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Cyber-physical modeling and simulation: A reference architecture for designing demonstrators for industrial cyber-physical systems

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Abstract

The application of models and simulations is well-established in systems engineering and development. To adapt this approach to the digital age, we propose the concept of "cyber-physical modeling and simulation (CPMS)" which enables to constitute cyber-physical systems (CPS) with scalable complexity, modularity and variability in size. Based thereon, we derive a reference architecture for designing demonstrators for industrial CPS. The reference architecture offers a structured design space and attributed components which constitute the demonstrators with regard to their application objectives and scenarios. As a viability assessment, we apply the proposed reference architecture by developing the instantiation "Portable Industrial Demonstrator for Cyber-Physical Systems (PID4CPS)".

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Keywords: Cyber-physical systems; cyber-physical modeling and simulation; reference architecture; demonstrator

1. Introduction

In the course of the digital transformation, the innovative technological concept of cyber-physical systems (CPS) gains importance within organizations, their infrastructure and processes [1,2]. Combined with further concepts like the internet of things (IoT) [3], big data [4] and artificial intelligence (AI) [5] as well as organizational approaches shaping the future of work [6], CPS affect all kinds of organizations, their individuals but also entire economies [7]. In the industrial context, under the term Industry 4.0 [8], CPS-based digitization of value creation offers wide-ranging potentials including further automatization and autonomization of processes with simultaneous increases in efficiency and effectiveness [9], highly individualized products via batch size one at costs of mass production [10] and data-driven business model enhancements [11]. On the downside, the introduction of industrial CPS and related digital concepts confronts organizations and their decision makers with substantial issues and challenges. Particularly noteworthy is the increasing complexity and diversity of production related systems, which impede the entire process of systems engineering and development [12]. In addition to the various aspects regarding technology management, employee concerns and reservations as well as juridical matters need to be addressed while safety and security issues arise alike [13]. For these reasons, there is an imperative need for well-founded methods and design knowledge which facilitate decision makers to systematically engineer and develop industrial CPS addressing the challenges mentioned in order to exploit the wide-ranging potentials of CPS-based Industry 4.0 [14].

This work contributes to these methods and design knowledge by adapting the proven approach of demonstrator deployment within the process of systems engineering and development [15] to the conditions of the digital age. Therefore, we propose the concept of "cyber-physical modeling and simulation (CPMS)", which joins the principles of system modeling and simulation with the characteristics of CPS. On the basis of the CPMS concept, we develop a

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reference architecture which provides structures and guidelines for designing industrial demonstrators to model and simulate CPS with scalable complexity, modularity and variability in size but yet with components from both their inherent digital and physical spheres.

Thereto, this paper proceeds as follows: First, the theoretical underpinning comprising industrial CPS and the particularities of their engineering and development as well as the foundations of modeling and simulation is given. Proceeding, the concept of CPMS with its characteristics is introduced. Next, we derive and arrange the reference architecture for industrial demonstrators before applying it in form of the instantiation “Portable Industrial Demonstrator for Cyber-Physical Systems (PID4CPS)” as a viability assessment. Lastly, the paper concludes with a discussion and outlook.

2. Theoretical background

2.1. Industrial cyber-physical systems

The concept of CPS describes the comprehensive integration of physical entities and operations with digital processing and virtual representations. Compared to conventional hardware and software combining systems, the innovative aspect of CPS is that continuous in real time executed reciprocal feedback loops between the cyber and physical spheres enable condition-based, (semi)-autonomous monitoring and control of processes [16]. The basis for this systematic approach is extensive equipping of embedded systems with sensors and actuators as well as the provision of digital infrastructure, algorithms and data processing capacities [8]. With the capability of state-based, data-driven and real-time process execution, CPS offer, especially for industrial applications, far-reaching potentials for optimizing existing processes but also for designing completely new value creation architectures [17].

Titled as industrial CPS, instantiations of this concept find application in several fields of pre-production, production and post-production (product in use) stages. These include production orchestration [2], predictive maintenance [18], self-organizing logistics [19], smart grid integration [20] and digital twins throughout the product lifecycle of smart products [21].

