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Engineering industrial cyber-physical systems: An application map based method

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Abstract

The extensive digitization in industry and the advancing introduction of cyber-physical systems (CPS) in manufacturing offer a wide-ranging potential for industrial value creation. To ensure effective engineering processes of these systems, technological and organizational challenges need to be addressed systematically. Thereto, we develop a method for the systematic engineering of industrial CPS in this paper. The operational framework of the suggested method provides a guided process for (1) the selection of application fields for industrial CPS under the consideration of economic and technological necessities as well as (2) guidelines for the subsequent system configuration with components and functionalities.

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Keywords: Industrial cyber-physical systems; system configuration; system engineering; method development

1. Introduction

The ongoing digitization is one of the leading drivers of change at present. It affects several spheres of life of individuals as well as entire social and economic structures altogether [1]. Especially in the field of manufacturing, digitization leads to a novel understanding of industrial value creation. In this context, the ongoing development not only relates to changes in the execution of production processes, but furthermore leads to an advancement of the entire production logic and new strategic alignments of businesses [2,3].

Among others, cyber-physical systems (CPS) are fundamental technical enablers in this context [4] joining physical processes with digital entities and procedures in a systematic manner [5]. Informed by numerous contributions from several disciplines and research communities [6], the convergence of the physical and digital world in the form of CPS has reached a sound level of development. It qualifies as a general purpose technology (GPT) [7] for the further realization of Industry 4.0. Besides the association with wide-ranging potential regarding production efficiency, process innovation and further automatization, Industry 4.0 and the respective technologies subsumed under this term increase the complexity of industrial value creation in several ways [8]. To address this enhanced level of complexity, the engineering of CPS in the industrial context calls for systematic methods supporting decision-makers in the whole process of system planning, design and implementation.

This work therefore aims to develop a method that offers systematic guidance in the process of engineering industrial CPS with particular focus on the fit between particular organizational requirements and the specific solution designs in the respective fields of application. For this purpose, we approach the topic from a managerial perspective, addressing the question of how decision-makers in industry can design system configurations for industrial CPS with respect to their distinctive organizational characteristics.

After stating the theoretical background, we develop the method on the basis of a comprehensive application map, explain its utilization and proceed with its evaluation before providing conclusions and an outlook.

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With the development of this method, we intend to contribute to systematic usage of CPS for enhancements in general productivity, manufacturing execution, working conditions, product quality and in turn, customer satisfaction and further critical issues in industry [9].

2. Theoretical background

2.1. Industrial cyber-physical systems

CPS are defined by [5] as "[…] integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa." With their ability to sense physical conditions and processes via sensors, analyze them through digital data processing, and subsequently react and influence the physical conditions and processes via actuators, CPS offer broad application possibilities in the industrial domain [10,11]. Considering their technical, human/social and organizational dimensions, CPS affect industrial value creation in several ways [12]. In combination with technologies like big data, artificial intelligence and novel forms of human-machine interaction, CPS accelerate the capabilities of production in a self-configuring, self-optimizing, adaptive and context-aware direction. Frequently discussed use cases are predictive maintenance [13], additive manufacturing in combination with batch size one or an integrated supply and value chain. Moreover, CPS are considered a driver for service systems engineering, providing large amounts of data which can be the basis for production supporting services or hybrid products [14].

Furthermore, CPS dissolve the explicit distinction between production facilities on the one hand, and production parts during the production process and upon completion products in use on the other hand. This is the case if the production site is an industrial CPS and the manufactured products qualify as so-called smart products [15] and, therefore, account as a CPS by themselves [16]. The emergence of these industrial CPS fosters innovative value creation procedures and business models, which offer enhancements for both the production management as well as for the product user [17].

2.2. Complexity in system engineering

While the application of CPS in the industrial context offers a wide range of potential, their introduction leads to an increase in complexity. In the case of systems, complexity refers to the number of parts and components and their interconnections or interdependencies [18].

The increase in system complexity in the application of industrial CPS is evident in several ways. First, system architectures become more multilayered [19] and system boundaries dissolve into ad hoc systems of systems [1]. Second, formerly indirectly involved departments and stakeholders become part of the production process, necessitating advanced collaboration approaches [20]. Third, the decision-making processes in the factories need to be adapted in temporal terms due to the proceeding relevance of short-term and real-time production management [21].

In summary, the introduction of industrial CPS increases the complexity regarding system size and structure concerning the composition of technology [22], personnel [23] and organization [1], and, furthermore, in the temporal dimension. The increase is also evident in the engineering process of the system.

2.3. Complexity reduction via modularity

To enable effective and efficient engineering of industrial CPS with the goal of setting the accompanying potentials free, decision-makers are reliant on methods, guiding and structuring this process.

