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Morphology for Designing Cyber-Physical Systems in Supply Chain Planning and Control Processes

Endric Hetterscheid
Florian Schlüter

Graduate School of Logistics
TU Dortmund, Germany

Due to the increasing digitalization of supply chain processes, Industry 4.0 offers enormous innovation potential for companies and their partners. The use of Cyber-Physical Systems provides the necessary prerequisites for flexible planning and control of supply chains. However, the development of such systems represents a major challenge for companies. The paper proposes a morphological box for the design of Cyber-Physical Systems regarding the planning and control of supply chain processes. Its applicability is presented in two use cases of a German steel company.

[Keywords: Cyber-Physical Systems; Digital Transformation; Industry 4.0; Planning and Control; Supply Chain Management]

1 INTRODUCTION

Customer demand for individualized products lead to a growing complexity in planning and control of supply chains (SCs). In order to achieve at the same time a maximum of flexibility and efficiency, digitalization of business processes is an important trend and a necessary requirement (Kersten et al. 2016). The concepts and technologies of Industry 4.0 (I4.0), especially Cyber-Physical Systems (CPS) as key enabler, will become increasingly important for the digital transformation of SCs (Bischoff 2015; Vernim et al. 2017). The introduction of such technologies often means disruptive effects in an organization, so that it is the task of the management to support the transformation processes (Gehrke 2017). In this context, it has become an increasing management task to deal with the changes, but also with design of functionalities of new systems (Bartolomei et al. 2012). Especially CPS can contain a variety of different technical components and capabilities for different applications (Geisberger & Broy 2012). A support is needed, which allows the design of CPS for planning and control in SCs. This paper addresses this research gap by proposing a morphological box for designing CPS. For this purpose, the following research question (RQ) is defined: How can CPS be systematically designed with regard to their technical components and functions for planning and control processes in SCs?

In order to answer the RQ, the paper is organized as follows. In chapter 2, the research overview according to I4.0, digital transformation of SC processes, CPS and related work is described. Chapter 3 explains the methodology for developing a morphological box. The framework with the characteristics and expressions is developed in chapter 4, followed by an application at a German steel company in chapter 5. In chapter 6, the conclusion and further research are presented.

2 RESEARCH OVERVIEW

2.1 INDUSTRY 4.0 AND THE DIGITAL TRANSFORMATION OF SUPPLY CHAIN PROCESSES

Modern information and telecommunications technologies are used for today's coordination in networked SCs (Hertel et al. 2011). In Germany, this digitalization of industry is summarized under the hypernym "Industry 4.0" (Hirsch-Kreinsen 2014; Wang et al. 2015). Although the term "Industry 4.0" has existed for several years, there is still no uniform definition (Bauer et al. 2014; Roth 2016). *Bischoff* provides a holistic definition suitable for the scope of the paper. He defines I4.0 as development of production and value creation systems by linking the real and the digital world. This link is created by self-controlling CPSs that enable vertical and horizontal integration for efficient, decentralized and flexible production of products or services along the SC (Bischoff 2015). For achieving an I4.0, digitalization is regarded as a necessary prerequisite (Schuh et al. 2017; Vernim et al. 2017). Therefore, companies in a SC are developing digitalization strategies to coordinate their digital transformation initiatives and projects (Mertens et al. 2017). In this context, digital transformation is referred to as the improvement of a company's performance and scope through the use of digital technologies (Westerman et al. 2014; Gehrke 2017). The following definition is valid for the digital transformation of processes and will be used for this paper. Digital transformation is the combination of changes in company processes through the use of digital technologies with the aim of maintaining or increasing competitiveness (Berghaus et al. 2015). Such digital technologies are CPS, which are explained in more detail in the next chapter.