2.2. Industrial cyber-physical systems engineering and development

In the course of engineering and developing industrial CPS, three dimensions, which are inherent to these systems, comprising a technical, a human/social and an organizational one, require consideration [7]. Thereby, due to the multi-layered and many-faceted complexity of industrial CPS, their engineering and development process is likewise characterized as highly complex [22]. The high degree of complexity is a consequence of the following factors: First, in the technical dimension, formally independent systems converge with each other or merge context-dependent to ad hoc systems of systems [1]. In the systems engineering and development process, this means that the conceptualization and realization of the industrial CPS become technically more challenging. The required design knowledge regarding technical realizations and system architectures increases accordingly. Second, in the human/social dimension, due to the networking character of industrial CPS, more stakeholder groups become directly involved in the industrial value creation process and affected by the systems in place [23]. This means higher coordination efforts and an increased need for agreements among stakeholder groups which have to be established during the engineering and development process. Suitable measures for stakeholder integration are also of importance in this context. Thirdly, in the organizational dimension, the application of industrial CPS should be aligned with the organizational structure and managerial processes to foster and innovate the value creation logic and the business model of the company [7].

On account of the high degree of complexity and the often indeterminate system boundaries combined with the need to consider a multitude of involved and affected stakeholders, the implementation of industrial CPS proves to be challenging. For this reason, profound design knowledge, including methods, reference architectures, taxonomies, standards, etc., is essential for the effective and efficient engineering and development of industrial CPS [24].

2.3. Modeling and simulation as well as demonstrators in systems engineering and development

In the engineering and development process of complex systems, the utilization of models and simulations as well as the application of demonstrators has a long history [15,25]. Against this backdrop, a model serves as a facilitating representation of natural or artificial entities, in which intentional reduction and omission result in an individual abstraction of the original. Thereby, models can be of different form. These include formal descriptions, physical objects and computer-based virtualizations. The application of models in which they represent the real entity is referred to as simulation. In the course of simulations, insights regarding characteristics, behavior, coherence, etc. of the original can be determined. In addition, simulations are used to determine or influence user behavior. Like the model itself, the simulation can be performed physically or computer-based [26]. The term demonstrator is commonly used, if the model and the simulations carried out with it are used in particular to visualize functionalities and modes of operation. The demonstrator serves as a boundary object that provides a central reference for the user interaction with the simulated system, but also for the interactions among each other [27].

In summary, it can be concluded that the application of models and simulations in form of demonstrators has potential for engineering and developing industrial CPS in several respects: On the one hand, complex systems structures can be presented in condensed form. On the other hand, it offers an adequate means for stakeholder-oriented and stakeholder-centered system design.

3. Cyber-physical modeling and simulation

Models and simulations are used both for the description and for the engineering and development of CPS. In this context, Karsai and Sztipanovits [28] highlight the benefits of model-based views when developing CPS. In line with this, contributions by Larsen et al. [29] and Jensen et. al. [30] propose model-based design methodologies for CPS. Most of the models described in the literature are computer-based virtualizations or formal descriptions. These include formal modeling of CPS [31], models for cloud-based CPS [32], tool work processes [33] and future modeling of CPS-based factories. When models have the form of physical objects they mostly focus on certain facets of CPS and do not fulfill a holistic representation, e.g. [34].

Applications of models in simulations have often very specific scopes and objectives and focus on demarcated aspects and behaviors of the overall CPS. In addition, to examine individual system components and aspects, interactions of CPS among each other, in the context of systems of systems, is a further field of interest for simulations [31].

Moreover, it is noteworthy that the applications of models and simulations described in the literature focus almost exclusively only on one of the two spheres of CPS. Representing entities either of the cyber or the physical one and not in an integrated form.

This does not have to be necessary when characteristics and behaviors are in focus, in which CPS do not differ from traditional systems. However, when it comes to investigating particularities which are determined by the cyber and physical interconnection inherent to CPS, there is a need for models and simulation methods which allow a holistic representation of these systems.

