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Procedia CIRP 84 (2019) 973–978

www.elsevier.com/locate/procedia

29th CIRP Design 2019 (CIRP Design 2019)

A framework to classify Industry 4.0 technologies across production and product development

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Abstract

Industry 4.0 is a diffuse term describing a wide range of technologies to connect systems and regulate processes based on information generation and analysis. Existing definitions and models to describe functions and properties of Industry 4.0 technologies often focus on production systems and therefore do not provide a framework to describe technologies covering the whole product generation process.We introduce a framework to describe and classify Industry 4.0 technologies, affecting both - production and product development. The proposed framework is intended to serve as a basis of a structured and unified description of existing technologies as well as to distinguish the impacted activities within the product generation process. The basic idea is to couple existing models of cyber-physical production systems with established descriptions of central product development process activities to create a framework describing Industry 4.0 technologies within production and product development.

Keywords: Classification model, Industry 4.0 technologies, cyber-physical production systems, production, product development

1. Introduction

The core idea of Industry 4.0 can be explained by an increasing networking of machines, products and humans realized by continuous information exchange. According to Gartener's emerging technologies hype cycle, Industry 4.0 technologies have reached the peak of "inflated expectations" in last three years [1]. The omnipresence of Industry 4.0 technologies implies a diffuse understanding and manifold definitions of the technologies themselves. There are almost no concepts to structure and describe the underlying functionalities in a consistent way. We aim at providing a framework to support classification of Industry 4.0 technologies with regard to their main functionalities.

1.1. Industry 4.0 technologies and cyber-physical systems

The functionalities of Industry 4.0 technologies are defined and analyzed from a process point of view involving both - production and product development. KANG ET AL. and we see the cyber-physical system as a core element of Industry 4.0 technologies which describes essential functionalities and the interactions between those functionalities; such as physical processes and simulation or analytical models – the cyber world [2]. Interactions of computers with physical processes as an essential concept of embedded systems are addressed in research on cyber-physical systems (CPS) [3]. LEE AND SESHIA state that *"a cyber-physical system is an integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect*

10.1016/j.procir.2019.04.218

computations and vice versa" [4]. This definition expresses the character of an information loop and defines main functions to be realized by CPS.

1.2. Objective and focus of research

In this contribution we aim at providing a sound framework to describe and classify technologies in the context of Industry 4.0. Basis for the proposed framework is a process-related description of essential functionalities that allow to allocate existing technologies to main activities of the development and production process. Thus, the framework covers the whole process of product generation, beginning with the collection of customer needs and requirements and ending with the production of the physical product [5].

Therefore, in this paper we focus on the combination of existing cyber-physcial production system frameworks and processes of product development. Objectives and limitations of the proposed framework are:

- We aim at providing a generic framework, defining basic functions to be fulfilled by Industry 4.0 technologies.
- We aim at identifying and characterizing basic types of Industry 4.0 technologies and their fields of impact with regard to production and product development (PD).
- We do not provide a framework to evaluate the level of maturity of existing technologies.
- We do not characterize the functionalities of existing technologies in detail rather than supporting a general classification of these.

In line with these objectives, in the following sections we introduce the proposed framework. In section 2, we focus on the basic elements of the framework. In section 3 the framework of production and product development is described. Based on this, we define five basics types of Industry 4.0 technologies and highlight their differences by examples of existing technologies. Examples for application of the framework and trends for further research conclude the paper (section 5).

