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Bridging two worlds: How Cyber-Physical Systems advance Supply Chain Management

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Abstract:

The implementation of Cyber-Physical Systems (CPS) promises a broad variety of potential benefits within Supply Chain Management (SCM). The CPS concept has moreover already reached practical application inside supply chains and other operational processes and economic practice therefore seems to be still ahead of the more theory-oriented scientific community. Nevertheless, a certain ambiguity surrounding this terminology remains. This paper delivers a comprehensive, interdisciplinary, concept-centric literature review on CPS-related research resulting in a scientifically elaborated, generic definition for CPS. It furthermore clarifies the practical relevance of CPS by conducting focus group workshops and thereby linking technologies, applications, as well as objectives of an enhanced SCM to each another. It finally presents an outline of potential directions for future research.

JEL Classification: M15 (IT Management), O32 (Management of Technological Innovation and R&D), O33 (Technological Change: Choices and Consequences)

Keywords: Cyber-Physical Systems (CPS), Information and Communication Technologies (ICT), literature review, focus group workshops, research agenda

1 Introduction

Information and communication technology (ICT) is an important enabler for modern Supply Chain Management (SCM). In this respect, the reflection of scientific literature on hand identifies two different prevailing research streams. The first one tackles the integration of IT-systems of supply chain actors, using electronic data interchange (EDI) (Tan et al. 2010) and the Internet (Porter 2001). The prior focus of the second one is the integration of the real and the virtual world, based on Radio Frequency Identification (Sarac et al. 2010; Strassner and Fleisch 2005), Wireless Sensor Networks (Haan et al. 2013; Ota and Wright 2006) and other functional-equivalent "Auto-ID" technologies (Hafliðason et al. 2012; Raab et al. 2011). A combination of these two worlds is still almost completely missing in today's scientific SCM literature. Other disciplines, however, have already started a discussion on the emerging technological concept of Cyber-Physical Systems (CPS), thereby addressing both integration approaches simultaneously. The in-principle character of this innovation, the potential benefits for companies and supply chains (being recognized and also more and more utilized by economic practice), as well as the accompanying implementation challenges justify if not require a comprehensive discussion from the scientific SCM community. It is, once again, of foremost importance in this regard, that such discussions go beyond the previous isolated consideration of only one of the two abovementioned streams.

According to EDWARD A LEE, a CPS uses "computations and communication deeply embedded in and interacting with physical processes to add new capabilities to physical systems." (Lee 2009, p. 71). Such systems do integrate sensors and actuators into physical devices, connect them with cyber components and hence are capable of independent decision-making and of adapting intelligently to changing conditions (Sahingoz 2013; Verl et al. 2012). In a SCM context, the implementation of CPS allows the transfer of decision-making to "smart" products, containers, machines and infrastructures (Porter and Heppelmann 2014, Sanchez Lopez et al. 2011) and has to an increasing extent meanwhile reached economic practice (which therefore seems to be still ahead of the more theory-oriented scientific community). So called "smart boxes" or entire "intelligent containers", equipped with embedded and networked microelectronics, are for instance able to monitor transportation processes, detect critical situations, create events and initiate exception processes (Lang et al. 2011). "Intelligent bins" for electronic Kanban again, can use small, embedded cameras to determine their filling level of c-parts or assembly components (Prasse et al. 2014). If that level falls below a given limit, the container connects wirelessly to the environment and sends a replenishment order to the manufacturer autonomously. In both cases, the CPS and the corresponding application delivers certain benefits to the company.