CPMS addresses this topic. Considering the changes which come along the introduction of CPS, namely the further integration of cyber and physical entities, CPMS postulates the subsequent adaptation of modeling and simulation. In doing so, it complements existing modeling and simulation techniques with the capability to represent CPS holistically in the coaction of cyber and physical entities. Therefore, CPMS is especially valuable for the demonstration of systems, as it provides a complete overview of their configuration and functionality. This is particularly relevant for objectives that require stakeholder integration: E.g., system demonstration and explanation to personnel, user-centered system development including innovation, evaluation, expectation and attitude moderation as well as conflict regulation or boundary object-supported business model development. In these cases, CPMS is instantiated in form of demonstrators. So far, there are only very rudimentary CPS-oriented demonstrators that also only cover partial aspects of CPS [35,36]. Among others, this is attributable to the lack of profound design knowledge, which is in need to foster and structure the engineering and development of CPS representing demonstrators.

A suitable means to organize design processes are reference architectures as they offer comprehensive design spaces. Moreover, they arrange and represent the aspects of a subject in universalizing form. With regard to CPS, a number of architectures has been established already [37]. These include architectures for smart CPS [38], Industry 4.0-based manufacturing systems [39], self-aware machines [40], view consistencies [41], hierarchical security [42], digital twins [32] and further.

However, since there is no reference architecture for CPMS enabling demonstrators yet, it will be elaborated in the following.

4. Reference architecture for designing demonstrators for industrial cyber-physical systems

Based on the contents, structures and causalities of already established architectures regarding CPS, especially with focus on industrial applications, the reference architecture for designing demonstrators for industrial CPS is derived. Since the demonstrators are intended to replicate the entire characteristic of industrial CPS, the principle layout of the demonstrator design space does not differ from actual CPS. In contrast, the design elements are abstracted from the ones of genuine CPS but according to the constraints of demonstrators. Following, the systematic and modular design approach of the reference architecture is presented in detail:

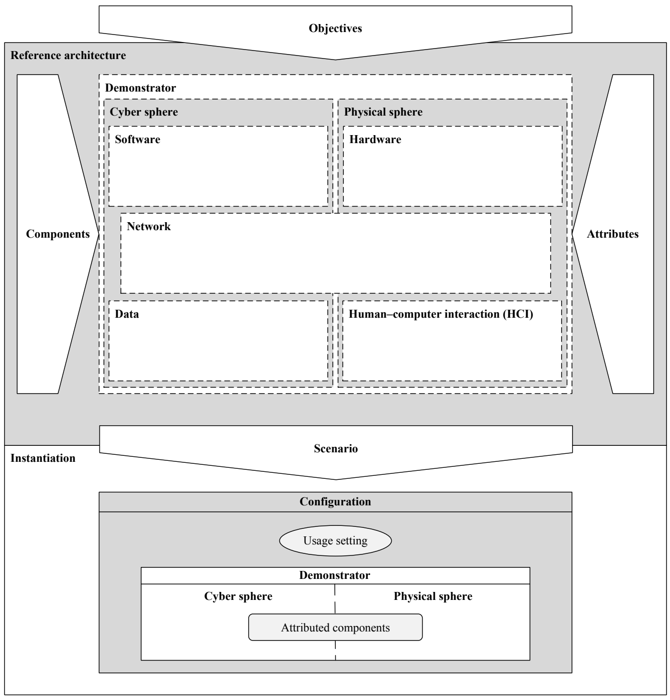

Fig. 1. Conceptual structure of the reference architecture.

