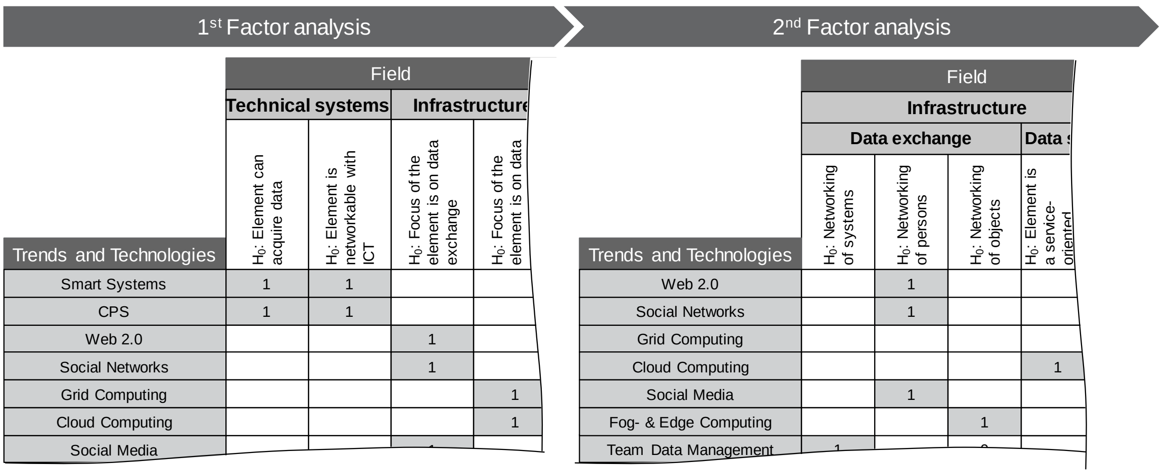

Figure 5. Overview of two-stage factor analysis

As a result of the factor analysis, the trends and technologies identified in the literature analysis are aggregated and allocated in the framework. The framework is structured in four fields and has eight subordinate elements. Each element includes generic technologies which have been allocated to the element based on the factor analysis. The generic technologies comprise the various trends and technologies, which have been identified in the literature analysis. They have a similar level of granularity. The generic technologies within the framework are shown in an overview in Figure 6.

Field	Elements and generic technologies			
Technical systems	Enhanced mechatronics	Embedded hard- and software	Self-optimizing control	
	Intelligent mechatronics	Smart systems	CPS / CTS	
Infrastructure	Network	System network	Person network	Wirless network
	Platform	Service-oriented platform	Software-defined platform	
Tools	Analysing systems	Analysis, Optimization & Prediction	Expert system & KI	
	Software systems	Modeling & Simulation systems	Virtualisation systems	
Interfaces	H2M interfaces	Explicit interface technology	Implicit interface technology	
	M2M interfaces	Wireless communication	Plug & Play / Plug & Produce	

Figure 6. Generic Technologies per field in the framework based on factor analysis

3.5 Characteristics of the identified generic technologies.

For each of the generic technologies in the framework, a brief description with key characteristics of the technologies has been elaborated. The descriptions represent a detailed understanding of the technologies and thus support the classification of further technological trends within the framework. The descriptions are generically formulated, so that they subsume specific technologies which were allocated in the framework by help of the factor analysis. These descriptions are presented in the following:

- *Embedded hard- and software* includes technologies which enable an integrated data processing.
- *Self-optimizing control* includes mechatronic systems with self-optimizing information processing, which are able to react to external influences and optimize themselves.
- *Smart systems* are objects with embedded intelligence and ICT elements for wireless networking, autonomous action, which are configurable by the user.
- *CPS/ CTS* are systems which consist of interacting subsystems with embedded intelligence and the ability to adapt themselves to environmental conditions.
- *System networks* are networks of software systems, which exchange data.
- *Person networks* are networks between persons, which support interaction and communication.
- *Wireless networks* are networks between physical objects with ICT.
- *Software-defined platforms* are platforms which provide resources for storage of data as basis for analysing systems.
- *Service-oriented platforms* are platforms which provide services for various users.
- *Analysing, Optimization and Prediction* include technologies for analyses of large data sets to derive optimization measures or predictions.
- *Expert systems and KI* include self-learning and autonomously acting systems.
- *Modelling and simulation systems* include systems for definition of products in all relevant product development processes and domains.
- *Virtualisation systems* support the realistic description and visualisation of products with their geometric characteristics and functions.
- *Explicit interface technologies* include technologies for interaction between human users and technical systems.
- *Implicit interface technologies* include technologies for recognition of signals of human communication.