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2.2 Cyber-Physical Systems

The definition above clarified that CPS play an essential role in I4.0, as they form the basis and key technology (Kagermann 2013, Obermaier 2016; Bauernhansl 2017). CPS have the task of linking the physical and digital world (Broy 2010; acatech 2011; Spath 2013). Focusing the planning and control of a SC, they can not only actively support tasks, but also carry them out autonomously (Hetterscheid & Beißert 2018). One of the first and most widely used definitions of CPS provides *Lee:* „Cyber physical systems are integrations of computation of physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa" (Lee 2008). Since in this definition embedded systems are also described as CPS, this description is not sufficient (Kowalewski et al. 2012) . In addition, *Broy* describes as an essential property of CPS that they can network and thus interact and cooperate (Broy 2010). However, the novelty does not comprise in the general ability of networking in the form of closed networks, as it has been common in automation technology in the context of mechatronic systems for years. Rather, networking via open and global information networks, in particular the internet, is the significant renewal of CPS (Kowalewski et al. 2012; Hehenberger et al. 2016). Open and networked systems based on physical units are emerging that connect the virtual world of information technology with the physical world of processes (Broy 2010; Geisberger & Broy 2012). As a result, CPSs have the opportunity to take over planning and control tasks in SCs while being able to react in an efficient manner through their collaboration and real-time properties (Schuh et al. 2014). In addition to the explanations the following definition for CPS in the context planning and control in SC is valid and used in this work: „CPS are a form of socio-technical systems that are characterized by the interaction of different technologies, forcing the strengthening of collaboration between both internal and external customers along the SC in order to minimize interface problems and maximize synergy effects."

2.3 Related work

For the design of operative IT systems, different classifaction and systematization models exist in literature. In the following, selected models or approaches are described to give an overview of the current state of the art.

Böse and Windt present a catalogue of criteria in the form of a morphological scheme for the description of properties of autonomous systems in production logistics. This scheme addresses the different levels of autonomous control of IT systems (Böse & Windt 2007). *Meyer et al.* introduce a classification scheme for intelligent products. The model can be used to describe intelligent products in various dimensions (Meyer et al. 2009). *Rhensius* presents a morphology for RFID applications. RFID applications are designed by taking into account technical feasibility and individual process characteristics (Rhensius 2010). *Windelband et al.* develop in their work a description model for the classification of the internet of things. The model enables to make a technological classification of applications in the context of the internet of things (Windelband et al. 2010). *López et al.* present in their work a taxonomy for smart objects. The taxonomy describes five essential characteristics and capabilities of these systems (López et al. 2011). *Schuh and Deindl* set up a morphological box to systematize smart objects for the design of their application in production and logistics (Schuh & Deindl 2013). *Schuh et al.* developed a systematization model for sensor system applications and sensor data in production. It is also a morphological box that combines sensor systems with individual process properties and requirements (Schuh et al. 2015). *Richter et al*. present a morphology for the development of intelligent logistics spaces. The morphological box supports the technical design of logistics-related spaces depending on the characteristics of a process (Richter et al. 2015). In addition, *Endres and Sejdić* develop in their work a morphological box for the assignment of CPS technologies to intralogistics processes (Endres & Sejdić 2018).

To summarize the current state of the art, no classification and systematization model can be found that supports the design of CPS with regard to applicable technical components and functions in planning and control of SC processes. To achieve the research objective and to answer the RQ, the methodology of the paper is explained in the next chapter.

3 Methodology

In accordance to systems theory, a system can consist of different elements that relate to each other and represent the structure of the system (Haberfellner 2015). The complexity of a system rises with the increasing number of elements and the diversity of properties and configurations (Deubzer et al. 2012). In order to achieve a systematization or representation of different combinations of system elements, the morphological box is often used as a method in systems engineering. The idea of a morphological box is similar to the principle of variant formation, since there are several alternative solutions to each problem and these are presented comprehensively (Haberfellner 2015). The complete consideration of a problem and the unbiased assessment of all solutions results in a system of characteristics, in which the problem is sub-divided into characteristics and expressions of the characteristics. This system forms a multi-dimensional matrix, called a morphological box, which represents the best known and most used morphological method (Schulte-Zurhausen 2014). As a result, a morphological box represents a classification scheme, describing e.g. different components, functions and characteristics of systems. The basic procedure for the development and application of a morphological box was

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developed by *Zwicky* (Zwicky 1969). According to his approach, the following steps for the development of a morphological box is conducted in this paper (see Figure 1).