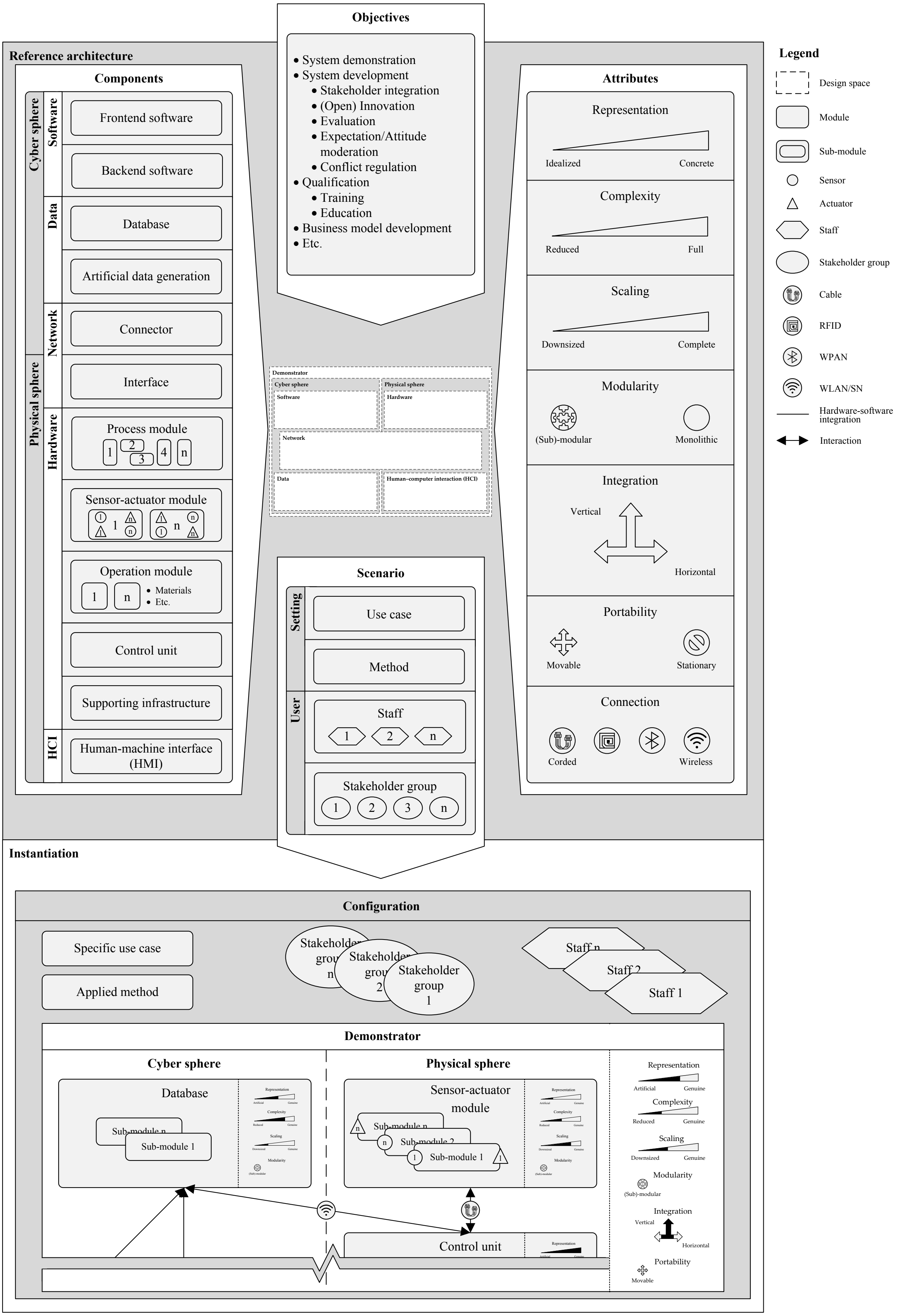

Fig. 2. Content-wise arrangement within the reference architecture.

The *reference architecture* serves as a framework to configure objective- and scenario-specific demonstrators that facilitate the concept of CPMS. In the first instance, the reference architecture provides a *demonstrator* design space that is divided into two *spheres*, the *cyber* and the *physical*. Inside the cyber sphere are the fields *software* and *data*. The physical sphere contains the fields *hardware* and *human-computer interaction (HCI)*.

