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EXPLAINING THE ROLE OF SERVICE-ORIENTED ARCHITECTURE FOR CYBER-PHYSICAL SYSTEMS BY ESTABLISHING LOGICAL LINKS

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Research paper

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Abstract

In the context of the so-called fourth industrial revolution, cyber-physical systems (CPS) build the technological foundation for the increasing digitalisation of our world. Because guidelines to overcome challenges of building such systems (e.g. security concerns, missing know-how, and lack of standards) are scarce, researchers and practitioners alike have begun to analyse the role of the mature paradigm of service-oriented architecture (SOA) in implementing CPS. However, the relationship between SOA and CPS is not entirely understood. To close this gap, we analyse SOA's role for CPS based on a concept-driven literature review. The analysis of 12 publications that address the interrelation between SOA and CPS yielded four groups of CPS benefits that can be achieved by leveraging SOA. Combining these benefits with architectural layers and SOA's design principles, we identify logical links that explain the role of SOA for CPS. Future research might concentrate on dominant patterns to scrutinise how a specific benefit can be achieved by leveraging SOA. Designers of CPS can leverage the identified patterns to understand the importance of specific characteristics of SOA to address the unique requirements of their CPS.

Keywords: Service-oriented Architectures, Cyber-physical Systems, Literature Review, Benefits, Logical Links.

1 Introduction

Increasing competition among manufactures, shortening of innovation cycles, and growing importance of resource-efficient manufacturing for companies demand a higher versatility of factory automation (Loskyll et al., 2012). Digital technologies radically change the organisation of value chains (Schwab, 2016). Such changes are often seen as consequences of the fourth industrial revolution (Roth, 2016). In this context, visionaries describe manufacturing processes closely linked with digitally interconnected machines and components (Chung, 2015), which can be handled as Lego-bricks by standardisation to establish larger systems than before (Kolberg and Zühlke, 2015). This degree of interconnectedness is key to mass customisation, which allows companies to produce large quantities of various individual articles with individual customer configurations (Neuböck and Schrefl, 2015). Thus, all components must work together to deliver the products when the customers expect them. Hence, value chains need to be optimized by implementing an autonomously controlled and dynamic production.

To address these challenges, several industrial initiatives such as "Industry 4.0" have been put forward. Industry 4.0, as a prominent example, is part of the political program of the German Federal Government for the future digitisation agenda (German Federal Government, 2014). It can be defined as the intelligent networking of people, machines, and industrial processes, which in product components communicate with the production gear by embedded sensors creating ubiquitous cyber-physical systems (CPS) and enabling analysis of all relevant data (BMWi, 2016; McKinsey Digital, 2015). Initiatives such as Industry 4.0 generally share the idea that a critical aspect concerns the merger of physical and virtual worlds. CPS can be considered as the technological foundation for the increasing digitalisation of our world (Vogel-Heuser and Hess, 2016). Organisations invest in CPS to continue digitalising their enterprises (BMWi, 2015b). However, these organisations face several challenges such as large investments, entry barriers, security concerns and missing know-how for their future digitalisation (EY, 2016). Guidelines from research are scarce because CPS represent a new phenomenon in literature. Insights into middleware architectures and platforms for realising CPS applications are missing (Hoang et al., 2012). To address these concerns, researchers and practitioners alike have begun looking into service-oriented architecture (SOA) to become the architecture standard for CPS implementation (Yue et al., 2015). SOA stems from a mature stream of literature on enterprise architecture to design loosely-coupled systems with the help of services while adhering to a set principles proven as good practice. However, the relationship between SOA and CPS is not entirely understood (Hoang et al., 2012). Literature lacks an analysis of the role of SOA for CPS. Thus, we pose the research question: *Which role does SOA play in the context of CPS?*

To answer this question, we provide an overview of how authors put SOA into perspective to be the architectural paradigm for CPS by applying a systematic, concept-driven literature review. We analyse SOA's role for CPS by identifying the benefits that stem from SOA as an architectural foundation for CPS. To provide explanations for researchers and practitioners alike, we establish logical links from the groups of CPS benefits to SOA's design principles and architectural layers.

This paper is structured as follows. In Section 2, we introduce our two main concepts CPS and SOA and their interrelation. We describe our research approach in Section 3. In Section 4, the findings covering the role of SOA for CPS are presented. We then discuss results and limitations of our study in Section 5. Finally, we conclude our paper in Section 6.