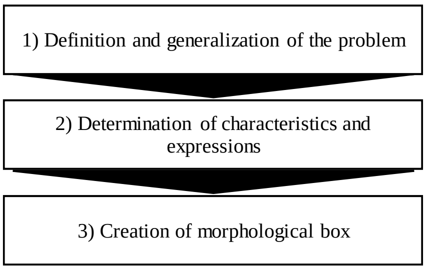

Figure 1. Methodical steps for the development of the morphological box

4 Development of a Morphological Box for Designing Cyber-Physical Systems

4.1 Definition and Generalization of the Problem

As explained in chapter 1, the design of CPS can face significant challenges as it can consist of a variety of technical components and individual functions. These often depend on the field of application and the intended purpose of the CPS (Hehenberger et al. 2016). Depending on the circumstances of a process, not all technologies can be used sensibly in planning and control. Thus, by designing a CPS, there can be different possible solutions depending on the requirements of the planning and control processes.

4.2 Determination of Characteristics and Expressions

Chapter 2.2 illustrates that CPS has both process-related characteristics and technology-related characteristics. Since CPS are often integrated in existing organizational environments and have a close connection to material and information flow, **process-related characteristics** play an important role in the designing phase. These characteristics can be derived from the classifications and systematizations presented in chapter 2.3. Planning and control processes in SCs are characterized by decisions to be made, which can be found and executed in different ways. By designing CPS, it is essential to define the division of responsibility between human and system (Veigt et al. 2013). The first characteristic that can be mentioned is the **type of decision support**. The following expressions according to the *Blutner and Witthaut* can be made (Blutner & Witthaut 2007): human-based, distributed, machine-based.

There is a need for coordination when decision-making interdependencies and interfaces exist between individual elements of a system, such as organizational units or processes, which can be regarded as a result of the division of labor (Schuh & Stich 2012). *Böse and Windt* distinguish between a heterachic and a hierarchical form of coordination as well as to intermediate manifestations. In heterachic coordination the highest degree of self-control can be achieved, in which the individual elements of a system coordinate each other with regard to decision-making (Böse & Windt 2007). *Schuh and Deindl* take up this aspect in his work for smart objects and elaborates on it by distinguishing between three **forms of coordination** (Schuh & Deindl 2013): vertically, combined, horizontally.

The use of technologies enable a CPS to perform various functions. These can significantly support the execution of planning and control tasks in SCs. By designing CPS, functional requirements are determined which characterize the behavior and functionalities of a system (Broy 2010). Based on the taxonomy according to *Lopéz et al.*, on the morphological box according to *Schuh and Deindl* as well as the characteristic abilities of a CPS according to *Geisberger and Broy*, the expressions of the characteristic **'function'** are given (López et al. 2011; Geisberger & Broy 2012; Schuh & Deindl 2013): identification, data storage, data collection, data capture, data provision, actuation, decision making, networking.

The function of a CPS can be negatively influenced by environmental factors. Depending on the area of application, these can be extremely individual and can significantly impair the integration or operation of a CPS. It has to be ensured that the CPS must work reliably even under complex environmental conditions (Wang et al. 2015). Environmental factors contain aspects of particularly productive environments that may have an impact on the operation of the system (Schuh et al. 2015). In the context of this paper, they are referred to as **disruptive factors** which are essentially characterized by the negative impact on a CPS in the process. Since CPS represent a combination of physical and virtual characteristics the following expressions can be made: no disruptive factor, material flow factor, information flow factor.