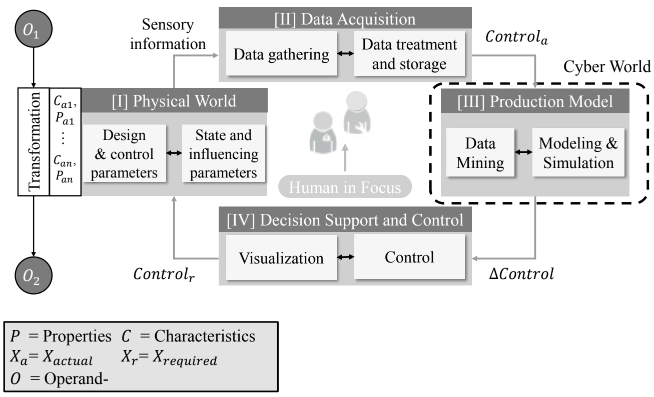
2. Elements of a framework for classification

We intend to provide a basis for the structured description and classification of existing technologies and to differentiate their main impacts within the product generation process. Basic concept is a coupling of models describing collection, processing and use of information in production and PD. In this section, we introduce the basic elements of the framework, starting with the production information loop.

2.1. Production information loop

From a production perspective, the main elements of Industry 4.0 are cyber-physical systems (CPS). Due to their application context they are called cyber-physical production systems (CPPS). Those systems can be implemented on different levels of a production system, i.e. on machine level, process level and factory level. [6] Nevertheless, they have several aspects in common. To identify CPPS technologies, THIEDE describes a framework for CPPS consisting of five main elements – the *Physical World* (I), *Data Acquisition* (II), *Cyber World* (III), *Decision Support or Control* (IV) and *Human in Focus* (V) (shown in Fig. 1). Furthermore, the interfaces between these elements are described. If a technology covers all five elements, it is defined as CPPS. The aim of the resulting production information loop is to manually or automatically influence the process performed in the *Physical World* in order to assure the required characteristics and properties of the component or assembly.

Fig. 1. Production information loop according to THIEDE [6].



The *Physical World* (I) ensures the transformation of an operand from an initial to the intended final state, as described by HUBKA [7]. It consists of physical production equipment, such as machines, processes or plants. These machines are run by certain design and control parameters as well as performance criteria and are influenced by internal and external disturbing variables. The state of a production entity is determined by several measurable variables.

The *Data Acquisition* (II) of the disturbing variables as well as the measurable variables is performed by sensors or other IT-systems (e.g. ERP-systems) in the *Physical World*. Data base structures process and store the gathered data, allowing them to be used in the *Cyber World*.

In the *Cyber World* (III) advanced analytic production models as well as numeric simulations are applied in order to gather forecasting information, resulting in an output for the *Decision Support and Control* of the CPPS.

This *Decision Support and Control* (IV) can be used by different stakeholders (V) for decision-making or can directly be integrated into the physical equipment as automated control. For a decision support function, the information or action recommendations need to be visualized.

By linking the described elements, the defined functionalities of CPPS (see Introduction) are realized. For all elements of the CPPS, different levels exist [8] whereas humans are excluded in this regard.

2.2. Product development information loop

In analogy to the CPPS, the main activities of the product development process can be described as an information loop.

Our understanding of this loop is based on the established abstract process models defining theories and conceptual insights concerning the design and development processes [9] as proposed by GERO [10] or WEBER [11]. Thus, the development is based on required functions or properties and leads to a design description defining the structure of the product to be produced. In order to define the main inputs and outputs of the elements within the product development loop, we used the distinction between characteristics and properties (cf. WEBER). According to WEBER, characteristics (C) define parameters that can directly be influenced by the engineers like the geometry or material of a component. Product properties (P) describe the intended and actual behaviour of the product like reliability or costs and result from the determined characteristics as well as relations defined by physical effects. In order to realize the required properties of the product, an iteration of analysis and synthesis activities is performed during the product development supported by product models [11].

The product development loop used to describe the main development activities within the framework is shown in Fig. 2. Based on *Product Information Acquisition* (A), essential information and requirements for the development process are gathered. Aside from the initial acquisition of customer information, further customer feedback may be necessary to agree with changed requirements or limitations in a later phase of development. For instance, based on a first customer information and requirements feasibility evaluation, product performance and restrictions, e.g. costs, are evaluated within the following elements of the product development information loop.