In order to understand the nature of these benefits, a further look at the main challenges for today's supply chain managers becomes necessary. After decades of relative stability, the cost-cutting and problem-solving potential of the lean philosophy reaches its limits within many supply chains (Christopher and Holweg 2011). Supply chains now furthermore have to cope with increasingly dynamic customer demands and a broad variety of external disturbances within a rapidly changing economic environment. Increased flexibility and agility is needed and processes have to be accelerated and made transparent or visible (Caridi et al. 2014) in order to enhance supply chain responsiveness (Christopher 2011). This is exactly where CPS display their strength by contributing to an overall enhanced SCM. Proceeding from the examples outlined above and their expected benefits with respect to the transparency of transport processes or c-parts consumption, the acceleration of exception processes in case of problem detection, or the smoother adaption to consumption dynamics, it can be assumed that comparable patterns emerge when other objects are turned into and used as CPS within a supply chain. Following this line of thinking, enhanced SCM has to be understood as a new form of itself, where objectives with regard to cost reduction, additional customer value, process velocity and visibility, as well as responsiveness are achieved to a higher extent, not least through the utilization of modern information and communication technologies (ICT).

The purpose of the underlying research project is the triggering of a more comprehensive scientific discussion on the innovation power and the benefits of CPS within SCM. Therefore, the prevailing ambiguity surrounding CPS has to be resolved by generating a generally applicable and consistent definition of the terminology "Cyber-Physical Systems", by analyzing contemplable fields of application and potential thereof resulting benefits, as well as by outlining directions for future research. For these purposes, a concept-centric literature review was conducted to elaborate a suitable generic CPS definition. In a second step, industrial companies were confronted with this definition during focus group workshops in order to identify potential CPS applications, to describe the corresponding problem solutions on a first level of detail, to identify benefits for enhanced SCM and to develop an outline for future research.

Against this background, four research questions (RQs) were raised:

- RQ1: Which attributes are most suitable for defining CPS on an abstract level?
- RQ2: Which fields of CPS application are of particular relevance for supply chain processes and what kind of benefits can be derived out of them?
- RQ3: How do resulting problem solutions contribute to enhanced SCM?
- RQ4: What are relevant research questions concerning the future implementation of CPS in industrial supply chains?

This paper is divided into six sections. After introducing the topic, the second section defines the methodological approach of the underlying literature review and focus group workshops. Section 3 provides a scientifically elaborated definition for the term CPS, while the subsequent fourth section identifies relevant fields of CPS application and furthermore shows how consequential resulting problem solutions contribute to enhanced SCM. Outlines for future research on CPS within SCM, in the sense of a prospective research agenda, are provided within the fifth section, before the paper finally concludes with a brief summary and an evaluation of essential findings.

2 Research Approach

In order to gain an overview over the state of CPS research and to collect relevant literature for enabling a consistent wording, a concept-centric literature review following WEBSTER AND WATSON's approach was conducted. This procedure is not only valid for mature topics, where a broader variety of literature exists, but also for tackling "an emerging issue that would benefit from exposure to potential theoretical foundations" (Webster and Watson 2002, p. xiv). The investigation of relevant literature involved a time period from 2009 to 2013, starting with EDWARD A LEE's efforts and endeavors concerning Embedded Systems in general and CPS in particular (Lee 2008; Lee 2009). Within the observed period, publication quantity significantly increased each year – a development that appears to continue subsequently. In order to meet the requirement of providing a consistent scientific perspective on the field, practical papers as well as textbooks, news reports, master/bachelor theses and doctoral dissertations have been excluded. This exclusion follows the assumption, that articles in scientific journals are the most suitable and reliable source of information and new findings (Ngai et al. 2008). Furthermore, unpublished working papers, editorials and comments have been eliminated as well.