The environmental factors are closely linked to the objects in a company's material flow. They represent the basic system of a CPS (Broy 2010). A large number of such physical objects are located in SC processes, e.g. in the form of products, buildings, means of transport, production facilities or logistics components (Broy 2010; Bauernhansl 2017), and can therefore be counted as process-related characteristics of a CPS. In order to limit the possible objects, the scope is based on material objects in the SC. Such objects are primarily considered important for CPS in terms of production and logistics resources (Schuh et al. 2017). Furthermore, these can be both stationary and mobile objects (Schuh & Deindl 2013). In the following, the individual expressions for the characteristic '**physical object'** are given: work equipment, work aid, area, material, human.

Closely linked to the process-related characteristics are the technological components contained in a CPS. These **technology-related characteristics** make it possible to execute individual functions for support in planning

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and control tasks in SCs. CPS do not have a uniform definition and therefore the technical components or characteristics of these systems are also not defined uniformly (Roy 2017). In addition to the definition of *Lee*, a variety of other definitions of CPS are proposed in the literature. *Roy* provides an overview of selected definitions of CPS in his work (Roy 2017). Additionally, a literature analysis according to further definitions of CPS is carried out in order to identify the most important technological components of a CPS. These will represent further characteristics of the morphological box. The results of the literature analysis are summarized in the Appendix 1 of this paper. Based on the definitions, the essential technological components of a CPS can be set in dependency (see Figure 2). The basis of each CPS is a physical object that is located in the process environment (Monostori et al. 2016; Bauernhansl 2017). These are supplemented by sensors, actuators and high-performance microcomputers and evolve into embedded systems (Siepmann 2016). Based on those, they will become a CPS through networking via communication networks, such as the Internet, with clouds and other objects as well as systems (Obermaier & Kirsch 2015). In the following, the individual technical components that represent the characteristics of the morphological box are explained (see Figure 2). The expressions for the characteristics are conducted on the basis of a further literature search.

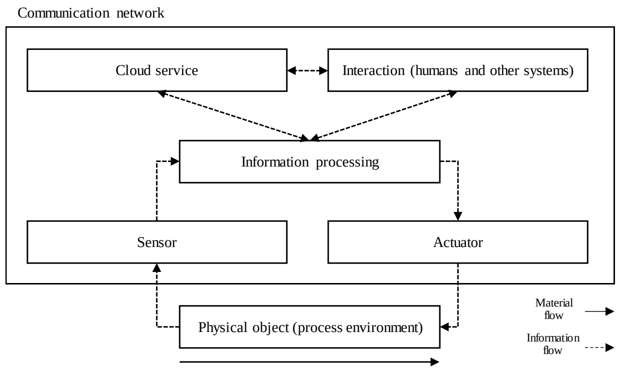

Figure 2. Dependencies of the technical components of a CPS

To equip an object with intelligence, it is essential that the physical object has knowledge of its own state and environment. Sensor technology offers the possibility of recording and measuring the conditions of the real world and converting them into electrical signals (Hering & Schönfelder 2012; Heinrich et al. 2017). In the context of I4.0, sensors represent an essential prerequisite for technical changes and further developments (Hering & Schönfelder 2012; Fürstenberg & Kirsch 2017). According to *Schuh et al.* and *Lopéz et al.,* **Sensors** can have the following essential technical characteristics (López et al. 2011; Schuh et al. 2015): identification sensor, integrated and smart sensor, wireless sensor network.

Actuators make it possible to interact with and influence the environment (Ollesch et al. 2016). They enable physical objects to react (Roy 2017). **Actuators** are an important component for closing control loops, whereby processes can be automated (Schuh & Deindl 2013). They can be distinguished according to their capabilities. In the morphological box of *Schuh and Deindl*, the following expressions are made (Schuh & Deindl 2013): feedback, physical action and user interaction.

Another technical component of a CPS and thus a characteristic of the morphological box is **information processing** (see Figure 2). In the processing of information, the actions necessary to influence a state parameter are generally determined (VDI 2004). *Schuh and Deindl* as well as *Böse and Windt* address the location of information processing in their systematizations (Böse & Windt 2007; Schuh & Deindl 2013). Following these, three different forms of information processing can be given: outsourced, combined, embedded.