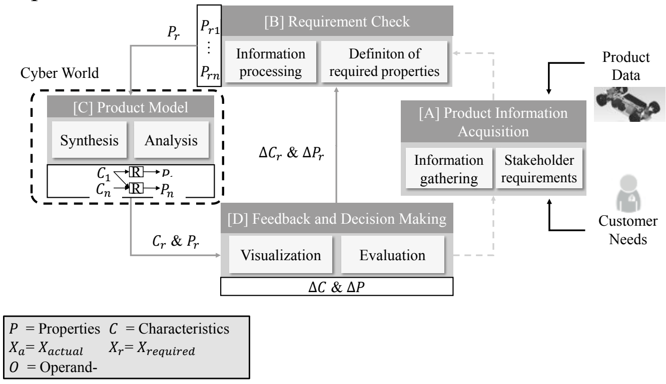


Fig. 2. Product development information loop within the framework.

The product information and requirements are used in the *Requirement Check* (B) to define required properties of the product (P_r). Therefore, the product to be developed is described with regard to technical and economic aspects in more detail using the information of existing products. In addition to the stakeholder requirements, the *Requirement Check* (B) also processes required changes of product properties based on deviations identified in the *Feedback and Decision-Making* (D) element.

The defined required properties (P_r) serve as inputs for the *Product Model* (C), where synthesis and analysis are carried out using different product models. During synthesis, product models are generated defining physical effects and dependencies between components as well as characteristics to realize the required properties of the product. In this way, important characteristics are identified and determined in order to achieve the required product properties. At the same time, the *Product Model (C)* serves to evaluate the impact of changed characteristics on the properties within the analysis activities. The required properties and characteristics determined by the *Product Model* (C) as well as deviations of these are inputs for the *Feedback and Decision-Making* (D) element. Here, they are evaluated and tested, e.g. for technical feasibility or manufacturability. Therefore, the defined characteristics and properties are analyzed on a strategic level in order to accomplish approvals, e.g. for the production of single components. Needed changes of properties and characteristics (delta C and P) are passed on to the *Requirement Check* (B), as long as the requirements initially defined by the customer are not confirmed.

Based on the four elements, two loops (see different lines in Fig. 2) can be defined in the PD control loop to define the properties and characteristics of the components and assemblies to be produced.

2.3. Integration Model

In order to connect the production and product development information loops described above, we use an integration model. In this context, the core task of the *Integration Model* is to ensure networking and communication between the *Product Model* and the *Production Model* in the *Cyber World*. Therefore, product data, essentially required properties and characteristics of the product (design description) have to be processed for the *Production Model*. This interface has to ensure that information can be transferred consistently in both directions [12]. Thus, a holistic functional integration of systems of different domains, fused to a *Integration Model* containing intelligent algorithms, are required.

Such an *Integration Model* includes different methods and technologies to connect the *Product Model* to the *Production Model* in sense of function integration. For example, the tools of product data management (PDM) can be used to track and control data related to a particular product, creating a connection between the product and integration models. By using a manufacturing process management (MPM), an interface to the *Production Model* is created from the product characteristics and parameters stored in the PDM. One possible way to feed PDM and MPM tools with data would be the generation of a modular and classified bill of materials (BOM).

Each of the individual disciplines depends on its own (simulation-) environment and thus data sets. The merging of the relevant information from the respective tools is accomplished by tool integration. The interfaces play an essential role in successful integration. Therefore, all information, e.g. requirements and data acquisition from the different domains, are taken into account.

