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Architecture and development approach for integrated cyber-physical production-service systems (CPPSS)

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ABSTRACT

Product-Service Systems (PSS) have been recognized as one of the key concepts driving product innovation and value enhancement. PSS offer of a function of integrated product-service-combinations aiming to be competitive by satisfying customer needs. At the same time Cyber-Physical Production Systems (CPPS) provide the potential to extract information from the manufacturing of technical products. Both, PSS and CPPS have shown their potential to support sustainable manufacturing. This paper provides an integrated consideration of PSS and CPPS and presents a framework in the form of an architecture and development approach. The framework will be applied for the use-case of 3D printing.

1. Introduction

Manufacturing has been and still is a driving force for the development and prosperity of nations. However, despite its positive economic and social aspects, the processing of raw materials into products is also associated with negative environmental impacts. Therefore, different approaches are investigated to reduce material and energy consumption and to support industrial sustainability (Herrmann et al., 2014). Two of these approaches are Product-Service Systems (PSS) and Cyber-Physical Production Systems (CPPS). PSS have been recognized as one of the key concepts driving product innovation and value enhancement through offering a function of integrated product-service-combinations aiming to be competitive by satisfying customer needs. A successful implementation of PSS can reduce costs and environmental impacts, e.g. through an increasing use intensity and lifetime of products as well as optimal use patterns (Berger, 2014; Mont, 2002; Kjaer et al., 2016). However, the physical part of the PSS, the physical product, may also be handled less carefully, and thus premature wear can be expected if users are no longer owners (Tukker, 2004). Also, rebound effects may result in efficiency potentials being offset or overcompensated by additional demand (Aurich et al., 2006). Besides PSS, also CPPS can have a positive impact on sustainability (Thiede, 2018). Here, a computing device interacts with the physical production environment in a feedback loop. CPPS can support the manufacturing efficiency through the extraction and improved processing of manufacturing related data and with this, e.g. reduce the energy consumption of manufacturing. However, also new components such as sensors or IT equipment may be required, effecting the environmental balance of CPPS negatively (Thiede, 2018). Since both, PSS and CPPS have the potential to effect industrial sustainability positively, the integrated consideration of these systems needs to be investigated. Therefore, the structure of this paper is as follows: first, the theoretical background of PSS and CPPS is given. Thereby, the state of research is presented and the integration of PSS and CPPS is discussed. Based on this, an architecture and a development approach for integrated Cyber-Physical Production-Service Systems (CPPSS) are introduced helping to reduce the implementation effort of CPPSS. Both are validated in a case study on 3D printing.

2. Theoretical background and state of research

This chapter provides the overview on the theoretical background, namely PSS, CPPS and their integration into CPPSS. The po-

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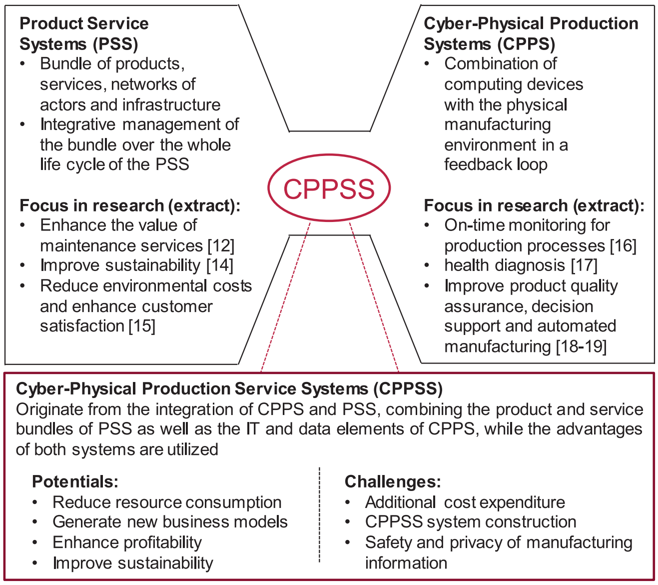

Fig. 1. Integrating CPPS and PSS – Potentials and Challenges.

tentials and challenges of integrating PSS and CPPS are discussed. The main findings are summarized in Fig. 1.