Relevant literature is dispersed over a wide range of journals. Therefore, a preselection of and initial restriction on a certain spectrum of journals was unrewarding due to the high potential of excluding relevant papers. With that in mind, the widest possible range of publications was investigated by using EBSCO Business Source Complete, Emerald Insight, Journal STORage, Science Direct and Springer Link as electronic databases. The literature search was based on the term "cyber physical systems", bearing in mind Title, Abstract and Keywords (Subject Terms). Subsequently, duplications and non-English speaking publications have been removed. In a second step, the abstract of each paper was examined in order to eliminate such papers not directly related to the scope of research. Furthermore, the complete text of each article was reviewed excluding further irrelevances. This step was necessary to avoid uncertainty about the relevance of borderline publications. Nevertheless, if any uncertainty remained after the sampling process, the paper in question stayed included. Finally, 92 papers have been identified. Within the investigation of the initial literature sample, sharper focus was placed on in total 38 papers carrying out a specific definition of what CPS actually are. In order to gain insights into the several specific components of the different CPS definitions, a matrix analysis following SALIPANTE ET AL.'s approach – in the adaption of WEBSTER AND WATSON – was conducted (Salipante et al. 1982; Webster and Watson 2002). This procedure results in the compilation of a concept matrix, consisting of two different dimensions. The first dimension identifies the relevant papers containing findings and the second one displays the findings themselves. In this particular case, the main objective of that procedure was the identification of core attributes for CPS and the subsequent aggregation towards a generic CPS definition from the given sample of studies. This practice follows the idea of developing a logical approach for identifying and grouping the key concepts to be uncovered (Salipante et al. 1982; Webster and Watson 2002). In order to avoid biases concerning the compilation of the concept matrix, a team of always at least two independently operating researchers discussed the results. If there were any inconsistences coming up, the certain aspect had to be set under further review until a consensus was achieved (Ngai et al. 2008).

In a further step, the generic definition was used as input for a series of workshop-based focus groups (Hevner and Chatterjee 2010; Stewart and Shamdasani 2015), taking place during the second half of 2014. These focus groups had the task of identifying and describing potential fields of CPS application and benefits to be expected within SCM. For each single group, employees of one company from a specific segment of the German metal and electrical industry were brought together in a one-day workshop. The number of participants per workshop varied between seven and ten. Within each workshop, participating employees represented the whole life cycle of the respective company's main product and had backgrounds in product design, production management, logistics, SCM, as well as service operations. This selection procedure constitutes a multiple-informant approach by integrating the perspective of different actors and by thereby providing a more complete picture of the particular focus groups (Kaufmann and Saw 2014), which in turn significantly increases reliability and validity of the results (Wagner et al. 2010).

Each workshop began with a short, target-oriented presentation on relevant aspects concerning CPS in order to create a common vision and to enable discussion. In a second step, the generic definition was presented, discussed and used as a mental framework for the creative identification of potential CPS applications within the company and the corresponding supply chain using the 6-3-5 brainwriting method (Holt 1996). Application ideas were clustered during the discussion using "Metaplan"-techniques (Habershon 1993). After a short wrap-up, the participants had the opportunity to prioritize the different clusters individually with special emphasis on the relevance of the application for their company. In this respect, technical feasibility and expected benefits were used as prioritization criteria. The workshop participants were asked to mentally assess the different applications in relation to each other and to indicate the most important ones. The individual assessments were subsequently consolidated by accumulating the individual indications and an overall ranking was deducted. A previously prepared template was used in a next step to describe specific problem solutions derived from the fields of application with the highest score on an increased level of detail. The template included the name of the application, a clear description of the problem addressed, a list of benefits to be expected and a description of the solution from a more technical perspective. In a last post-processing step, generated results were aggregated and merged together with regard to the scope of investigation. During this step, based on central learnings derived from the discussions with the workshop participants, a set of questions for future research, predominantly relevant from a practice-oriented perspective, was furthermore identified.

3 Defining Cyber-Physical Systems

During the analysis of relevant literature, primarily functional aspects have been taken into consideration. During the research process, characteristic attributes found within the definitions provided by the scientific literature were collected and subsequently assigned to seven different functional clusters. In a third step, a general description of these functions was deducted from the various definitions on hand. *Table 1* shows the results of this approach, with the first column naming the seven functions of CPS and the second one providing a description of their characteristics.