- *Wireless communication* includes technologies for spontaneous communication between technical systems at low distance.
- *Plug & Play / Plug & Produce* include interface systems which allow a flexible exchange of connecting devices with low effort for the set-up.

4 Conclusion

In this paper, the results of an analysis regarding trends and technologies of Industry 4.0 that affect product development in manufacturing industry were presented. First, the methodological approach based on systems theory and factor analysis was explained. Second, a framework for trends and technologies consisting of four fields was elaborated. Third, the framework was validated and technological trends were allocated based on a two-stage factor analysis. The framework was enriched with subordinate elements and generic technologies. Finally, a generic description was formulated for each of the technologies, which defines the detailed understanding of each technology.

The framework supports responsible persons in manufacturing industry to gain an overview over relevant trends and technologies in the field of Industry 4.0, which influence product development. The generic technologies can be used as a reference for the assessment of the technological competences of a company. Further research will focus on a detailed analysis of the impact the described technologies have on collaboration in product development (Schuh, Riesener, & Mattern, 2018). Especially technologies that affect communication between persons and systems as well as technologies supporting data exchange, storage and analysis are expected to have an impact on collaboration and collaboration productivity in product development (Mattern, Riesener, & Schuh, 2017).

5 References

Anderl, R., Bauer, K., Bauernhansl, T., Berlik, S., Broy, M., Diegner, B., Zeidler, C. (2016). Forschungsagenda Industrie 4.0: Aktualisierung des Forschungsbedarfs. Berlin.

Backhaus, K., Plinke, W., Erichson, B., & Weiber, R. (2011). Multivariate Analysemethoden: Eine anwendungsorientierte Einführung (13. Aufl.). Berlin: Springer.

Bauer, W., Schlund, S., & Marrenbach, D. (2014). Industrie 4.0: Volkswirtschaftliches Potential für Deutschland. Studie. Berlin.

Baum, G. (2013a). Innovation als Basis der nächsten Industrierevolution. In U. Sendler (Ed.), Xpert.press. Industrie 4.0: Beherrschung der industriellen Komplexität mit SysLM (pp. 37–54). Berlin: Springer Vieweg.

Baum, G. (2013b). Innovationen als Basis der nächsten Industrierevolution. In U. Sendler (Ed.), Industrie 4.0: Beherrschung der industriellen Komplexität mit SysLM (pp. 37–53). Berlin, Heidelberg: Springer Vieweg.

Broy, M., & Geisberger, E. (2012). AgendaCPS: Integrierte Forschungsagenda Cyber-Physical Systems. acatech STUDIE. Berlin, Heidelberg: Springer.

Ehrlenspiel, K. (2009). Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit (4., aktualisierte Aufl.). München, Wien: Hanser.

Eigner, M. (2014). Modellbasierte virtuelle Produktentwicklung. In M. Eigner, D. Roubanov, & R. Zafirov (Eds.), Modellbasierte virtuelle Produktentwicklung (pp. 1–13). Berlin, Heidelberg: Springer Vieweg.

Eigner, M. (2016). Das Industrial Internet: Engineering Prozesse und IT-Lösungen. In U. Sendler (Ed.), Industrie 4.0 grenzenlos (pp. 137–168). Berlin, Heidelberg: Springer Vieweg.

Eigner, M., & Stelzer, R. (2009). Product Lifecycle Management: Ein Leitfaden für Product Development und Life Cycle Management (2. Aufl.). Dodrecht, Heidelberg, London, New York: Springer.

Fallenbeck, N., & Eckert, C. (2017). IT-Sicherheit und Cloud Computing. In B. Vogel-Heuser, T. Bauernhansl, & M. ten Hompel (Eds.), Handbuch Industrie 4.0 Bd.4: Allgemeine Grundlagen (2nd ed., pp. 135–170). Berlin, Germany: Springer Vieweg.

Feldhusen, J., & Grote, K.-H. (Eds.). (2013). Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung (8. Aufl.). Berlin, Heidelberg: Springer Vieweg.