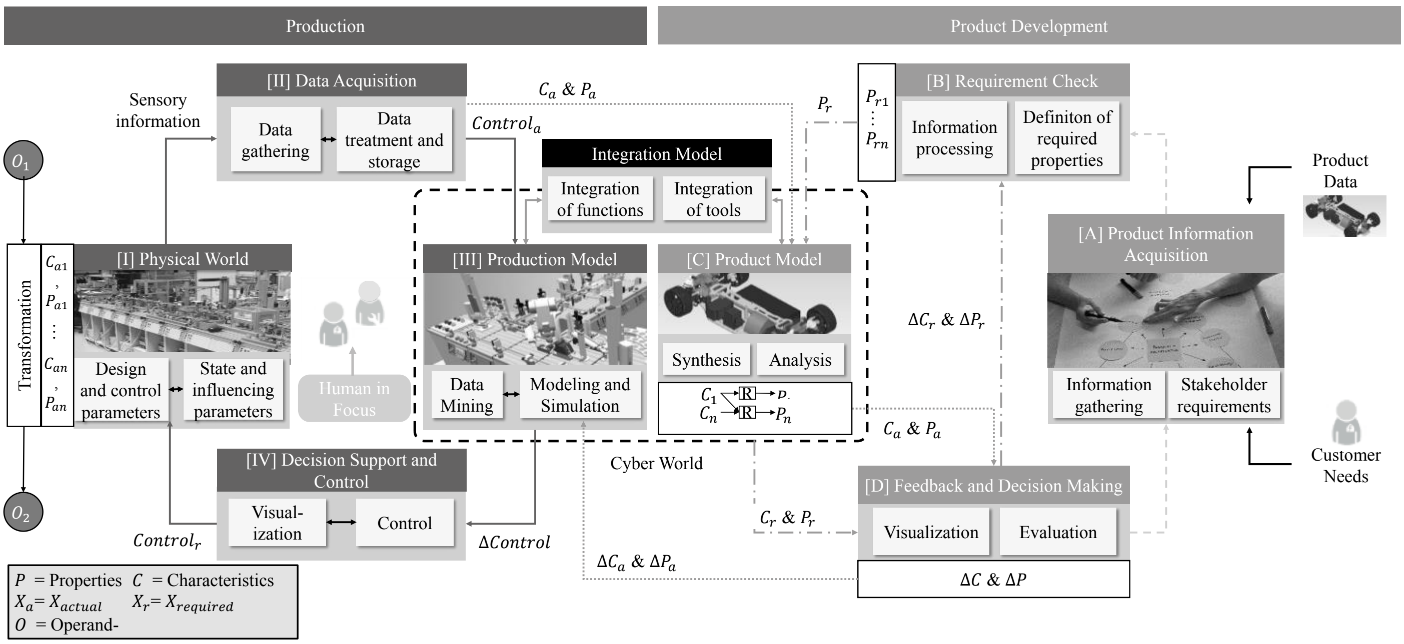


Fig. 3. Framework to support classification of Industry 4.0 technologies across production and product development.

In addition to generating production-relevant information, another task of the *Integration Model* is to check this information for optimization and feasibility. If there is a need to revise the characteristics and properties transferred by the PD, a new iteration loop is triggered. The simulation of the integrated overall functions of the CPS is backed by a self-developed multi-domain simulation platform.

The loops explaining the information flows in production and PD as well as the integration model described are constituents of the framework to classify Industry 4.0 technologies to be applied in the product generation process.

3. A framework to classify Industry 4.0 technologies

The framework is shown in Fig. 3. The product development and the production information loop are coupled using the elements of the *Production* and *Product Model*. These models form the so-called *Cyber World* of the framework. The concept of the *Cyber World* is based on the fact that the calculations and applied models or simulations carried out in the production and product model are implemented on a virtual level. The coupling of both models based on the function of the integration model realizes further information flows (⋯⋯▶). Thus, the *Production Model* (III) not only receives the required product properties (P_r) and characteristics (C_r) from the *Product Model* (C), but also the *actual* product characteristics (C_a) and properties (P_a) realized during production. At the same time the actual characteristics and properties are inputs for the *Product Model*. Based on this information of the production loop, the impact of deviations can be evaluated by analysis and synthesis within the *Product Model*. The generated information is returned to the product information control loop and handled as described in section 2.2. Based on the connection between *Production* and *Product Model* within the cyber world, the required changes of properties and characteristics can be evaluated not only with regard to determinations within product development, but detailed analysis within the *Product Model*. In addition to the direct and indirect transfer (i.e. without or with customer feedback) of these changes to the *Requirement Check*, the direct transfer of this information back to the *Production Model* is enabled. This allows to guarantee and check the implementation of product-related customer requirements in the production process. In addition to sensor and control data, information on actual product characteristics are also recorded and communicated to the CPPS.