For a long time, the process of systems engineering has been analyzed for the effects on organizations caused by the introduction of information technologies [24] and the systematic measurements for systems engineering efficiency [25]. However, existing methods are increasingly insufficient when confronted with the complexity level of CPS architectures [26]. Therefore, development of new methods is needed to reduce complexity to a manageable level and to provide systematic approaches for the entire engineering process of industrial CPS consisting of planning [27], designing [28,29] and implementing [22].

To that end, utilization of the established approach of complexity reduction by modularity seems reasonable. The concept of modularity describes the decomposability of systems into terminable components. The components, interchangeable due to standardized interfaces, are organized by an underlying system architecture. Applying the concept of modularity enables even non-expert users to develop systems, e.g., products, by a structured solution space [30].

In the industrial context, modularity has been successfully applied in the design process of complex engineering systems [31]. Moreover, it has been identified as a useful approach to manage technical change in the digital age [32]. Initial examples of usage of modularity for industrial CPS can be found in the European tool making industry [33].

3. Proposed application map based method

3.1. Positioning and purpose of the method

Technology and its application affect organizational development extensively. To harness the potentials of new technologies for the company and its value creation, the process of organizational change requires systematic approaches [34]. This requirement is true for industrial CPS as well. However, as described before, existing methods of systems engineering are only partly applicable because of the enhanced complexity of CPS.

Therefore, our work aims to develop a method that provides a holistic and structured process for engineering industrial CPS complementing other methods with their rather specific focus, e.g. [28,35]. Since the level of development in the organizational dimension regarding CPS is somewhat rudimentary compared to its technical and human/social counterparts [12], this paper focuses on CPS engineering from an organizational perspective while not leaving the other dimensions aside. With regards to the chronological flowchart of the CPS engineering process, our work is concerned with the stages of system planning and design as an enablement for subsequent implementation.

We aim to provide a method with broad applicability to support system engineers in OEMs, but also SMEs or startups. This is highly relevant since especially SMEs and smaller sized companies often struggle with the application of CPS in their production processes while they have the most significant concerns of enterprise type and value creation contribution in most economies [36].

3.2. Requirements for the method

The method has to meet a catalog of conditions to offer the proposed value for system engineers. First, to reduce complexity with the aim to make the engineering process manageable it has to include a modularity concept of sub-classifying application areas while maintaining a holistic overview of application possibilities. Second, the method must consider the logic of industrial CPS containing both digitized production processes and products in use. Third, as a holistic approach, it must take into account the three dimensions of industrial CPS (technical, human/social and organizational). Fourth, the guided process of CPS engineering needs to enable specific and individual configurations concerning the size and sector of each company. Fifth and final, the method should allow distinguishing between internal and external components and processes within the CPS configuration related to the specific value creation constellation.

3.3. Introduction of the method

The proposed method for the engineering of industrial CPS configurations under consideration of the previously stated requirements is based on the construct of an application map for industrial CPS by [12]. Providing an overview of potential application fields for CPS in the industrial context, this construct offers a holistic categorization consisting of different spheres and containing subfields as modules. The four superordinate spheres are smart factory, smart data, smart services and smart products. As seen in Fig. 1, the map is divided into two halves. While the upper half contains the smart factory [37] sphere, and the lower half the smart products [16] sphere, the two spheres of smart data and smart services are spread over both halves.

The layout follows the logic of a proceeding integration of production processes and smart products in use [17]. This integration is based on the extensive data availability gathered by CPS sensors. Transformed to valuable information via big data analytics like pattern recognition, the collected data is the basis for new services applied both within the factory and as complements to smart products [15,28,38]. The utilization of these services leads to new data, which then again runs the entire cycle further. Eventually, data and service driven processes offer wide-ranging improvements for production processes within the smart factory and for smart products as product-service systems [39].

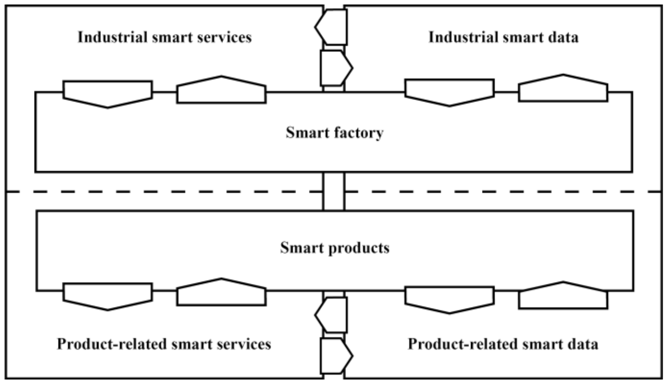

Fig. 1. Spheres of the application map.

To realize these potentials, we propose the utilization of the application map based method that we designed and evaluated with the motivation of structuring the industrial CPS engineering. The resulting method consists of four phases.