2 Theoretical Background

2.1 Cyber-physical Systems

CPS can be considered as the technological foundation for the increasing digitalisation of our world as they enable the merger of the physical and the virtual world by bringing computational intelligence to physical devices (Vogel-Heuser and Hess, 2016). CPS applications range from small-scale (e.g. pace makers) to large-scale ones such as power-grids (Lin and Panahi, 2010). The term CPS is widely used with more than one definition (Hermann et al., 2016) because several innovation programs have been started by various communities and political actors. A prominent example is the initiative Industry 4.0 of the German industry and government to accelerate digitalisation (BMBF, 2014; Kagermann et al., 2013; BMWi, 2015a). In this paper, we define CPS as the integration of computation and physical processes. CPS consist of embedded computers and networks that monitor and control physical processes, usually with feedback loops in which physical processes affect computations and vice versa (Lee, 2008). CPS autonomously perform these complex computations and critical tasks, meaning that dependability and resilience are two key properties for their design (Alho and Mattila, 2015). Visions of future CPS exceed current systems in terms of adaptability, autonomy, efficiency, functionality, reliability, safety, and usability (National Science Foundation, 2008), transforming not only how humans interact with and control the physical world around us (Rajkumar et al., 2010) but also enabling organisations to significantly increase autonomy and efficiency. Thus, enabling organisations to develop innovative products and new services, for instance, for manufacturing and assembly processes (Lee et al., 2014). Research advances in the area of CPS indicate transformation of our world by systems that respond more quickly, are more precise, work in dangerous or inaccessible environments, provide large-scale, distributed coordination, are highly efficient, augment human capabilities and enhance societal well-being (National Science Foundation, 2008). Thus, CPS will have an enormous impact to several industries including electric power generation and delivery, infrastructure, personalized health care, military and manufacturing. Therefore, organisations invest in CPS to continue digitalising their enterprises (BMWi, 2015b). In consequence, CPS become increasingly critical to the business success of many companies and the mission success of governments (National Institute of Standards and Technology, 2013).

To successfully enable this transformation, CPS must meet several design requirements. For example, enabling dynamic resource composition for physical entities is important because physical entities are exclusive resources, in contrast to services, which can be used by several consumers at the same time (Yu et al., 2012; Dong et al., 2014). Another requirement for CPS design include to ensure a simple integration of different heterogeneous physical entities (e.g. sensors) (Alho and Mattila, 2015). Considerable challenges exist to meet these requirements, particularly because physical entities of CPS introduce safety and reliability requirements that differ from those in general computing (Lee, 2008). Although extensive research has been conducted on CPS to investigate models that improve availability, adaptability, and security (Yu et al., 2012), these requirements are insufficiently met in practice due to the inconclusiveness of technology foundations covering design methodology, for example, for system integration (Hoang et al., 2012) and security issues such as fault tolerance (Alho and Mattila, 2015). SOA as a matured research stream on systems architecture and integration might represent the required foundation for CPS to provide underlying well-formulated design principles and a rigorous framework of layered system architectures.

2.2 Service-oriented Architecture

The term SOA has been used in various contexts with different purposes (Erl, 2005). In general, service orientation apprehends the idea of breaking down a problem into separate smaller aspects in order to manage and solve it (Erl, 2005). Since SOA comprises several design principles and is not bound to any particular implementation technology (McGovern et al., 2003), it can be seen as an architectural style or paradigm (Erl, 2005; Fielding, 2000). While there is debate on the exact set of design principles, the core set that is usually referred to in IS research comprises service orientation, modularity, loose coupling, standards, and platform independence (Richter and Basten, 2016). Based on the information system (IS) paradigm of service-oriented computing (Papazoglou and Georgakopoulos, 2003), services represent the fundamental element for developing applications (Baskerville et al., 2005) and are architectural elements encapsulating business or application functionality (Ren and Lyytinen, 2008). Modularity means that SOA decomposes existing application architecture and structures it into a manageable number of partially autonomous subsystems (Mueller et al., 2010). Those subsystems can be recomposed with other services to create new applications which meet current requirements. Loose coupling enables a dynamic binding of components by reducing the logical and run-time dependencies between services (Brown et al., 2005; Krafzig et al., 2004). Encapsulating elements of an IS architecture into interoperable services requires that interfaces and data representations have to be defined in a neutral and open manner governed by standards (Walker, 2007). SOA is platform independent and not restricted to any implementation technology, which is essential in in heterogeneous environments.

Traditionally, research on SOA focused on technical aspects (Viering et al., 2009), but more recently business and organisational impacts gained importance as well because organisations implement SOA to unlock economic potential (Mueller et al., 2010). SOA can reduce hardware acquisition costs, enhance reliability of the architecture, enables dynamic search and connectivity to other service, and provides real-time decision-making applications (Motiwalla and Thompson, 2014). Its general idea and design principles can be applied as an architectural style for IT landscapes' middleware design of enterprises in order to simplify it into a manageable layered architecture especially in distributed systems (Gu et al., 2005; Lee et al., 2005).