The described integration of the information loops in production and product development highlights the potential occurring from the extended and continuous exchange of information. Furthermore, it indicates essential interfaces and functions to be fulfilled by Industry 4.0 technologies to cover the whole product generation process. Based on the introduced framework in the following section, basic types of Industry 4.0 technologies are defined.

4. Basic classifications of Industry 4.0 technologies

In this section we make use of the classification model and introduce five basic types of Industry 4.0 technologies and define their main functionalities. By looking at different existing CPS and CPPS, we assume that every Industry 4.0 technology has to include the *Cyber World* and furthermore has to form an information loop. If the information flows are further considered in the classification model under this assumption, five basic types can be identified. These five basic types were verified in the next step by a catalog of technologies, whereby a total of 22 Industry 4.0 technologies were analyzed. These Industry 4.0 technology types are listed in Table 1 and explained in more detail below.

Table 1. Basic Industry 4.0 technology types in production and PE.

Basic Type	Involved Elements	Examples
Production (Domain specific)	Physical World, Data Acquisition, Production Model, Decision and Support Control	Machine condition monitoring for production process optimization
Product Development (Domain specific)	Requirement Check, Product Model, Feedback and Decision Making	Virtual start-up for testing functions, process parameters and controllers of a machine
Stakeholder (Domain specific)	Product Information Acquisition, Requirement Check, Product Model, Feedback and Decision Making	"Customer app" for improving product individualization and requirements acquisition
Cyber World (Domain spanning)	Product Model, Integration Management, Production Model	Automated generation of 3D models based on parameteric models
Field Use (Domain spanning)	Product Information Acquisition, Requirement Check, Product Model, Feedback and Decision Making, Production Model	Predictive maintenance for product optimization and maintenance cost reduction

4.1. Type I. Production (Domain specific)

Type I is equivalent to a CPPS (see Section 2.1) and therefore involves the elements *Physical World, Data Acquisition, Production Model and Decision Support and Control.* Technologies of this type support process optimization in production and increase process flexibility.

An example for this type are machine condition monitoring technologies [13]. Here, condition and performance data of the machines in the *Physical World* are collected *(Data Acquisition*) and analysed in a *Production Model* using e.g. methods from data mining. Based on the simulations and analyses in the *Production Model,* the production process is adapted. This adaption can be done manually based on the output of a recommendation, or automated by the machine condition recognition. These activities are assigned to the *Decision Support and Control*.

4.2. Type II. Product Development (Domain specific)

The second type of Industry 4.0 technologies involves the elements of the product development information loop, expect for *Product Information Acquisition*. Technologies of this type can lead to an increased flexibility during PD and to a more effective error detection as well as prevention.

One example for this technology type is the virtual start-up. Here functions, process parameters and controllers of a machine are tested virtually before the actual start-up [14]. Therefore, a virtual model of the machine is connected to a machine controller system using a simulation software. The resulting overall behaviour of the machine can thus be recorded and tested virtually. In the framework, this is assigned to the element *Product Model*. By testing the virtual model, errors in the structure of the machine or the software are identified. This procedure is linked to the *Feedback and Decision Making*. If no errors occur, the manufacturing documents can be handed on to the production. If errors occur, changes to the system are made in such a way that the previously recorded requirements (*Requirement Check*) are not violated.