1. Phase: Following the theory of modularity as an approach to reduce complexity, the first phase guides the selection of system components out of 32 application fields organized in the four superordinate spheres. The spheres function as classifications [40] for the application fields, organizing them by scope as seen in Fig. 2. Depending on the purpose of the to-be-engineered CPS, one application field has to be chosen as an anchor point, thereby building the functional core of the system configuration. Outward from the anchor point, additional application fields as system components are chosen and marked by circles.

2. Phase: In the second phase, the chosen system components are configured into a holistic functional system aligned to the specific functionality and business context of the applying organization. To illustrate the flow of material and information between the interconnected application fields, lines are used as conjunction elements. While solid lines and circles represent essential system components, dashed ones stand for facultative components. The option to distinguish between essential and facultative components allows prioritizing within CPS functionalities. To illustrate if the application field and its functionality are located within the organization or performed by an external provider, each selected component is marked with an "I" for internal, "E" for external or "I/E" for a combined solution.

The interim result of the second phase is a holistic overview of the compiled CPS configuration. Since prediction in production is of great interest in CPS oriented research [13,41], the case of a predictive maintenance system as a CPS configuration is demonstrated in Fig. 2.

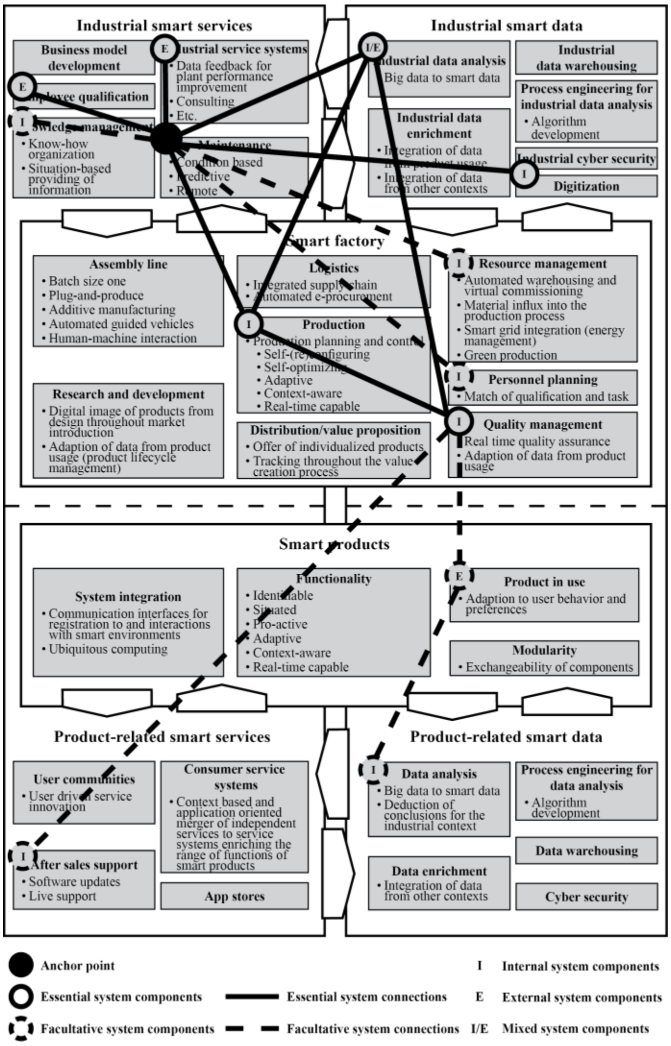

Fig. 2. CPS configuration of a predictive maintenance system (adapted from [12]).

The map with the exemplary predictive maintenance configuration is interpreted in the following way: Given the purpose of the system, the application field of maintenance serves as the anchor point. Then, sensors in production facilities continuously gather data on operating conditions (Production). When falling below or exceeding specific values, alerts or errors are given and maintenance personnel are directly informed (Maintenance). Beyond that, the continuously gathered data is merged and analyzed using pattern recognition. In this way, the early fault detection improves over the course of time (Industrial data analyses). With the continuously increasing data basis, industrial services such as the provision of live-information and recommendations for action for error-handling for maintainers or remote-maintenance services are applied (Industrial service systems). To ensure proper handling of the system by the workforce, measures for employee qualification should be offered (Employee qualification). To provide an effective maintenance system without unnecessary media discontinuities, it is necessary to digitalize and catalog analog data sources, such as operating manuals, plant drawings, etc. (Digitization). Beyond those essential system components, further facultative components can be integrated into the system. The implicit knowledge of individual employees, due to documented problem-solving guidelines for previous repairs, are made available to the whole department (Knowledge management). Furthermore, information about personnel qualifications and its availability (Personnel planning) as well as inventories of spare parts and tool availability from storage can be integrated into the configuration (Resource management). In addition to the components within the enterprise, the system can also be extended beyond company boundaries. In particular, data of product behavior during use by users or operators (Product in use; Data analysis) can give meaningful information about possible quality defects, which are not detected during the manufacturing process by the quality management (Quality management). In response to this, not only can the maintenance personnel correct defective plant settings in the production, but also, where possible, error-correcting updates for the product can be provided (After sales support).