A CPS can have various interfaces to physical objects, people and other systems. One expression is the human-machine interaction. Due to the increasing complexity of tasks and processes, humans must be supported by adequate technologies (Geisberger & Broy 2012; Bischoff 2015). But there are also essential interfaces to other physical objects and information systems, since the efficient exploitation of CPS potentials is only possible through interaction and collaboration with other systems (Khaitan & McCalley 2015). The design of such an **interaction interface** can take place on the basis of the two following characteristics: human-machine interaction, machine-machine interaction.

To enable physical objects, people or systems to interact and exchange data, they are connected in the form of networks (Bischoff 2015). As described in chapter 2.2, the internet represents an essential **communication network** for CPS. However, communication does not necessarily have to take place via a global and open network. For this reason, the type of network connection of a system will be focused according to *Schuh and Deindl* (Schuh & Deindl 2013): wired, wireless, mobile network.

The literature analysis on CPS definitions shows that clouds are sometimes mentioned in context of CPS (see Appendix 1). Local physical objects can be globally networked with one another via a virtual platform (Siepmann 2016; Bauernhansl 2017). Cloud computing promotes the cross-company interaction of these objects by providing IT infrastructure, such as software, data storage or services. These IT resources are made available to users through computer centers accessible via network connections such as the Internet (Kubach 2017). A distinction is made between different operator models, which are given in the following as expressions of a **cloud service**: private cloud, public cloud, hybrid cloud.

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4.3 CREATION OF MORPHOLOGICAL BOX

In the last step of development, the morphological box with its identified characteristics and expressions is set up. The characteristics are arranged in the left column and the individual expressions are entered in the respective rows of the characteristics (see Figure 3).

Characteristics		Expressions						
process-relaed	Type of decision support	human-based	distributed	machine-based				
	Form of coordination	vertically	combined	horizontally				
	Function	identification	data storage	data collection	data provision	actuation	decision-making	networking
	Disruptive factor	no disruptive factor	material flow factor	information flow factor				
	Physical object	work equipment	work aid	area	material	human		
technology-related	Sensor	identification sensor	integrated and smart sensor	wireless sensor network				
	Actuator	feedback	user interaction	physical action				
	Information processing	outsourced	combined	embedded				
	Interaction interface	human-machine interaction	machine-machine interaction					
	Communication network	wired	wireless	mobile network				
	Cloud service	private cloud	hybrid cloud	public cloud				

Figure 3. Morphological box for designing CPS in planning and control processes of SCs

5 FRAMEWORK APPLICATION AT A GERMAN STEEL COMPANY

5.1 JUSTIFICATION OF APPLICATION IN THE STEEL INDUSTRY AND OF THE STEEL COMPANY

The planning and control of SCs in the steel industry is considered particularly challenging due to its high complexity (Labitzke 2011). From a planning and logistical point of view, the timely supply of individual internal and intercompany production and processing stages represents a significant challenge (Rotmann 2016). In practice, the dynamic environment and complex processes often lead to a variety of disruptions, which often results in short-term changes in the planning basis (Fischer et al. 2004; Labitzke 2011; Krumeich et al.). This has a particular impact on compliance with delivery dates to the customer. In order to secure the competitiveness of the steel industry and other related industrial sectors, the term I4.0 and its technologies such as CPS promise great potentials (Bode et al. 2017; Reifferscheid 2017).

The selected company is one of the largest German steel producers in terms of annual production. The company employs more than 25,000 people and is active worldwide with various locations. It is one of the leading suppliers of carbon flat steel and has e.g. customers in mechanical and plant engineering as well as in the automotive and construction industries. The finished products to be sold are heavy plate, hot-rolled strip and organically coated, hot-dip coated, uncoated and electrolytically coated cold rolled strip.

5.2 DESIGNING CYBER-PHYSICAL SYSTEMS WITH THE MORPHOLOGICAL BOX

The morphological box is used as a creativity method to design CPS in two use case in the production and logistics area of the steel company. The determination of the individual expressions was carried out in workshops with experts from the respective area. A total of eight CPS-based system solutions were developed for various processes, two of which are presented in the following.