2.1. Product-Service systems

In recent years, PSS have aroused increased interest as they are associated with combining economic prosperity and waste reduction and lower resource consumption (Richter, 2010). In general, several definitions of PSS exist (Reim et al., 2015; Annarelli et al., 2016; Schallehn et al., 2019). In a common understanding it refers to “a bundle of products, services, networks of actors and the supporting infrastructure with the aim to be competitive by satisfying the customers’ needs and at the same time to have a lower environmental impact than traditional business models” (Herrmann et al., 2012). The bundle has to be managed integratively over the whole life cycle of the PSS, from the PSS idea to its end of life (Herrmann et al., 2012). A core focus in latest PSS literature has been set on incorporating sustainability into the PSS paradigm (Mamrot et al., 2016; Hüer et al., 2018; Fargnoli et al., 2018). A special focus is on providing information on product use and maintenance, since these will affect whether customers continue to use an offered PSS of a company in the future.

2.2. Cyber-Physical production systems

A CPPS can be regarded a multi-dimensional technology system, which combines virtual models with sensors and actuators in a manufacturing environment. In general, CPPS are systems that contain physical and cyber subsystems, which in turn are supplemented by data acquisition and decision support components (Thiede, 2018). The essence is the combined consideration of people, machines and objects, extending the control of resources in terms of time and space. In a manufacturing facility, where people and machines interact frequently, CPPS can increase the adaptability, automation, efficiency, functionality and usability of manufacturing systems. In latest research, foci are set on machine real-time monitoring (Li et al., 2017), health diagnosis (Zhang et al., 2019), resource reconfiguration (Gellrich et al., 2019; Tao et al., 2014), new software and hardware development (Mikusz, 2014), as well as energy consumption and management (Thiede, 2018; Neef et al., 2019).

2.3. Integration of PSS and CPPS

Even though data can be retrieved by a CPPS to improve manufacturing conditions (performance, efficiency, resiliency), there is still a lack of effective integration into business models and related services. These can be offered helping to enhance sustainability related company objectives.

Therefore, a closer integration of PSS and CPPS is proposed to discuss. So far, the integrated consideration of PSS and CPPS has not been expressively discussed in literature. However, several authors focus on the integrated consideration of PSS and the more generic Cyber-Physical Systems (CPS), which do not necessarily have the focus on manufacturing. Chowdhury et al. (2018) provide a literature review on smart PSS in industrial firms . Herterich et al. (2015) discuss the impact of CPS on industrial services in manufacturing. Mikusz (2015) propose CPS as service systems in the sense of a service-dominant (S-D) logic and show how it can help driving the development of the S-D logic itself. Lützenberger et al. (2016) used the product usage information and a knowledge based engineering (KBE) model to gather information from sensors and to identify improved information for designing next generation washing machines. Wiesner et al. (2017) underline that integrating multi-disciplinary requirements engineering, information technology and services are key factors for systems engineering in the future. The authors define Cyber-Physical Product-Service Systems (CPSS) as CPS-based PSS. Here, a PSS and the associated business processes are built under continuous integration of CPS. The positive impact of this results in the reduction of time to market, waste and failures, as well as the improvement of quality and cost effectiveness. Wiesner and Thoben point out the impact of CPSS on the engineering field, especially on cross-domain requirements, and the service models (Wiesner and Thoben, 2017).

With the integration of PSS and CPPS to CPPSS, the attributes of CPSS, as elaborated by Wiesner et al. (Wiesner et al., 2017; Wiesner and Thoben, 2017), are applied to the manufacturing domain. Therefore, the product and service bundles are combined in a CPPSS. Potentials of such an integration may result from improved energy efficiency and new business model approaches that can enhance profitability and flexibility. For example, data related to the environmental performance of a manufacturing system can be collected, analyzed and interpreted in a cyber-system to be used for the optimization of the physical manufacturing system. This in turn can be achieved through new service-based approaches, improving the environmental performance of the manufacturing system.