2.3 Link between Cyber-physical Systems and Service-oriented Architecture

SOA stems from a mature stream of literature on enterprise architecture to design loosely-coupled systems with the help of services while adhering to a set principles proven as good practice. Thus, SOA has been adopted in a variety of industrial systems due to its integration flexibility and process composability (Lin and Panahi, 2010). In the CPS literature, authors mostly refer to SOA for design purposes due to SOA's architectural style for middleware design. In particular, SOA's design principles are applied on CPS middleware design to simplify the integration of computation and physical processes by establishing a layered architecture that provides separations of concerns in application development (Mechitov and Agha, 2012). Thus, the link between SOA and CPS is characterized by SOA's architectural style which allows to break down issues into separate concerns to manage, carry out, and to construct a solution to a larger problem in a collection of smaller pieces. This breakdown is needed in CPS due to their complexity and lack of standards (Hoang et al., 2012). For instance, CPS require common interfaces that are provided by a middleware to enable a seamless integration of different physical entities (Chen et al., 2015) which in turn can be used to create reusable and composable services. SOA as a middleware design can abstract from devices and functions of the machines, providing, for example, services that control motor capabilities in CPS. Applying SOA, large industrial systems can compose and optimize production processes for sustainability objectives. CPS and their autonomous nature makes service components easier to monitor, manage and be reactive (Lin and Panahi, 2010). Conjointly, CPS and SOA offer the capabilities not only to inspect, manage and predict the overall performance, but also to understand the operational flaws and hidden service problems. These insights can be used to make proactive real-time decisions that may improve the sustainability of industrial systems and hence improve manufacturing and assembly processes (Lin and Panahi, 2010). The adoption of SOA in CPS could therefore provide a solution for the problem of increasing scale and complexity in CPS.

However, investments as well as entry barriers, security concerns, missing know-how as well as a lack of standards are the biggest challenges for enterprises to develop CPS (EY, 2016). Besides, guidelines from research are scarce because CPS represent a recent phenomenon in literature. Insights into middleware architectures and platforms are missing for realising CPS applications (Hoang et al., 2012). In order to address these concerns, researchers and practitioners have begun looking into service-oriented architecture (SOA) to become the architecture standard for CPS implementation (Yue et al., 2015).

3 Research Method

3.1 Literature Search

Although researchers have begun to consider SOA as a foundation for CPS in empirical as well as conceptual or experimental endeavours, research lacks a comprehensive overview that synthesises the role SOA plays in the context of CPS and how SOA can be beneficially leveraged. Therefore, we performed a concept-driven literature review, relying on an adjusted five-phase identification and selection process which was originally derived by vom Brocke et al. (2009) (see Figure 1).

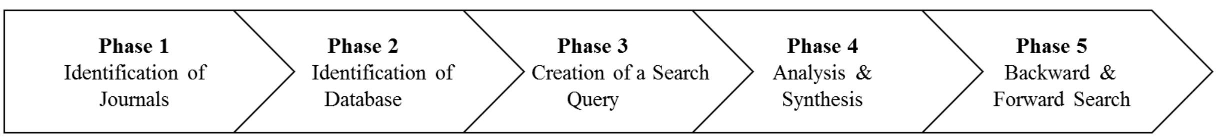


Figure 1. Literature review process

According to vom Brocke et al. (2009), journals are determined in the first phase. It is recommended to focus on articles published in scholarly journals as these articles are usually peer-reviewed before publication (Rowley and Slack, 2004). Likewise, Webster and Watson (2002) suggest to use proceedings of renowned conferences. Due to those recommendations, only articles which are peer-reviewed are chosen for further analysis. Databases used in the second phase often do not label the articles as peer-reviewed correctly. Thus, articles of interest might drop out of scope. To ensure that articles are peer-reviewed for further examination, we manually checked the corresponding conference's or journal's website whether articles are peer-reviewed. In the second phase of the data collection process, we selected databases for examination. This study includes databases related to the IS discipline: IEEE Xplore (IEEE), ProQuest, AIS Electronic Library (AISeL), and ACM Digital Library (ACM) – as well as more general databases: EBSCO Host (EBSCO) and ScienceDirect. The third phase requires the construction of a search query that includes search phrases and is executed on the databases chosen in the second phase. It is commonly recommended to use a set of search phrases as precise as possible to exclude results covering topics or research questions, which do not contribute to the research issue (Rowley and Slack, 2004). Thus, potentially relevant papers have to match the search phrases in Figure 2 for title, abstract, or keywords.