The first use case is about an incoming goods inspection in which the identification of delivered slabs is to be facilitated by a CPS. The slabs are transported by rail from the port of Rotterdam to a company's plants in Germany. At present, the material pieces cannot be precisely identified because the identification number can change on the transport route between supplier and customer. As a consequence, the slabs cannot be controlled and the storage cannot be carried out. In near future, the slabs should be equipped with a RFID tag. They store the material piece number, which makes the pieces uniquely identifiable. In the goods receiving area, the rail passes through an RFID gate so that the RFID tags of the slabs are read out and the identification numbers returned. After the feedback of the data with the order data, the information is made available to the crane operator via a warehouse management system, so that the slabs can be stored. The process is controlled mainly by distributed decisions and vertical coordination. The warehouse relevant information is displayed to the crane operator via a monitor and is also made available to the production control system. The communication between the systems is essentially wired and the provision, storage and processing of the data takes place via central, internal databases.

Characteristics		Expressions						
process-relaed	Type of decision support	human-based	**distributed**	machine-based				
	Form of coordination	**vertically**	combined	horizontally				
	Function	**identification**	**data storage**	data collection	**data provision**	actuation	decision-making	**networking**
	Disruptive factor	no disruptive factor	material flow factor	**information flow factor**				
	Physical object	work equipment	work aid	area	**material**	human		
technology-related	Sensor	**identification sensor**	integrated and smart sensor	wireless sensor network				
	Actuator	**feedback**	**user interaction**	physical action				
	Information processing	**outsourced**	combined	embedded				
	Interaction interface	**human-machine interaction**	**machine-machine interaction**					
	Communication network	**wired**	wireless	mobile network				
	Cloud service	**private cloud**	hybrid cloud	public cloud				

Figure 4. Filled morphological box for designing CPS in the first use case

In the second use case, the process involves the production of steel coils and internal transport between the two processing stages. At present, this process is controlled manually, resulting in high coordination costs and long processing times. In the future, the two production units, buffer areas, produced coils, transport vehicles and cranes will be connected via a wireless sensor network. These resources can clearly identify themselves, record, store and report back current data from the process. This information

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is processed decentrally at the physical objects and made available to the operative employees via smartphones and tablets. The upstream production unit coordinates with the downstream production unit the machine utilization planning, taking into account information such as the current capacity utilization level, plant malfunctions or production program. Such data is stored in the cloud, analyzed via analytics services and relevant information is made centrally available to the process participants. As soon as the production of the coil is completed at the first processing stage, the piece of material initiates its intermediate storage by communicating with the autonomous means of transport and crane. Similarly, the retrieval of a required coil is initiated by the downstream production unit. This overall system enables machine-based decision making and execution as well as horizontal coordination. The main communication takes place via mobile network, which can also lead to problems with regard to data transmission quality in the production halls. Furthermore, the production of steel coils is subject to high mechanical and thermal stresses.

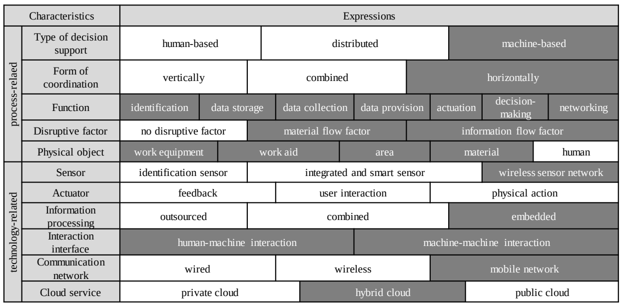

Figure 5. Filled morphological box for designing CPS in the second use case

6 CONCLUSION AND FURTHER RESEARCH

6.1 CONCLUSION

The paper presents a morphological box for designing CPS in planning and control processes of SCs. For this purpose, a literature analysis was conducted to identify a total of eleven characteristics with different expressions. These are divided into process-related and technology-related characteristics. Moreover, the morphology was applied in two use case with a steel production company. In summary, the technology-related features address the development with regard to the systemic design of a CPS. The inclusion of process-related characteristics in the morphological box also consider the requirements for such system solutions in the context of SC planning and control processes. In addition, the process owners are involved in an early phase of the CPS design. As a result, the defined RQ could be answered (see Chapter 1).