In order to elaborate the relative importance of the different functions, a modified matrix analysis has been conducted *(Appendix 1)*. It describes in detail which functions are indicated how often within the 38 CPS definitions obtained from scientific literature. There is a large consensus in the observed literature, that *automation and decentralized control* is the central functional capability of a CPS. Furthermore, *information and data processing* as well as *integration* and *networking functions* can be regarded as indispensable and essential conditions in this context, regardless whether they are referred to in a formal definition or not. Thus, a first set of core functions for a CPS has been identified. Apart from that, a closer look at the scientific publications emphasizing automation and control shows, that a high quantity of these articles also addresses *sensors* as an important functional capability. Therefore, sensing capabilities extend the first set of core functions. As far as *actuators* are concerned, the literature on hand differentiates between machine-centric (tool machines, robots, etc.) and process-centric (production, assembly, logistics, etc.)

applications. In the first case, actuators are mandatory, in the second they are not absolutely necessary. Therefore, the integration of actuators can be regarded as a rather optional element of CPS. Finally, *adaptability* receives a somewhat limited attention within the observed literature, but related articles can be found in ascending quantity towards the end of the observation period. With that in mind, it appears to be an emerging issue and should be regarded at least as an optional element.

Function	**Description of characteristic attributes**
Integration	CPS integrate components of the physical and the virtual world, both inside a company as well as in cross-company contexts. Basal at this juncture is the precise and automated identification of physical objects.
Sensors	CPS are capable of an enclosing monitoring of the physical reality by the use of sensors, e.g. for temperature, pressure, location, etc.
Data processing	CPS own the technical preconditions of processing data. In so doing, Microcontrollers and Microprocessors are essential elements of such systems.
Automation and control	CPS partially operate based on their own intelligence and are therefore capable of autonomous decision making beyond central instances or decision rules and of controlling processes and objects in the physical world.
Networks	CPS own the technical capabilities in order to communicate and coordinate themselves with other CPS, as well as with existing information systems and with human users and decision makers.
Actuators	CPS control physical entities via actuators as needed and do thereby affect processes in an active and physical manner. This capability is of particular importance within the context of robotics applications.
Adaptability	CPS are, dependent on the respective context, capable of responding intelligently to dynamic changes and of improving their abilities based on own experience and knowledge.

Table 1: Functions and characteristic attributes of CPS

Besides the elaborated core functions, several additional characteristics emerged during the literature analysis. Essential for almost every definition examined is the decentralized management and control of relevant processes through the *integration of microelectronic devices* into physical objects. At this point, the core functions mentioned above can be implemented as *combinations of hardware and software*. The fact, that software is becoming more and more important in relation to hardware, as it ensures a direct customer interface and access, and that the term software can be used synonymously with the term adaptability can be interpreted as a clear indication of the future importance of the hitherto potentially underestimated function adaptability. Apart from that, in connection with the use of actuators in machine-centric applications, the importance of *real-time capabilities* and *deterministic behavior* of CPS emerges as well. Furthermore, the term *Big Data* gained central relevance over the course of time (Akter and Fosso Wamba 2016). In a series of sensor-related CPS applications, large amounts of heterogeneous data are generated. Those datasets have to be evaluated and analyzed rapidly in order to generate value for the operator or user.

Pulling together the different functional aspects and additional characteristics of CPS, a generally applicable definition can be composed as follows: "Cyber-Physical Systems (CPS) are networked embedded systems integrated into physical objects that have the capability to process information and data and to interact with the environment. They monitor, automate and control processes of the physical world via sensors, microprocessors and, if needed, actuators. CPS integrate the obtained data into the virtual world of information and distinguish themselves by a deterministic behavior, a high level of adaptability and by mastering complex data structures."

4 Contributions to enhanced Supply Chain Management

During the focus-group workshops, industry experts were confronted with the elaborated CPS definition and asked to identify and describe potential fields of CPS application within their company's supply chain processes along the entire product life cycle as well as benefits to be expected thereof. The resulting findings are summarized in *Table 2*: The first column indicates the respective company at which the workshop was conducted, while the second one describes the associated supply chain context (industry, value creation stage, central product). Finally, the third column lists the potential fields of CPS application identified within the workshops as well as the related CPS itself. It also indicates the specific implementation priority (1: highest priority; 5: lowest priority) assigned by the workshop participants to the respective field of application.