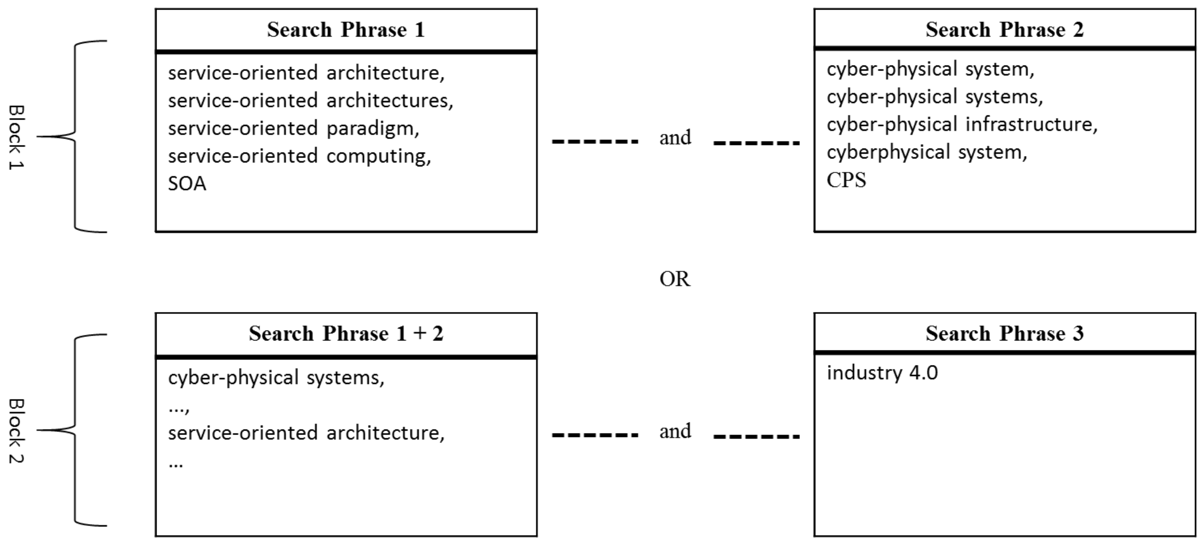
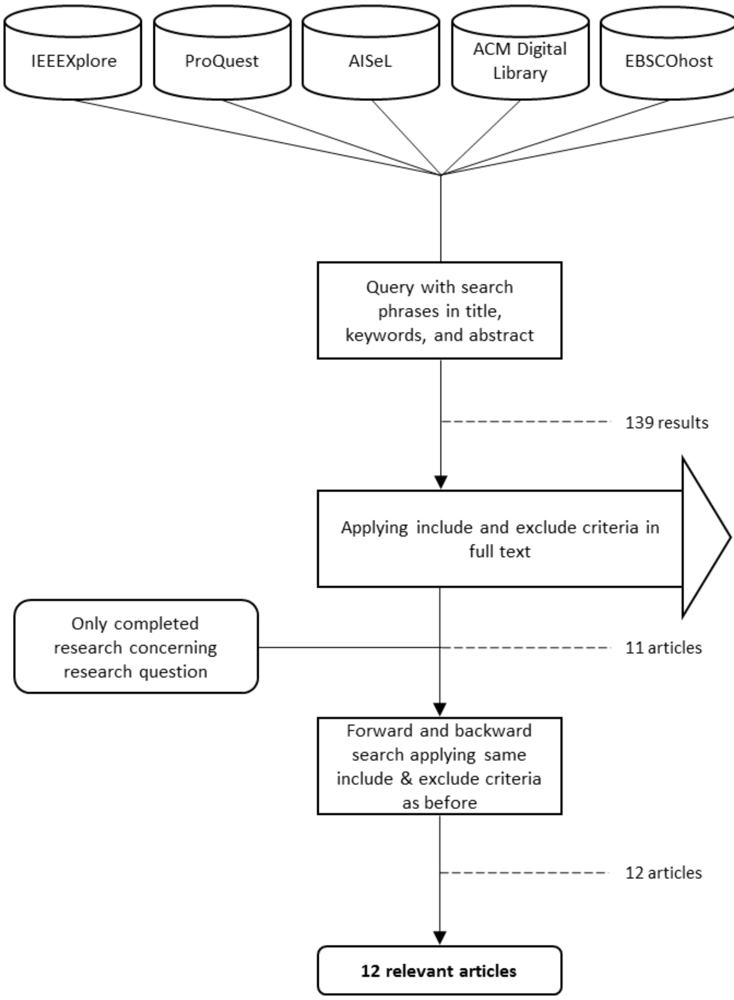


Figure 2. Search phrases for title, abstract, and keyword

The first block of the search phrases for the search query includes the combination of different expressions of CPS and SOA as well as a short form and singular and plural expressions. The second block of the search phrases is added because articles which are deemed to be relevant for this paper are missing while using just the first block. This approach is recommended by Kitchenham et al. (2007). Hence, the second block which is connected to the first block with an OR operator ensures that relevant articles are found and the application examines the relationship between CPS and SOA in the context of Industry 4.0.

The above-mentioned search phrases are each transformed to the specific syntaxes of the literature databases. Only for the IEEE Xplore database, the phrases are divided into two different parts due to a limitation of parameters. The search resulted in a total of 139 articles (the numbers are as of 25 May 2016). These articles' full texts are assessed with regard to the include and exclude criteria (see Figure 3). In this study, results are limited to articles focusing on the relationship between CPS and SOA and especially on the architectural layer style which is provided by SOA to assure to get insights into their relationship. After applying the include/exclude criteria, 11 articles remained being relevant. In the fifth phase, the 11 remaining articles from the fourth phase are accumulated by identifying further relevant studies using the approach, as suggested by Webster and Watson (2002), of searching forward and backward. The Web of Science, as recommended by Webster and Watson (2002) is used to search forward. Additionally, Google Scholar is used since researchers’ experience showed that Google Scholar provides a more comprehensive impression on the actual number of citations (Richter and Basten, 2014). These articles are evaluated using the method described in the fourth phase and, if identified as relevant, are added to the pool of results. This search reveals another relevant article. The literature review process is finished after the identified articles do not provide further articles or cite already identified ones. As a result, we identified 12 articles in total. Figure 3 summarizes the results of the literature review process. For the further analysis, a concept matrix is used which is explained in Section 4.