3. Concept of integrating CPPS and PSS

The introduction of CPPSS in an industrial environment can be a challenging task, especially for small and medium sized enterprises (SMEs), due to the required expertise in IT and business development. Therefore, a suitable framework is required that helps to develop CPPSS in such a way that potential disadvantages do not outweigh the advantages. In order to keep the entry hurdle low, low investments, short amortization times for the infrastructure, no additional skilled personnel and low downtimes for the installation can be identified as central requirements. In consequence, it is necessary to set up a measurement infrastructure in a minimally invasive manner. This also means that both sensor installation and network operation must only have a minimal influence on the running manufacturing operation. In order to meet these requirements, the introduction of a CPPSS should not lead to increased effort for companies and should thus be based on an approach that supports the implementation of a CPPSS, especially for SMEs. Therefore, in the following a CPPSS architecture and a de-

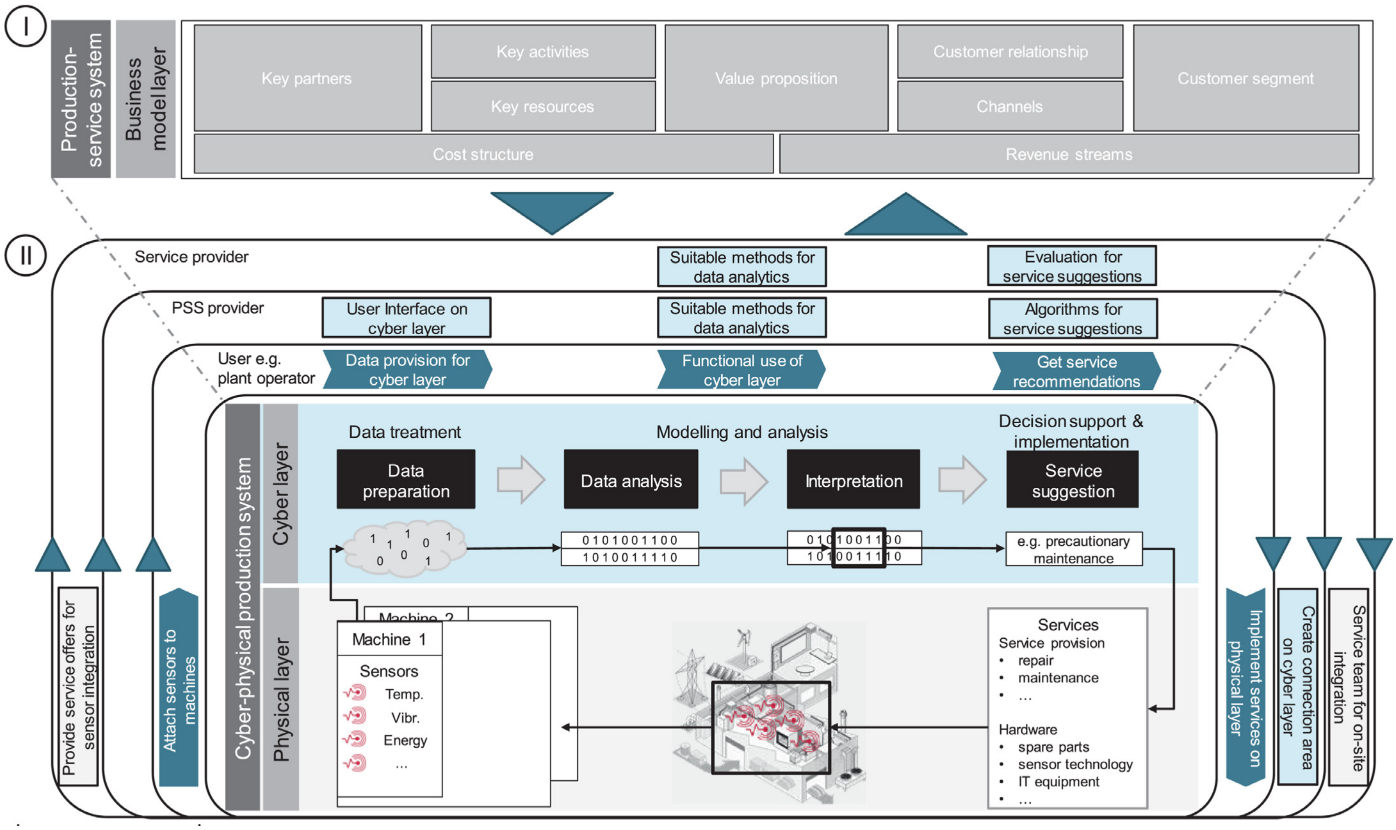

Fig. 2. CPPSS Architecture.

velopment approach for CPPSS are presented addressing these requirements.