The *network* field acts as a link between the two spheres. The spheres and fields serve as a regulatory framework within the demonstrator design space. According to the *objective* pursued with the deployment of the demonstrator, respective *components* with distinct individual *attributes* are selected and merged according to the regulatory framework. The specific application *scenario* determines the particular *configuration* of the *demonstrator* and the *usage setting* in its *instantiation*. The conceptual structure of the reference architecture with particular focus on the demonstrator design space is given in Fig. 1.

As illustrated in Fig. 2, the conceptual structure of the *reference architecture* contains the following content-wise arrangement: The initial impetus for the design of the *demonstrator* are the respective *objectives*, which are intended to be achieved by applying the demonstrator. Exemplary objectives include system demonstration, system development, personnel qualification and business model development.

In the section of the reference architecture titled as *components*, the demonstrator *modules* are listed, classified by *spheres* and *fields* of the demonstrator design space. Within the *cyber* sphere, the *software* field contains the modules for the *frontend* and *backend software*. The frontend software is applied to the respective *human-machine interface (HMI)*. This can be either individual software developed for the demonstrator or publicly available standard software. The backend software is used to control the demonstrator during its application by the staff. It includes, on the one hand, the operating systems of the individual hardware modules, on the other hand, the digital control panel with which the demonstrator is operated as a whole. The field *data* contains a *database* module, which provides a structure for processing and storing the demonstrator's data, and an *artificial data generation* module. The purpose of this module is to artificially generate or retrieve the data required for simulations when the demonstrator and its sensors cannot gather the data sets themselves, e.g. extensive big data sets.

The modules of the *physical* sphere constitute the components of the physical model of the demonstrator. The *hardware* field contains a *process module* for the simulation of industrial processes, a *sensor-actuator module* enabling the demonstration of sensing and effecting physical states as well as genuine data generation and an *operation module*, which can be utilized for demonstrating the execution of industry-typical work. Furthermore, the hardware field includes a *control unit* module used to operate the demonstrator and a *supporting infrastructure* module that complements other modules for the purpose of their functionality. An example of this can be the provision of energy, compressed air, etc. The *HCI* field features an HMI module via which users interact with the demonstrator.

As a link between the cyber and physical spheres, the *network* field holds the modules *connector* and *interface*. Connectors are responsible for integrating the individual components in a purposeful manner ensuring the functioning of the demonstrator as a holistic system. Interfaces enable to connect to and interact with systems beyond the demonstrator.

The *attributes* engender the particular layout of the individual modules from the component list. The attribution has different categories and is conducted in form of continuous scales and either-or variables. In this context, the *representation* scale describes the extent to which the module is *idealized* or *concrete* to its modeled original. Likewise, scales are used to indicate the degree of *complexity* from *reduced* to *full* as well as the *scaling* of the modules from *downsized* to *complete* in comparison to the genuine represented. With either-or variables, it is shown whether the components are *(sub)-modular* or *monolithic* in their structure. Concerning *integration*, the scales show the extent of *horizontal* and *vertical* incorporation. Further attributions are whether the modules are *moveable* or only applicable in a *stationary* setting and what kind of *connection* is applied in-between the individual modules.

The attributions of the individual modules eventually result in the attribution of the entire demonstrator (e.g. the average complexity of the modules results in the overall complexity of the demonstrator, the entire demonstrator loses its mobility when a stationary module is installed, etc.).

In addition to the initial objectives pursued with a demonstrator, the application *scenario* also has an effect on the eventual *configuration* achieved by applying the reference architecture. The scenario includes the *setting* and the *users* of the demonstrator utilization. The setting consists of the *use case* which is simulated and the *method* by which the demonstrator is applied. Accordingly, an exemplary setting could be the simulation of a CPS-based predictive maintenance system (use case), which is demonstrated within a workshop (method). The users represent the *staff* who control the demonstrator and moderate its application as well as the participants from the *stakeholder groups*.