Include criteria	Exclude criteria	Filtered results
Research articles	Books, dissertations, newsletter, whitepapers, comments, editorials, research-in-progress, etc.	11
Language: English	Other language	1
Peer-reviewed	Not-peer reviewed	44
Article focuses on the SOA-CPS-relationship and on the architectural layer style provided by SOA	Article does not focus on the SOA-CPS-relationship - OR - Article does not focus on architectural layer style provided by SOA	72

Figure 3. Overview of literature selection process

3.2 Data Analysis

We aim to analyse SOA’s role for CPS and which benefits stem from SOA as an architectural foundation for CPS. Therefore, to enable a comparison between the identified articles and to find patterns in the application of SOA for CPS, we analysed our identified articles by four consecutive steps which are described in the following.

First, we performed a qualitative content analysis of the articles and coded the context of the study, whether it comprise empirical data and the architectural style described by the authors. Second, we matched the architectural style described in each article for CPS middleware design to a common three-layered architecture (Hoang et al., 2012). This step was necessary, since we want to make the articles comparable in order to find benefits in the use of SOA for CPS. Third, during harmonizing architectural layers, we collected information about the mentioned benefits of SOA for CPS middleware design and merged similar benefits into groups. To improve clarity and to find semantically coherent groups, the benefits were clustered into benefits groups if they were logically related to the same subject. We followed the theoretical approach of clustering proposed by Jankowicz (2003). Afterwards, we counted the occurrences of each benefit found in the articles for each benefit group. A total of 23 benefits were identified which were clustered into four benefit groups. As the last step, we developed a concept matrix that is based on the findings of the previous steps. This concept matrix is used to find patterns in the application of SOA for CPS to show which role SOA plays is in the context of CPS. The applied approach is to analyse SOA implementation projects based on written case material that describes how the SOA concept is applied on CPS. Specifically, the impact of SOA and its benefits on the particular layer for CPS are analysed. Following the logic of gradually decomposing complex concepts to make them more easily accessible, these impacts and benefits, altogether, form a cause-and-effect structure. By coding the impacts and benefits evident in the case material, the relationship between SOA and CPS is investigated and structured to build logic chains. These logic chains are then analysed for reoccurring patterns. These patterns may help us gain an understanding of SOA's and CPS' relationship.

4 Results

4.1 Overview of Selected Articles

Table 1 provides an overview of the 12 articles identified in the literature review process. The majority of the articles differ in context and the articles cover a broad variety of topics. Thus, various viewpoints on SOA and CPS are adopted. Two pairs of articles contain strong overlaps in content and are based on the same fundamental considerations (1: La and Kim, 2010; Zhang and Zhang, 2015; 2: Wang et al., 2012a; Wang et al., 2012b). Furthermore, authors of six articles rely on empirical evidence in their analyses. The empirical articles cover a high diversity of applications to which SOA was applied for CPS middleware design. For example, ranging from a teleoperating industrial robot manipulator in a distributed real-time control system for vacuuming radioactive particles (Alho and Mattila, 2015) through an open geospatial monitoring system for precision in agriculture monitoring (Chen et al., 2015) to a hazardous chemical transport CPS (Wang et al., 2012b). All studies approve that SOA meets the requirements of an architecture paradigm for CPS. However, authors of one study challenge SOA's ability to fully meet deterministic requirements in hard-real time systems (Morgan and O'Donnell, 2015).

The majority of the articles (11) consider modelling, designing, and developing aspects of a service-oriented middleware architecture for CPS (e.g. the design of a service-based CPS that can handle complex and resource-consuming physical processes with a downsized Mobile Internet Device (La and Kim, 2010). Three articles focus on software engineering aspects (e.g. the implementation of fault tolerance to improve service quality in a middleware-based real-time SOA for CPS (Alho and Mattila, 2015)). Two articles investigate SOA's and CPS' application in the current literature focussing on literature reviews and classifications (Hoang et al., 2012; Hu et al., 2012). Only one article deals with security aspects on a side note (Hu et al., 2012).