Gausemeier, J., Ebbesmeyer, P., & Kallmeyer, F. (2001). Produktinnovation: Strategische Planung und Entwicklung der Produkte von morgen. München: Hanser.

Kenn, H. (2016). Architekturen für das "Internet der Dinge". In C. Manzei, L. Schleuper, & R. Heinze (Eds.), Beuth Innovation. Industrie 4.0 im internationalen Kontext: Kernkonzepte, Ergebnisse, Trends (1st ed., pp. 30–35). Berlin: Beuth; VDE Verlag GmbH.

Leimeister, J.-M. (2014). Collaboration Engineering: IT-gestützte Zusammenarbeitsprozesse systematisch entwickeln und durchführen. Berlin, Heidelberg: Springer Gabler.

Lindemann, U. (Ed.). (2016). Handbuch Produktentwicklung. München: Carl Hanser.

Mattern, C., Riesener, M., & Schuh, G. (2017). Approach to design collaboration in interdisciplinary product development using dependency features. 7. WGP-Jahreskongress Aachen, 5.-6 Oktober 2017, 373–380.

Mattern, F., & Flörkemeier, C. (2010). Vom Internet der Computer zum Internet der Dinge. Informatik-Spektrum, 33(2), 107–121.

Ritsert, J., Stracke, E., & Heider, F. (1976). Grundzüge der Varianz- und Faktorenanalyse. Texte: Gesellschaftswissenschaften. Frankfurt: Campus Verlag.

Ropohl, G. (1979). Eine Systemtheorie der Technik: Zur Grundlegung der Allgemeinen Technologie. München, Wien: Hanser.

Roubanov, D. (2014). Produktmodelle und Simulation (CAE). In M. Eigner, D. Roubanov, & R. Zafirov (Eds.), Modellbasierte virtuelle Produktentwicklung (pp. 175–196). Berlin, Germany: Springer Vieweg.

Schuh, G., Anderl, R., Gausemeier, J., Hompel, M. ten, & Wahlster, W. (2017). Industrie 4.0 Maturity Index: Die digitale Transformation von Unternehmen gestalten. acatech STUDIE. München: Herbert Utz.

Schuh, G., Potente, T., Varandani, R., Hausberg, C., & Fränken, B. (2014). Collaboration Moves Productivity To The Next Level. Procedia CIRP. (17), 3–8.

Schuh, G., Potente, T., Wesch-Potente, C., Weber, A. R., & Prote, J.-P. (2014). Collaboration Mechanisms to increase Productivity in the Context of Industrie 4.0. Proceedia CIRP. (19), 51–56.

Schuh, G., Riesener, M., & Mattern, C. (2018). Examining Collaboration in Interdisciplinary Product Development Focusing on Dependencies. Proceedings of the 51st Hawaii International Conference on System Sciences, Hawaii International Conference on System Sciences (HICSS); January 3-6, 2018 Hawaii, 155–163.

Sendler, U. (Ed.). (2016). Industrie 4.0 grenzenlos. Berlin, Heidelberg: Springer Vieweg.

Spath, D., & Dangelmaier, M. (2016a). Produktentwicklung Quo Vadis. In U. Lindemann (Ed.), Handbuch Produktentwicklung (pp. 1–111). München: Carl Hanser Verlag.

Spath, D., & Dangelmaier, M. (2016b). Produktentwicklung Quo Vadis. In U. Lindemann (Ed.), Handbuch Produktentwicklung (pp. 3–7). München: Carl Hanser.

Überla, K. (1977). Faktorenanalyse: Eine systematische Einführung für Psychologen, Mediziner, Wirtschafts- und Sozialwissenschaftler (Nachdruck der 2. Auflage). Berlin: Springer-Verlag.

Vietor, T., & Stechert, C. (2013). Produktarten zur Rationalisierung des Entwicklungs- udn Konstruktionsprozesses: Konventionelle Ansätze. In J. Feldhusen & K.-H. Grote (Eds.), Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung (8th ed., pp. 817–871). Berlin, Heidelberg: Springer Vieweg.

Zhang, H., Chen, G., Ooi, B. C., Tan, K.-L., & Zhang, M. (2015). In-Memory Big Data Management and Processing: A Survey. IEEE Transactions on Knowledge and Data Engineering, 27(7), 1920–1948.