3.1. CPPSS architecture

The aim of the CPPSS architecture is to capture and structure essential elements of a CPPSS in such a way that building a coherent overall system is supported. Therefore, Fig. 2 shows the proposed CPPSS architecture which is based on a layered structure. The architecture consists of two main system sections: the production-service system (I) and the cyber-physical production system (II). Thereby, the CPPSS as a whole can be developed either in a top-down or bottom-up approach (see also Section 3.2). This results in an integrative intervention of the production-service system in the cyber-physical production system. The service strategy of the individual stakeholders serves as a connectivity element between the two system sections.

The business model layer in the production-service system (I) contains relevant elements of a CPPSS from a service / business perspective and is located in the production-service system. For the structuring of these elements a business model canvas is used (Joyce and Paquin, 2016). Thus, the business model layer contains the elements: key partners, activities and resources, the value proposition, the customer relationship, channels as well as the customer segment. Furthermore, cost structures and revenue streams are included. For each of these elements, concretizations can be given. An example for such a concretization will be given in the case study. Services can arise from the interaction of all layers. At the business model layer, the requirements and key elements for providing services are defined. Based on this, either physical or digital services can be provided. These services have a direct correlation to the layers shown in the lower section of the figure (II). The cyber-physical production system provides the core-layers for the architecture. It consists of the physical and the cyber layer and is separated into three columns, which represent the connection between the layers and describe the data treatment, modeling and analysis as well as decision support and implementation. The physical layer implies the networking of machines in production and their monitoring. Data is generated by means of sensors and the measurement of operating information. The data is forwarded to the cyber layer. At the cyber layer, this data is processed, i.e. prepared and analyzed, so that after an interpretation of the results, service proposals can be submitted. Nevertheless, the service proposals need certain triggers that arise from the information. This could be, for example, a pattern or a unique relationship in the data record. To illustrate the general use of this architecture and the three layers, the service classification is mapped according to specific stakeholders. The user, the provider of the PSS and the service provider are taken into account. The service generation focuses on the user, who must provide the prerequisites for the PSS and service provider. The basic principle of this architecture is thus the flexible design of services, regardless of whether this is done from the physical or business model perspective.

3.2. CPPSS development approach

As highlighted by Thiede (2018) for CPPS, the trade-off of an initial ‘environmental investment’, e.g. through additional electronic components, and the resulting increases in efficiency has to be similarly considered for CPPSS as well. Thus, the break-even time to a positive environmental balance is all the shorter, the higher the increase in efficiency through the integration of the CPPSS is. Therefore, the design of CPPSS requires efficient structures so that potential advantages are not compensated by disadvantages. This requires a systematic development approach. It en-

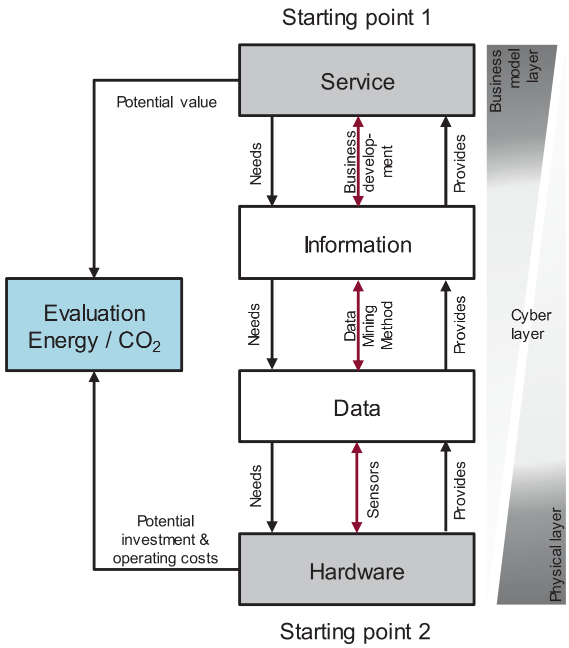

Fig. 3. CPPSS Development Approach.

ables the full potential to be exploited during its introduction and implementation.