Consequently, the reference architecture can be used to design demonstrators for CPMS: Initiated by the objectives and determined by the scenario, an *instantiation* in the form of a particular configuration consisting of a specified *demonstrator* and its usage setting emerges in the design space of the reference architecture by selection of attributed modules. A schematic and abbreviated exemplary instantiation is presented in the lower part of Fig. 2.

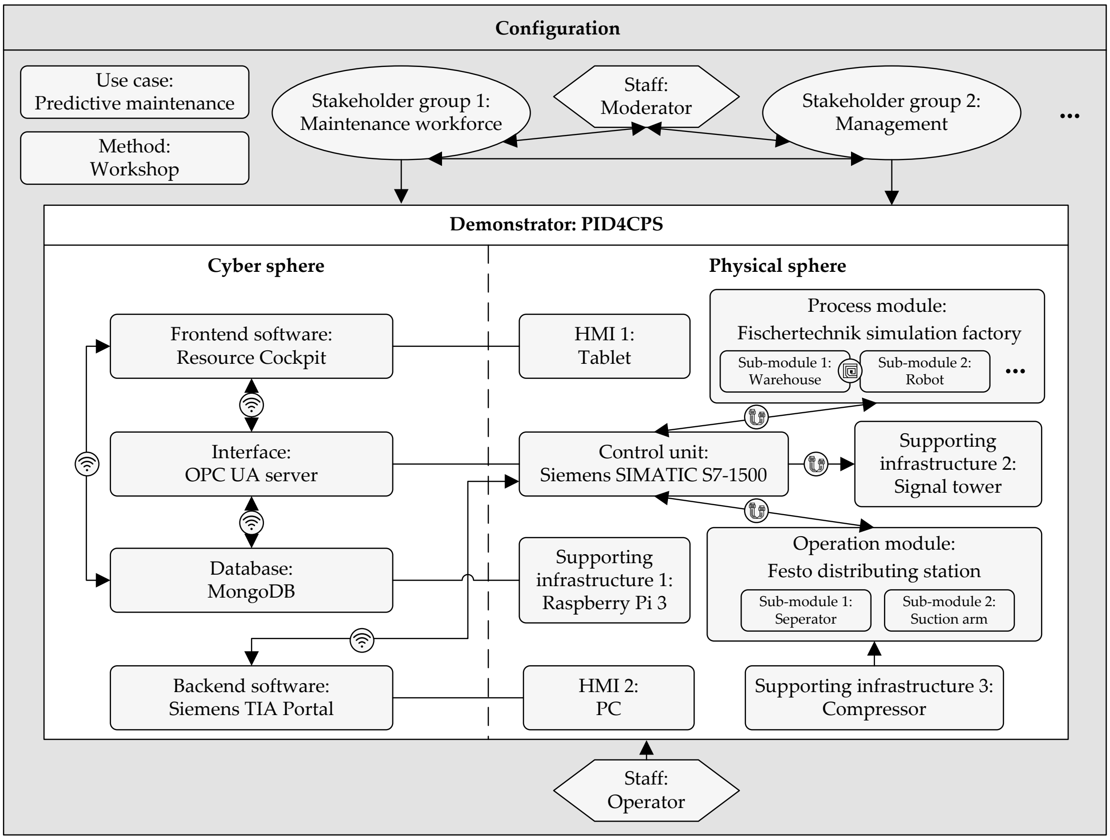

Fig. 3. Configuration of the demonstrator PID4CPS.

5. Instantiation – "Portable Industrial Demonstrator for Cyber-Physical Systems (PID4CPS)"

To assess its viability in design processes, the proposed reference architecture was applied for the design of the instantiation PID4CPS. The demonstrator was designed addressing objectives including the provision of a boundary object for stakeholder-centered CPS design. In early system development phases it should promote the generation of ideas while in late phases the evaluation of system configurations is strived. Another objective is the settlement of stakeholder conflicts with help of the demonstrator. For this purpose, the demonstrator has a simulation factory as a process module to illustrate processes and a workstation as an operation module where tasks can be performed manually. Sensors and actuators added to both modules ensure integrated linkage of the cyber and physical spheres of the demonstrator. HCI is conducted via tablets on which an industrial maintenance suite is installed. The industrial programmable logic controller (PLC) Siemens SIMATIC S7-1500 controls the individual modules. Supportive infrastructures complement the described modules. A MongoDB database hosted on a Raspberry Pi 3 provides the processes and contents of the demonstrator's simulation scenarios. An OPC UA server distributes the data from sensors and processes and provides an interface to the larger IT infrastructure of the organization employing the demonstrator. The demonstrator is used in this configuration: The use case is predictive maintenance and the method applied is a workshop format. The staff consists of