4.3. Type III. Stakeholder (Domain specific)

Technologies belonging to this type involve the *Product Information Acquisition*, the *Requirement Check* and the *Product Model*. They support capturing of stakeholder requirements and their transformation into a product model. In this way, product individualization and customer integration into the PD can be supported. An established example for this type of technology is a "Customer app" supporting product individualization and requirements acquisition [15]. Based on this software application, configurations and specifications of the product can be performed and displayed by the customer. The functionality of the app is based on a product model representing architecture and logic of an existing product as well as limitations for adaptions. This ensures that any customer input leads to a manufacturable and functioning product. For this reason, the requirement check can be skipped when the customer enters data. The customer app functions as a construction kit in which a complete product model can be assembled from predefined elements. These activities of the customer are allocated to the *Product Information Acquisition*. On the basis of the acquired product requirements and wishes, an adaption of the basic product model is being generated. In this way, the handling of a company's product portfolio can be increased through improvement of the customer requirement acquisition. Furthermore, the process duration of the product model creation can be shortened.

4.4. Type IV. Cyber World (Domain spanning)

The forth type contains technologies settled only in the cyber world. The elements *Product Model*, *Integration Management* and *Production Model* are therefore affected. Technologies of this type mainly support the connection between both cyber models. This shortens the time needed to create the production-relevant information and at the same time increases the quality of the files transferred, e.g. in terms of consistency as well as the flexibility within production.

An example for a Type IV technology is the automated creation of 3D models, including the creation of 2D manufacturing drawings and the generation of NC programming for the production of these components, as described in [16]. By recording all relevant product properties and characteristics and linking them with each other within the product model, a parameterized model is created. The stored constraints can be used to automatically generate 2D manufacturing drawings, a generally work-intensive and expensive process. NC programming for component production can also be automated in this way.

4.5. Type V. Field Use (Domain spanning)

Technologies belonging to this type involve the whole product development loop as well as the *Production Model*. They support monitoring of products in use. This enables quality deficiencies to be quickly identified and mended by product and production optimization.

One example for a technology of this type is provided by predictive maintenance [17]. Here, product information is gathered during product use and sent to the manufacturer. In the *Requirement Check* this information is used to define the actually required properties. After synthesis and analysis in the product model, the actual and required product characteristics and properties can be compared. According to the result of the comparison, the product or production model can be adjusted and optimized. In addition, faulty product states can be identified and major failures can be avoided by appropriate (predictive) maintenance procedures.

The spanning of the five introduced types of Industry 4.0 technologies regarding the essential domains of the product generation process is shown in Fig. 4. It can be seen that the "Cyber World" and "Field Use"-technologies are the only ones that are linking PD and production domain.

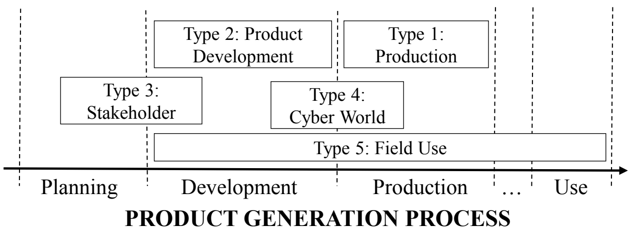


Fig. 4. Identified Industry 4.0 technology types in the product generation process

5. Conclusion and further research

The widespread use of the term "Industry 4.0" leads to a diffuse understanding and manifold definitions of applied technologies. Furthermore, existing definitions and models to describe functions and properties of Industry 4.0 technologies often focus on production systems and therefore do not provide a framework to describe technologies covering the whole product generation process.