Fig. 3 shows the proposed CPPSS development approach that is closely related to the CPPSS architecture. The development approach refers to the layers of the architecture and includes the four expansion stages hardware, data, information and service. The expansion stages can either be required or be provided by the previous step and can be reached via a suitable method (red links). In order to achieve an efficient design of the CPPSS, it must be checked whether one of the required expansion stages is already mapped by an existing CPPSS, or if the CPPSS must be extended accordingly. The development approach can then be read flexibly from different starting points. One possibility is the development based on a required service (top-down approach), which is considered as “Starting point 1″ in Fig. 3. The required service generates an information request on the business model layer, which triggers the request for data to be provided on the cyber layer. This results in the required hardware on the physical layer. Via data mining methods the data is transformed into information at the cyber layer and enables the provision of a service at the business model layer, which closes the iteration and can be reached through a business development approach. “Starting point 2″, which is at the physical layer (bottom-up approach) of Fig. 3, would be another option to start the development of a CPPSS. In this case, the iteration would be performed based on a specific existing hardware. The development of the CPPSS is similar to the previous example of “Starting point 1″ and can therefore be seen in Fig. 3. Any necessary actions at the business model, cyber and physical layer to set up a new CPPSS or extend an existing CPPSS must be evaluated from a potential value, cost and environmental point of view. This should ensure that possible reductions of downtimes are not compensated by higher costs or environmental impacts and lead to a reduction in energy and CO_2 consumption.

4. Case study

In order to reveal the applicability of the CPPSS architecture and development approach this study intercepts a CPPSS, which is based on a 3D printing system.

4.1. Motivation for a 3D printing CPPSS

Since the motivation of the framework is to simplify the introduction of a CPPSS for SMEs, this premise is also considered in the implementation of the case study. In addition, the investigation of potential environmental impacts of a 3D printing CPPSS is also focused, in order to discuss whether this can be met with the help of a suitable CPPSS architecture. Especially the quality of the components in the filament printing process has a big influence on material waste and time (Jiang et al., 2019). Inadequate quality of the printer components influences the products and the general waste problem of plastic printing. The increased waste can be caused by various events, such as maintenance failures or defective printer parts. At the same time, the choice of parameters and the filament used also has an impact. Due to these challenges, it is necessary to provide an overview of process parameters and wear in 3D printing.

4.2. Exemplary implementation in 3D printing

The case of the 3D printing CPPSS links a physical 3D printing production machine with a cyber-system. Both are combined with a production-service system which is able to provide modular industrial physical services (such as maintenance services) as well as digital service applications that are individually tailored to service users. The interface is formed by intelligent, scalable measuring and forecasting systems, which allow efficient and customer-specific surveys of operating and process data and to forecast the operating behavior of the production machine.

The *development* of the 3D printing CPPSS can be done by the approach presented in chapter 3.2. In the case of the 3D printer, "Starting point 2″ is selected, which means that the development cycle starts from the 3D printer. Since the 3D printer as a production object is not sufficient to generate enough data, the hardware iteration cycle begins. Various peripheral devices are required to map a complete hardware / sensor package. The details of the resulting architecture are presented in more detail below. The setup leads to data bundles, such as the process, machine, sensor and energy data of the system. From this data, information can be retrieved, which in this specific case, for example, can lead to the detection of failures of the 3D printer or possible process optimizations. With this, it is possible to define services that help the user of the production process.

Besides being developed by the means of the development approach, the experimental setup of the 3D printing CPPSS is further based on the *CPPSS architecture* (see Fig. 4).