	SC-context	Potential fields of application (CPS, priority)
Company 1	Energy sector, 2nd tier supplier, tap-changers for transformers	Energy efficient machinery (machines, 1); production logistics (tugger trains, 1); tracking of transport containers (containers, 1); monitoring of tool wear (tools, 2); customer order tracking (work stations, 2); predictive maintenance (machines, 2)
Company 2	Brown and white goods, OEM, TV sets	customer order tracking (workpiece carriers, 1); assembly processes (work stations, 2); energy efficient machinery (machines, 3); smart networked products (products, 3); predictive maintenance (machines, 3); tracking of transport containers (reusable transport items, sea containers, 4)
Company 3	Mechanical engineering, OEM, injection molding machines	Predictive maintenance (machines, 1); production logistics (fork lifts, 2); tool management (tools, 3); smart networked products (products, 3); networked work stations (machines, assembly stations 3); tracking of transport containers (reusable transportation items, 3)
Company 4	Automotive industry, 2nd tier supplier, cam chains	Energy efficient machinery (machines, 1); networked work stations (machines, assembly stations, manufacturing robots, 2); tracking of transport containers (reusable transport items, 2); tool management (machine tools, 3); predictive maintenance (machines, 4); infrastructure management (fixed assets, buildings, 5)
Company 5	Automotive industry, 1st tier supplier, gear boxes	networked machines (machines, 1); quality monitoring (machines, work stations, 2); predictive maintenance (machines, 2); customer order tracking (machines, work stations, 3); production logistics (transport trolleys, 4); smart networked products (gearboxes, 5); energy efficient machinery (machines, 5)
Company 6	Mechanical engineering, 1st tier supplier, casings	Predictive maintenance (machines, 1); energy efficient machinery (machines, 2); tracking of transport containers (reusable transport items, 3); customer order tracking (machines, work stations, 4); tool management (machine tools, 4)

Table 2: Workshop results with respect to fields of CPS application

In general, the identified fields of application are quite similar within the different supply chain contexts. Nevertheless, priorities assigned to the respective fields differ from each other. With regard to the prioritization criteria technical feasibility, participants assessed the innovation degree of the applications differently, as they had made different experiences with specific technologies and comparable applications and as the acceptance by employees was rated differently. As far as the expected benefits are concerned, assessment of the effects of an application on customer satisfaction, production costs, product quality and supply chain flexibility diverged as well. The willingness to implement a specific CPS application within a company therefore depends on several factors and framework conditions. There are furthermore certain barriers to overcome and “drivers” pushing the adoption process within a company can be observed. A second important finding is, that from a bird’s eye view, two different types of applications can be identified. The first one focuses on the optimization of the upstream process from the production of a supply part to the delivery of the final product to the end customer, leading to cost reduction and a more efficient supply chain. The second one concentrates on the product operation process at the point of use and on the potential feedback effects on design processes for supply parts and finished products, aiming at a higher turnover for a company. As a third finding, it can be stated that every field of application has to support the overall product life cycle in one way or another in order to find acceptance within a company.

In order to clarify and underline the contribution of CPS applications to enhanced SCM, *Table 3* covers the thereof resulting benefits to be expected and connects them with the strategic objectives of enhanced SCM. The latter are described in the following as well and can in broad parts be deducted from MARTIN CHRISTOPHER’S interpretation of SCM (Christopher 2011).

The objective *cost reduction* refers equally to process costs for economic processes, such as customer order processing or customer relationship and product lifecycle management, as well as to direct and indirect material costs. *Visibility* in turn includes transparency of physical flows (Francis 2008) on different object levels (Lumsden and Mirzabeiki 2008), as well as information sharing between companies (Schoenthaler 2003). The term *velocity* describes the time-period that is needed to fulfill the customer’s order. It can be increased by speeding up or by deleting activities within the SCM process (Christopher 2011). *Responsiveness* is defined as the capability of a supply chain to adapt to external disturbances or changes of customer demand (Christopher and Towill 2001). Finally, *value added* addresses additional customer value through new CPS-based services, which can be offered to the customer due to enriched capabilities of an enhanced physical product. Such services have the potential to increase the revenue of a company significantly as they affect value proposition, market segments, customer relationships, distribution channels, revenue streams, key activities, resources and partners, as well as cost structures.