3. Phase: In the third phase, the chosen application fields are extracted out of the application map and enhanced with specifications regarding the technical and human/social CPS dimensions. Therefor, technologies and services required for the each application field are listed. The resulting overview is valuable for decision-makers in the sense that it allows to determine whether the required know-how is already existing in the company or whether it needs to be acquired. A list of the stakeholders involved and affected in each application field is added as well. When all stakeholders of a CPS configuration are known, this information can be utilized for user-centered system development approaches as well as to make potential conflicts due to stakeholder group specific expectations from and attitudes towards industrial CPS become apparent. At length the financial investment costs of each configuration component are estimated. The estimate can be calculated with reliable figures or a scaled ranking if a determination of precise figures is not possible. With the addition of this information, the mainly organizational perspective is enriched by technical and human/social scope allowing a more integrated approach to evaluation of the engineered CPS configuration. The selection of application fields of the predictive maintenance system presented in Fig. 2 is shown in the sheet of Fig. 3.

	Smart factory				Industrial smart data		Industrial smart services				Smart products	Product-related smart data	Product-related smart services
	I	I	I	I	I/E	I	●	E	I	E	E	I	I
	Production	Resource management	Quality management	Personnel planning	Industrial data analysis	Digitization	Maintenance	Industrial service systems	Knowledge management	Employee qualification	Product in use	Data analysis	After sales support
Technology/Service													
Stakeholder													
Investment costs													

Fig. 3. CPS configuration estimation.

4. Phase: In the fourth and final phase, the planned and designed industrial CPS configuration is evaluated considering the information gathered in the organizational, technical and human/social dimension. In iterative cycles, the configuration is modified based on essential and facultative components, technical design, a combination of organization internal and external components, etc. until the configuration qualifies for further implementation steps.

3.4. Value proposition of the method

The application map based method offers assistance to decision-makers in several ways. It gives a holistic overview of application spheres and fields of industrial CPS and illustrates the linkage of both production and product allocated fields. Once the application map and CPS configuration estimation table are filled out, they offer the following benefits for the further development and application of industrial CPS: Interdependences between the different spheres and fields with their linkage become apparent. In this way, material, data and information streams are simple to follow. Essential and facultative CPS configuration components can be differentiated readily. The same applies for internally or externally rendered applications and services. The own role in value creation networks with different collaborators becomes more transparent [42]. The application map can therefore complement conventional business model development activities during CPS-related re-evaluations of existing business models or designs of new ones [43]. By matching each application field of a CPS configuration with to-be-applied technologies and services, as well as affected stakeholders with estimated technology acceptance [44,45] and likely investment cost, the method expands the assessibility of the chosen configuration. According to the individual situation of the company-specific case, further measures can be taken.

3.5. Evaluation of the method

The method has been applied and evaluated within four workshops involving decision-makers of two OEMs of the automotive industry, one SME manufacturing specialty machines, and a group of startups from the industrial service and consulting sector. The participants were asked to plan and design a CPS configuration according to the actual conditions within their company. After applying method phases one through three and part of the fourth, the participants were asked to present their results and give feedback regarding the usability and benefit of the method. The feedback was collected following a qualitative evaluation design [46].

In the workshops, several CPS configurations were engineered, including Fig. 2 that introduced a predictive maintenance application alongside configurations of production execution, remote maintenance systems, CPS oriented business model consulting and data analytics solutions. The evaluation of the concept and the functionality of the method gave the following results: The main points of the positive feedback were the structure and clarity of the map providing a holistic overview of the organizational dimension of CPS, the clear sequence of the entire method and the modular format enabling the engineering of a multitude of CPS configurations. Potential for improvement was seen for the third phase of the method. Participants asked for a catalog of utilizable technologies for each application field with cost estimations for technical components as an orientation.

4. Discussion and conclusion

In this paper, we present and discuss a method offering guidance in the process of industrial CPS engineering with a focus on distinctive organizational characteristics. We apply modularity to reduce complexity and present a holistic overview of industrial CPS applications under consideration of smart factory, smart products [47], smart data and smart services [48]. It results in a modular application map with a structured four-phase approach to engineer industrial CPS with a main organizational emphasis. The method allows evaluation of the chosen CPS configuration from an economic [49], technical, performance [50] and investment [51] perspective. With this functionality, the method offers a valuable complement to the predominant technical discussion of modeling, simulation and integration industrial CPS [52].

A future enhancement of the method will include a catalog of applicable technologies and services for each application field including reference values for financial cost and the involvement of several stakeholder groups for further cooperation and alignment of CPS configurations.

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