Motivated by this limitations, the objective of this work was to provide an approach for the consistent classification of Industry 4.0 technologies as well as to create a common understanding integrating the views of production and product development. For this reason, a classification model was developed and introduced. This model supports the understanding of information flows within the product generation process and does not only focus on production but also on product development. Thus, it allows to investigate technologies andto identify them as Industry 4.0 technologies. The introduced classification model is merely to be understood as an approach for a consistent identification and classification of Industry 4.0 technologies. The framework is not intended to describe single Industry 4.0 technologies in detail. However, it indicades *Cyber World* and *Field Use* as domain spanning technologies, linking the information loop of production and PD. The detailing of the needed *Integration Model* will be part of further research to gain knowledge about the independencies between production and PD. This knowledge will serve to identify potentials regarding product design and the design of production systems and insights for new Design for Manufacturing and Design for Assembly principles in context of Industry 4.0.

Acknowledgement

This paper was developed in the research project "Synus" (Methods and tools for the synergetic conception and evaluation of Industry 4.0 technologies) which is funded by the European Regional Development Fund (EFRE | ZW 6-85012454) and managed by the project management agency NBank.

References

[1] Dedehayir, O., Steinert, M., 2016. The hype cycle model: A review and future directions. Technological Forecasting and Social Change 108, 28–41.
[2] Kang, H.S., Lee, J.Y., Choi, S., Kim, H., Park, J.H., Son, J.Y., Kim, B.H., Noh, S.D., 2016. Smart manufacturing: Past research, present findings, and future directions. Int. J. of Precis. Eng. and Manuf.-Green Tech. 3 (1), 111–128.
[3] Baheti, R., Gill, H., 2011. The Impact of Control Technology: Cyber-physical Systems. IEEE Control Systems Society, 1–6.
[4] Lee, E.A., Seshia, S.A., 2011. Introduction to embedded systems: A cyber-physical systems approach, 1st ed. Lee Seshia, Lulu.
[5] Feldhusen, J., Grote, K.-H. (Eds.), 2013. Pahl-Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung, 8th ed. Springer Vieweg, Berlin.
[6] Thiede, S., 2018. Environmental Sustainability of Cyber Physical Production Systems. Procedia CIRP 69, 644–649.
[7] Hubka, V., Eder, W.E., 1988. Theory of technical systems: A total concept theory for engineering design. Springer Berlin Heidelberg, Berlin 278 ff.
[8] Thiede, S., Juraschek, M., Herrmann, C., 2016. Implementing Cyber-physical Production Systems in Learning Factories. Procedia CIRP 54, 7–12.
[9] Wynn, D.C., Clarkson, P.J., 2018. Process models in design and development. Res Eng Design 29 (2), 161–202.
[10] Gero, J., 1990. Design Prototypes: A Knowledge Representation Schema for Design. AI Magazine. 1990 (11), 26–36.
[11] Weber, C., 2014. Modelling products and product development based on characteristics and properties, in: , An anthology of theories and models of design : philosophy, approaches and empirical explorations. Springer, London, 327–352.
[12] Eigner, M., Koch, W., Muggeo, C. (Eds.), 2017. Modellbasierter Entwicklungsprozess cybertronischer Systeme: Der PLM-unterstützte Referenzentwicklungsprozess für Produkte und Produktionssysteme. Springer Vieweg, Berlin.
[13] Lee, J., Bagheri, B., Kao, H.-A., 2015. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters 3, 18–23.
[14] Wünsch, G., 2008. Methoden für die virtuelle Inbetriebnahme automatisierter Produktionssysteme. Zugl.: München, Techn. Univ., Diss., 2007. Utz, München, 194 ff.
[15] Saldivar, A.A.F., Goh, C., Chen, W.-n., Li, Y. Self-organizing tool for smart design with predictive customer needs and wants to realize Industry 4.0, in: 2016 IEEE Congress on Evolutionary Computation (CEC), Vancouver, BC, Canada, pp. 5317–5324.
[16] Anderson, D., Kristin Wood, 2018. A Design Process for Design Automation, 1st ed., Singapure.
[17] Li, Z., Wang, Y., Wang, K.-S., 2017. Intelligent predictive maintenance for fault diagnosis and prognosis in machine centers: Industry 4.0 scenario. Adv. Manuf. 5 (4), 377–387.