Briefly summarized, they have the power to change the business model of an enterprise and to reinvent competition (Porter and Heppelmann 2014).

Expected benefits from CPS applications	**SCM objectives**
Reduced energy (machines) and infrastructure (buildings) costs; optimized logistics processes (production logistics, transportation, inventory management); optimized assembly and maintenance (containers, machines, tools) processes; efficient machine operations; reduced investments in production resources; reduced controlling costs (automated generation of KPIs); enhanced quality monitoring; reduced quality management costs	Cost reduction along the supply chain
Higher product quality; enhanced traceability (products, supply and assembly parts); enhanced product life cycle management; higher product integrity (real-time data on customer behavior)	Value added for the customer
Higher resource availability; faster production cycles; reduced frictional losses (search for parts, products, resources); reduced delay-times (machinery downtimes); faster product development cycles (real-time data on customer behavior)	Increased supply chain velocity
Increased process visibility (logistics, production, assembling, product usage); increased stock transparency; increased information quality (scrap rate, process parameters); increased transparency of customer demand	Enhanced supply chain visibility
Increased process flexibility (paperless operations); enhanced planning processes (real-time, higher granularity); reduced batch sizes; improved process integration and coordination (logistics, production,); simplified set-up and configuration processes	Enhanced supply chain responsiveness

Table 3: Relation between expected benefits and SCM objectives

The previous course of observation demonstrates, that the implementation of CPS within supply chain processes along the lifecycle of a company's products in its entirety contributes significantly to enhanced SCM, as it is defined beforehand. In addition to that, 14 specific problem solutions resulting from the post-processing and aggregation of the workshops conducted can be identified. Some of them have to be – wholly or in part – regarded as future scenarios at the present time, while others have already found practical application. *Table 4* gives a complete lineup of these problem solutions and furthermore visualizes their respective contribution to enhanced SCM: The first column simply contains a counting number. The second one indicates the focus of the application (machine-, process-, human-, product-centric), while the third one introduces the actual problem solution. The following five columns then show in detail which SCM objectives are supported by the benefits resulting from CPS applications within this context.

#	F	Problem solution	Benefits concerning				
			Cost reduction	Value added	Velocity	Visibility	Responsiveness
1	M	Enhancement of machinery uptime	x		(x)	(x)	
2	P	Process-coordination across machineries	x		x	x	x
3	M	Reduction of machinery and equipment power consumption	x				
4	M	Efficiency enhancement within tool management	x			x	
5	H	Simplification of informational processes at machines	x				
6	H	Enhancement of flexibility and efficiency within assembly processes	x		x	x	
7	H	Dissolving of information asymmetries within manual fine planning	x		x	x	
8	P	Resilient data base for planning and control	x			x	
9	P	Traceability and localization of internal transportation containers	x		x	x	
10	P	Enhancement of efficiency within internal transportation	x		x	x	
11	PR	Continuous quality control along production processes	x	x		x	x
12	P	Enhancement of efficiency within c-parts supply	x			x	x
13	P	Thorough transparency within inter-locational transportation	(x)	(x)		x	x
14	PR	Enhancement of product and service integrity	(x)	x	x	x	x

F: focus; M: machine-centric; P: process-centric; H: human-centric; PR: product-centric

x: positive effect; (x): potential or contingent effect; empty column: no or negligible effect

Table 4: CPS-based problem solutions and their contribution to enhanced SCM

Every problem solution contributes to one or more of the benefits identified in the course of this paper. As far as cost reduction is concerned, all of them do contribute to some extent. With respect to the different types of applications, not only *machine-* and *process-*, but also *human-* and *product-centric* solutions can be determined. The main focus of the first group (machine-centric) is predominantly on cost reduction, while the second group (process-centric) contributes especially to higher velocity, visibility and responsiveness. The third group (human-centric) again mainly focusses on increased velocity and enhanced visibility within internal supply chains. Finally, the fourth group (product-centric), "outperforms" the other groups by enabling not only cost-reduction, velocity, visibility and responsiveness improvements, but by also providing value added services to the customer.