Article	Context	Empirical
Alho and Mattila (2015)	Design of a service-oriented approach to fault tolerance for CPS	yes
Chen et al. (2015)	Development of a CPS infrastructure for agriculture monitoring	yes
Dong et al. (2014)	Investigation of resource generation and allocation in CPS	no
Hoang et al. (2012)	Literature review and approach of CPS middleware design	no
Hu et al. (2012)	Review of works of CPS architecture including challenges and techniques	no
La and Kim (2010)	Development/design of a three-layer architecture for resolving "limited resource"	no
Morgan and O'Donnell (2015)	Identify the capabilities of SOA for CPS implementation in a manufacturing CPS	yes
Wan et al. (2014)	Applying a dynamic resource supply model in a smart grid	no
Wang et al. (2012a)	Development of a reliability assurance method for CPS components substitution	yes
Wang et al. (2012b)	Framework for CPS components composition	yes
Yu et al. (2012)	Framework for application rebuilding and lease protocol in CPS	yes
Zhang and Zhang (2015)	Framework for designing and modelling CPS by a service-based approach	no

Table 1. Overview of identified articles

4.2 Benefits of Using Service-oriented Architecture as an Architectural Style for Cyber-physical Systems

Although all identified articles use SOA to design a middleware for CPS, they differ in their primary purpose. During the assignment, information is collected about the mentioned benefits to use SOA and is merged into similar benefit groups. These benefits are clustered into categories whether they are logically related (see Table 2). A total of 23 benefits are identified, which are clustered into four clusters. The groups and related benefits are described as follows.

Resource composition: Five studies justify the use of SOA for CPS design due to the fact that it enables a dynamic resource composition. Basically, this benefit group describes that SOA enables a quick and easy substitution of physical components such as sensors which is an important issue for CPS troubleshooting and system upgrading (Wang et al., 2012a). In CPS, resource is not restricted to traditional computation and memory resources. Resource, in a generic sense, denotes an entity that is relevant in either producing or consuming a service. The authors conclude that SOA helps to improve limited resources availability and reusability. In particular, any component inside the infrastructure can easily be added, removed, and updated without affecting other physical components (Chen et al., 2015; Dong et al., 2014; Wan et al., 2014).

Service composition: SOA helps CPS to wrap the capabilities of the physical components and resources as services, which enables software and hardware components to be represented in the form of interoperable CPS services. CPS services are combined to realize complicated business requirements. Likewise, this benefit means that SOA decouples business functions, so that it solves business needs and technology to achieve the separation and implement the reusability of service. In concrete, seven authors underline this benefit of SOA for CPS.

Real-time capability: Four out of 12 analysed articles apply SOA to achieve a real-time capability for CPS. For some authors, this real-time capability means that SOA enhances sustainability and predictability in CPS. This results in a real-time SOA middleware that builds the support for service accountability and global resource management for real-time service processes. The middleware monitors the performance and reserves resources in advance for each service in the process to ensure its real-time feasibility (Lin and Panahi, 2010). Other authors describe this benefit on a deeper customer focus. For them, the real-time capability means that SOA provides the capability to produce ideal products for customer in real-time.

Integration of physical entities (interoperability): The next mentioned, seven times in total, benefit of SOA for CPS is the integration of physical entities. The review identified two major physical entities of integration: (1) Heterogeneous sensors and (2) industrial systems (Mechitov and Agha, 2012; Yue et al., 2015). This benefit helps to facilitate CPS' requirement to integrate the computational and physical worlds. Given the need for seamless integration and reusability, SOA's contribution is its openness and flexibility that allow the integration of all kinds of sensors, perceive the physical information around them, and transform these data to useful information (Chen et al., 2015). The identified articles describe SOA as a set of architectural tenets for building interoperable systems through loosely coupled web service (Morgan and O'Donnell, 2015). Several authors explain this benefit as the ability of a CPS to integrate different physical entities and systems from different vendors, and to interact with other systems in a distributed architecture regardless of their physical architecture and operating systems. Interoperability in CPS is especially required for the interaction of different sensors. Interoperability is achieved by SOA's design principle to conform to standards (Zhang and Zhang, 2015).

Article	Benefit groups of SOA on CPS			
	Resource composition	Service composition	Real-time capability	Integration of physical entities (interoperability)
Alho and Mattila (2015)			X	X
Chen et al. (2015)	X		X	X
Dong et al. (2014)	X			
Hoang et al. (2012)	X			X
Hu et al. (2012)		X		X
La and Kim (2010)		X		
Morgan and O'Donnell (2015)			X	X
Wan et al. (2014)	X	X	X	
Wang et al. (2012a)	X	X		X
Wang et al. (2012b)		X		
Yu et al. (2012)		X		
Zhang and Zhang (2015)		X		X

Table 2. Benefit groups mentioned by literature

4.3 Linkage between Design Principles, Architectural Layers, and Benefit Groups for Cyber-physical Systems

To improve clarity about the relationship between SOA and CPS it is analysed how SOA achieves benefits for CPS via each design principle and architectural layer (see Table 3).

The articles are analysed by searching for logical connection between the benefit groups for CPS and SOA design principles via an architectural layer. In a previous step, we matched the layered architecture of each article to a common three-layered architecture, which consists of a physical, a service, and an application layer. The physical layer provides a standard platform for physical devices. The service layer resides on top of the physical layer and provides a common repository of component services as well as a service framework that manages the services and interacts with service consumers. The application layer provides „high-level management and interaction with physical and software components" (Hoang et al., 2012: 82) beside controlling the applications (Yu et al., 2012).