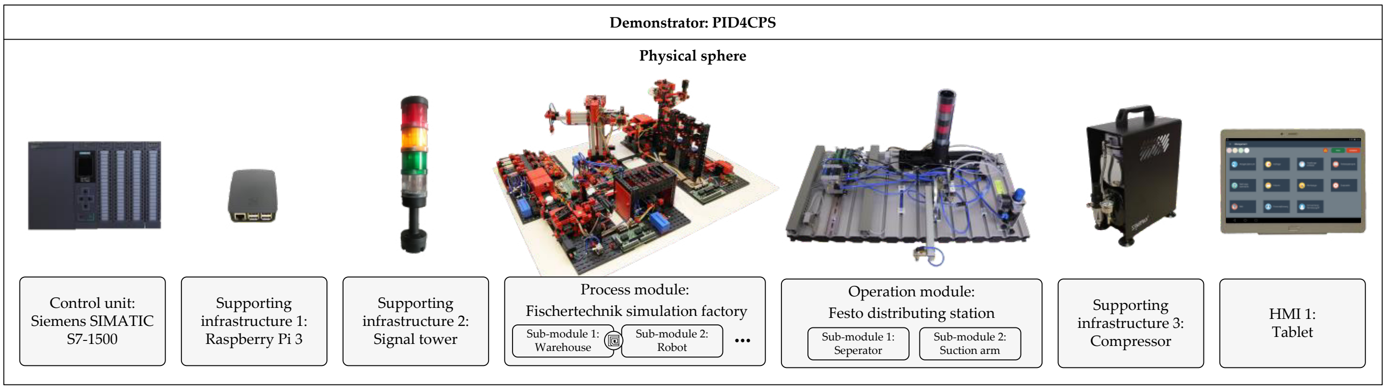

Fig. 4. Physical modules of the demonstrator PID4CPS.

two persons, one of whom leads the workshop and moderates the interaction between the stakeholders and one person who controls the demonstrator. The number and selection of stakeholder groups which may include management, maintenance personnel, employee representatives, etc., depends on application and organization. An overview of the demonstrator configuration of PID4CPS is given in Fig. 3 (to increase readability, the display of the attributions of the individual modules and the overall demonstrator is omitted).

Fig. 4 shows the actual instantiation of the demonstrator PID4CPS with the implemented modules of the physical sphere.

6. Discussion and conclusion

In this paper, we present and discuss the concept of CPMS and a reference architecture based on it for designing demonstrators for industrial CPS. With CPMS, we address the challenges associated with the introduction of CPS, in particular in the area of stakeholder-centered systems engineering and development, by orienting the existing modeling and simulation procedures towards them. Following the holistic approach of CPMS, we derive from CPS associated architectures a new reference architecture for the designing of demonstrators, which enable the representation of industrial CPS in different configurations regarding representation, complexity and scaling. In order to examine the viability and usability of the proposed reference architecture, we apply it in the design process of PID4CPS, a portable industrial demonstrator for CPS. Here, the reference architecture proves to be a helpful structuring factor in this process. On the one hand, the reference architecture supports the compilation of modules as well as their attribution during the design of the demonstrator. On the other hand, the reference architecture relates the design process of demonstrators directly to the strived objectives and planned application scenarios.

A future enhancement of the reference architecture will include a recommendation system that provides suggestions for appropriate modules and attributions based on selected objectives and application scenarios. In addition, the collection and allocation of best practices regarding CPMS applying demonstrators are planned.

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