6.2 FURTHER RESEARCH

The morphological box has mainly been applied for use cases in control processes in the steel industry. Further research contain the applications in more planning related processes and other industries. As a result, the different characteristics and expressions of the morphology can be more specified. By designing with the morphological box, different CPS-based solutions for one process can result. In order to make an informed decision, the costs and benefits of the solutions must be evaluated. Therefore *Hetterscheid and Schlüter* propose a decision support approach for selecting physical objects for CPS-transformation (Hetterscheid & Schlüter 2018). This approach can be expanded by integrating the developed morphological box.

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Endric Hetterscheid, M.Sc., PhD student in the Graduate School of Logistics at the Technical University of Dortmund. Endric Hetterscheid was born in 1989 in Essen, Germany. Between 2010 and 2016 he studied Industrial Engineering at the TU Dortmund.

Address: Graduate School of Logistics, TU Dortmund,
Leonhard-Euler Straße 5, 44227 Dortmund, Germany,
Phone: +49 2317558309
E-Mail: hetterscheid@gsoflog.de

Florian Schlüter, M.Sc., PhD student in the Graduate School of Logistics at the Technical University of Dortmund. Florian Schlüter was born in 1989 in Hameln, Germany. Between 2008 and 2015 he studied Industrial Engineering at the TU Dortmund.

Address: Graduate School of Logistics, TU Dortmund,
Leonhard-Euler Straße 5, 44227 Dortmund, Germany,
Phone: +49 2317558311
E-Mail: florian.schlueter@tu-dortmund.de

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APPENDIX 1. RESULTS ON THE TECHNICAL COMPONENTS OF A CPS BASED ON LITERATURE DEFINITIONS

Literature sources	Physical object	Sensor	Actuator	Information processing	Communication network	Cloud service	Interaction to	
							Humans	Other systems
acatech (2011)	X	X	X	X	X	X	X	X
Baheti & Gill Helen (2011)	X			X	X		X	X
Bauer et al. (2014)	X	X	X	X	X		X	X
Bauernhansl (2017)	X	X	X	X	X	X	X	X
Bischoff (2015)	X	X	X	X	X		X	X
Broy (2010)	X	X	X	X	X		X	X
Draht (2017)	X				X	X		X
Drossel et al. (2018)	X	X	X	X	X		X	X
Engell et al. (2015)	X			X				X
Geisberger & Broy (2012)	X	X	X	X	X		X	X
Hämmerle et al. (2018)	X	X	X	X	X		X	X
Hehenberger et al. (2016)	X	X	X	X	X			X
Jazdi (2014)	X	X	X	X	X	X		X
Kagermann (2017)	X	X	X	X	X			X
Kagermann (2013)	X	X	X	X	X		X	X
Karsai & Sztipanovits (2008)	X	X	X	X	X			
Kowalewski et al. (2012)	X			X	X			X
Lee & Seshia (2015)	X			X	X			
Lee (2008)	X			X	X			
Leitão et al. (2015)	X			X	X	X		X
Lin et al. (2010)	X	X	X	X	X			X
Lucke et al. (2017)	X	X	X	X	X		X	X
Lüth (2017)	X	X	X	X	X		X	X
Monostori et al. (2016)	X	X	X	X	X			X
Obermaier (2016)	X	X	X	X	X		X	X
Roy (2017)	X	X	X	X	X		X	X
Siepmann (2016)	X	X	X	X	X	X		
Spath (2013)	X			X	X		X	X
Wang et al. (2015)	X	X	X	X	X		X	X
Wu et al. (2011)	X	X			X		X	X