While examining the connection between the design principles of SOA, the architectural layers, and the benefit groups for CPS, the data gathered shows that the linkage between modularity, service layer, and service composition is one of four dominant linkages. Additionally, standards, the physical layer, and the integration of physical entities (interoperability) form another logical link. These connections are followed by the linkage between standards, physical layer, and service composition. The last observed pattern is the linkage between loose coupling, physical layer, and resource composition. The detailed results of the observed patterns are explained in the following subsections.

Article	SOA						CPS Benefit Groups			
	Design Principles			Architectural Layers						
	Standards	Loose coupling	Modularity	Physical layer	Service layer	Application layer	Resource composition	Integration of physical entities (interoperability)	Real-time capability	Service composition
Alho and Mattila (2015)		x		x				x	x	
Chen et al. (2015)	x	x		x			x	x	x	
Dong et al. (2014)	x				x		x			
Hoang et al. (2012)	x	x		x		x	x	x		x
Hu et al. (2012)	x	x		x				x		x
La and Kim (2010)	x		x	x	x					x
Morgan and O'Donnell (2015)	x	x		x				x	x	
Wan et al. (2014)		x		x			x		x	
Wang et al. (2012a)	x		x	x	x			x	x	x
Wang et al. (2012b)	x		x	x	x			x	x	x
Yu et al. (2012)			x		x	x				x
Zhang and Zhang (2015)	x		x	x	x			x		x

Table 3. Mapping of design principles, architectural layers, and benefit groups

4.3.1 Modularity, Service Layer, and Service Composition

Table 3 shows that five articles build a linkage between the modularity of SOA, the service layer of the middleware design, and the benefit group of service composition. The high number of occurrences emphasizes that SOA's and CPS' benefits only unfold if services are composable and encapsulate the business or application functionality. Some authors describe the service layer as the foundation of the service-oriented CPS architecture (Wang et al., 2012a). In general, the main goal of the service layer is to cope with the heterogeneity issues of different physical components provided by the access layer and software components (Hoang et al., 2012). Additionally, the results of the analysis show that modularity is also the driving force to enable service composition in CPS, which is one of the most mentioned desired benefit group. With respect to SOA's relationship to CPS, this linkage confirms that the relationship is decisively shaped by SOA's design principles and layered architecture.

4.3.2 Standards, Physical Layer, and Integration of Physical Entities (Interoperability)

According to the analysed articles, authors draw a linkage between the SOA design principle standards, the physical layer, and the integration of physical entities. The physical layer facilitates a standard platform for physical entities and provides a networking environment for connecting devices for CPS. It is responsible for device management by detecting and identifying physical entities and their resources (Hoang et al., 2012). Regardless of diverse operation interfaces, communication protocols, and sensors, the physical layer is the data input layer for CPS (Chen et al., 2015). The linkage guarantees interoperability and a seamless integration especially in heterogeneous environments, which are common for CPS. Seven of the identified articles draw this linkage. These findings continue the interpretations provided above with respect to the relationship between SOA and CPS.

4.3.3 Standards, Physical Layer, and Service Composition

Additionally, six out of 12 articles establish a connection between the standards of SOA, the physical layer, and service composition that is provided by SOA. As mentioned in Section 4.3.2, the physical layer facilitates a standard platform. This standard platform does not only enable the integration of physical entities, it also provides CPS service substitution and composition (Zhang and Zhang, 2015). As a result, the use of SOA for CPS ensures that service consumers can be provided with their required functionality with a minimum of computing resources due to the fact that services are reusable (La and Kim, 2010). In this context, SOA resolves the resource constraint problem (caused by limited resources on physical devices) by providing required CPS functionality through services.

4.3.4 Loose Coupling, Physical Layer, and Resource Composition

The analysis shows that three out of 12 articles denote a linkage between loose coupling, the physical layer of the middleware design, and resource composition. This indicates that SOA enhances a dynamic binding of components by reducing the logical and run-time dependencies between services and as a result it improves a quicker resource composition for CPS. Thus, the physical entities of a CPS should be organised in a loosely coupled manner to be independent of any specific hardware platform, operating system, and implementation language to enable resource composition. In particular, any component inside a CPS should easily be added, removed, and updated without affecting other components (Chen et al., 2015). Many of the authors regard SOA as a dynamically integrating paradigm, which is used for integrating loosely coupled resources (Hu et al., 2012).

5 Discussion

To elucidate the role of SOA for CPS, we identified benefit groups of using SOA as an architectural style for CPS. These groups are linked to SOA's design principles and architectural layers to establish logical links that disclose the interrelation between SOA and CPS. By investigating these links, patterns emerged for the benefit groups resource composition, service composition, and integration of physical entities. For the remaining benefit group – real-time capacity – no clear pattern could be identified indicating a higher-level benefit, which needs to be achieved by a combination of several SOA design principles and layers; thus, demonstrating CPS complexity.