The *physical layer* of the cyber-physical production system consists of the 3D printer, peripherals in the form of sensors for measuring the environmental and process data, Raspberry Pis for evaluating this data, as well as an energy measurement and an additional scale for measuring the ratio of product to waste weight. The environmental data is mainly given by a current meter and the internet of things sensor node Bosch XDK. For the selection of the devices and associated sensors, the principles have been focused on ‘low cost’ and ‘easy to implement’. This is the main reason why this experimental setup could also be used as a start equipment in an SME. With this structure on the physical layer, it is possible to provide data for the *cyber layer* and the data treatment column of the cyber-physical production system. In this case, a data mining procedure is used to prepare and analyze the data. However, a communication structure and a network are also necessary. In the experimental setup the internal communication is solved by the message protocol MQTT, while at the same time a WLAN network is hosted. The interpretations on the cyber layer allow targeted service proposals. The data interpretations generated here are transferred to the physical layer, while the service proposals are pro-

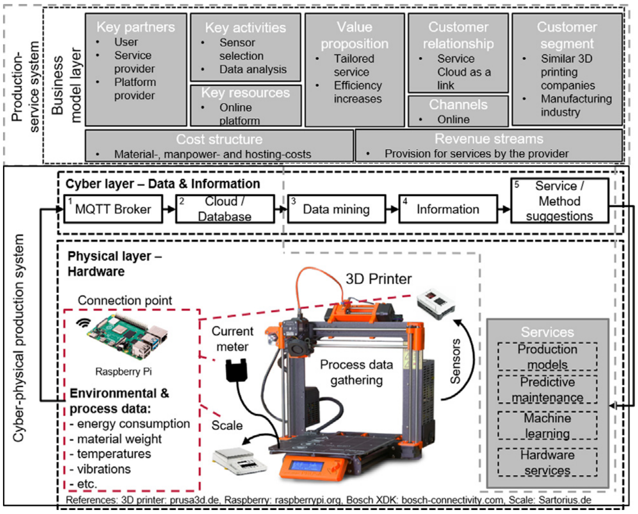

Fig. 4. Experimental Setup.

vided by service companies. In this transition from data processing on the cyber layer to the service provision, the business model of the CPPSS emerges. As shown in Fig. 2, different stakeholders can be involved through the architecture. The exemplary process from the CPPSS architecture for the user, PSS and service provider from sensor to service integration, can also be applied to this case study. The business model canvas of the *business model layer* in the production-service system supports this process. Especially the defined contents for the use case are decisive for the generation of new services. These services can be digital or physical. An example of a digital service in this case would be the provision of machine learning algorithms for the process analysis, while a physical service could be the maintenance of the 3D printer. Especially this physical service results in a use case of the built up system. In order to fulfill this maintenance approach, condition monitoring is necessary. Thereby the condition of the 3D printer is permanently recorded by means of the implemented hardware. For example, vibration analyses can be identified as a part of the condition monitoring. This allows conclusions about the longevity of the machine or in this case of the 3D printer. By which explicit decision support can be given to the user. In this case, whether it makes sense to manufacture the product in-house or rather to outsource it if the life cycle time of the printer is strongly affected. This eventually leads to a make or buy decision by the user.

4.3. Potentials and challenges for the 3D printing case study

One potential of using a 3D printing CPPSS is the user's access to CPPS structures and services, which would require considerable effort in conventional operation. Furthermore, by recording the energy and process data, the analysis of these is possible and a significant savings potential is achievable, which leads to a more sustainable operation in production. In addition, the early detection of waste and wastage in the process is possible, with simultaneously increasing product quality. The service-oriented cyber platform enables different providers to offer value adding physical and digital services creating new revenue streams for the CPPSS provider. However, also challenges must be considered. The integration level of the concept is relatively high, therefore especially very focused companies with a specific knowledge can fear the loss of competitive advantages, which can lead to a retreat attitude and thus to the failure of the concept. Consequently, a foresighted and step-by-step executed integration is needed.

5. Conclusion

This paper presents an architecture and development approach for integrated Cyber-Physical Production-Service Systems. First, the general approach for the development of a CPPSS was discussed, resulting in the CPPSS architecture and development approach. In order to reduce the abstraction of the concept, it has been transferred into an application case, which consists of an integration approach by means of a 3D printer. In this use case, a cloud environment has been created from which CPPSS providers can analyze data. Thus, it is possible to provide process- and product-relevant data through the introduction of an integrated information technology system and at the same time to offer a functioning production-service system. Without these possibilities for service providers, i.e. in the conventional operation of a 3D printer, there are possible quality losses in the product and process, which result in increased filament waste. The latter can be minimized by the existing system and detected at an early stage and also be counteracted with predictive maintenance approaches. This results in an environmentally more sensible use of 3D printing with fewer scrap parts and a higher long term in use time.

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