One of the strongest patterns observed is the linkage from modularity and service layer to service composition. The ability of service composition is particularly important for service innovations because it enables reuse of already implemented services and their recombination to create new services (Lee et al., 2014). To truly unlock the innovative strength of CPS by tapping into their unique characteristic – that is, integrating service-oriented systems that only exist in the cyberspace with physical entities – can be achieved by combining CPS with service-oriented technologies such as cloud computing that provide a flexible, elastic access to service in a location-independent manner (Morgan and O'Donnell, 2015).

From an academic perspective, our work provides important insights into the role of SOA in the emerging literature stream of CPS. We analysed the currently scarce research on CPS and SOA, identified desired benefits in the use of SOA for CPS, and linked our findings with the existing literature stream of SOA. As a result, we provided a unique contribution to an upcoming literature stream that will be highly relevant in the near future. More precisely, our applied mapping can be used in future research to classify and to identify further benefits of using SOA for CPS design. Given that our investigation has showed that there is no common standard methodology in literature on how to design a CPS with SOA (two-, three-, or four-layered design) yet, future research should focus on an industry-wide, standardized implementation framework that provides guidelines for practitioners. Such a framework is required, since CPS are used in complex and worldwide connected organizational industry environments with a plethora of interfaces and heterogeneous technologies. Our research model comprises relevant constructs – design principles, layers, benefit groups, and logical chains – that explain how SOA constitutes CPS benefits. Thus, we think that our results can be used to serve as a basis to establish a scientific framework for understanding how the IS architectural paradigm SOA generates value for CPS. In a next step, this framework can be extended by specific design and engineering requirements for CPS to establish an integrated framework for the implementation of service-oriented CPS. Furthermore, our exploratory study reveals essential elements that link SOA with CPS and serves as a bridge between the two literature streams. For example, reflecting on literature on SOA's economic value ((Mueller et al., 2010)) helps to address pressing challenges such as the underdeveloped economic potential of CPS (Lee, 2008).

From a practical perspective, our research has allowed us to determine on which design principles and architectural layers practitioners should focus to achieve desired CPS benefits. Hence, our results especially contribute to applied research and practice engaging in designing and engineering of CPS. Designers can leverage identified patterns to understand the importance of specific characteristics of SOA to address unique requirement situations of their CPS. Focusing on different parts of SOA will result in different CPS benefits. Practitioners can use our results as a guide to design their CPS by leveraging SOA. High-level benefits, such as real-time capability, may only be achieved by comprehensively leveraging SOA for CPS design.

While providing patterns of explanation for achieving specific requirements in CPS by leveraging architectural principles and layer designs of SOA, our results contribute to initiatives such as Industry 4.0 that seek to introduce CPS as a technological foundation for innovation in industries and services. Given that such initiatives try to digitalize enterprises by connecting enterprise-wide industrial plants, processes, and organizations, it is important to understand that these industrial entities have not been built with an interconnected CPS paradigm in mind and sometimes date back more than a quarter century when even information technology in general was in its infancy. Thus, we think that one of the major challenges of industry initiatives such as Industry 4.0 will be the merger and the replacement of legacy systems with upcoming systems in a distributed environment. Since SOA is already well accepted and widely distributed as an architectural paradigm in industrial automation (Jammes and Smit, 2005), we suggest that SOA and its concepts – especially in conjunction with an enterprise service bus – should be used as an architectural style for digitalizing enterprises. While we believe that our study also contributes to industrial initiatives in this context, it is an interesting observation that none of the analysed studies in our final sample explicitly focusses on a specific industry initiatives. On the one hand, this finding underscores the novelty of this research stream and that authors have rarely investigated initiatives such as Industry 4.0 concerning their architectural foundations. On the other hand, this finding draws attention to a potential shortcoming in literature. We seek to ignite further research on SOA as an architectural paradigm for CPS design in the context of industry initiatives.

This study is not free from limitations: First, it is noticeable that two pairs of the analysed articles each largely overlap in content as well as being written by the same author team in one case. Thus, our results may be biased because these authors' opinion has a higher weight. Second, the dataset consists of 12 articles only. Despite the small number of analysed articles our sample shows a high degree of topicality as half of the articles were recently published within the last three years (2014-2016). Third, as this study aims to improve comprehension of the role of SOA for CPS in the IS discipline, it is a reasonable assumption to say that not every characteristic is covered, partly due to the novelty of the topic. Studies covering new aspects are likely to be conducted in the near future. Thus, an extension of this study's scope can become relevant.

6 Conclusion

By investigating the role of SOA for CPS, we identified patterns of logical links from SOA design principles and architectural layers to CPS benefit groups. For research, the identified logical links provide a theoretical explanation of how SOA is linked to CPS. These findings represent foundational insights for future research on the architectural characteristics and design of CPS. Future research could concentrate on dominant patterns we identified to analyse in detail how a specific benefit can be achieved leveraging SOA. As different CPS implementations differently prioritise design requirements, not all CPS benefits are equally important for all application scenarios. Implications for practitioners are guidelines on which parts of SOA to concentrate on to achieve specific benefits that are relevant to the requirements specific application domains of CPS.

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