During the focus group workshops, it became obvious that the implementation and utilization of CPS in general is accompanied not only by the concept of the *Internet of Things (IoT)*, which it helps to realize by transforming simple physical objects into their "smart" counterparts (Fleisch 2010; Mazhelis et al. 2012; Sanchez Lopez et al. 2012), but also by other complementary innovations like *Cloud Computing*, *Mobile Computing*, *Big Data Analytics* and *Digital Social Networks*. From a technology and innovation management perspective, the implementation of CPS has to be understood as an in-principle innovation leading, in the first instance, to significant changes in the information systems of the enterprise and thus also to increasing implementation costs (Klötzer and Pflaum, 2015). These implementation costs have to be taken into account in feasibility studies as they might relativize the contributions identified within *Table 4* up to a certain degree. Another issue emerging from the workshops is the fact, that CPS are creating large amounts of data which can be turned into additional economic value for both, the manufacturer and the customer. In other words, the implementation of CPS within supply chain processes as well as the operation of CPS at the customer's site significantly drive the digital transformation of both, the enterprise and the supply chain (Berman 2012). These developments furthermore support the realization of a "data-driven enterprise" and of the "supply chain of the future" (Butner 2010; Christopher and Holweg, 2011).

5 Directions for future research

The elaborated definition of CPS, the compiled fields of application and the discussion of the consequential resulting problem solutions' contribution to strategic SCM objectives illustrate the fact of a strong connection between both, CPS and enhanced SCM. Todays' supply chains would therefore benefit significantly from the practical implementation of CPS. In order to realize such a vision of a "supply chain of the future", however, further developments and improvements with regard to the status quo are necessary. With respect to future research to be conducted in this respect, potential themes (from the author's perspective) refer to *decision-making*, *cost-benefit relations*, as well as to the *digital transformation* of companies and related supply chains. As a concluding result from the conducted workshops, *Table 5* summarizes the key learnings derived therefrom as well as consequential deducted research questions and thus serves the purpose of an accompanying research agenda giving outlines for future research on CPS within the scientific SCM community.

RT	Key learnings	Deducible research question
Decision making	One core function of CPS is the automation and decentralized control of processes. The control tasks addressed by applications differ from each other.	How can control tasks or decisions in supply chains be characterized and to what extent can they be automated and transferred from human resources to CPS?
	Due to sensing capabilities, CPS create large amounts of heterogeneous data and improve the process mapping quality within supply chains.	How does the higher availability and granularity of process information influence the decision behavior of supply chain managers?
Cost-benefits relations	In general, identified CPS applications are quite similar. However, the respectively assigned priorities differ.	What are the determining factors that lead to different priorities and application roadmaps in different industries and value creation stages?
	From a qualitative point of view, CPS contribute to cost reduction, value added, velocity, visibility and responsiveness within supply chains.	How can the contribution of CPS applications to different SCM objectives be measured and quantified in order to support economic feasibility studies?
	CPS-based applications have to be understood as in-principle innovations leading to a comprehensive change in the enterprise and the supply chain.	Which cost factors accompanying CPS utilization in the enterprise and in the supply chain have to be taken into account in order to support economic feasibility studies?

RT	Key learnings	Deducible research question
Digital transformation	CPS enable data-driven services and lead to a new understanding of values, with not only the physical product but also data carrying value.	What are the consequences of the change in understanding values for SCM from a theoretical and a practical point of view?
	The successful implementation of CPS in companies and supply chains depends on different preconditions, barriers and drivers.	Which are these preconditions, barriers and drivers for CPS implementation and how important are those in different industries and supply chains?
	Turning products into CPS has the potential to transform a company's business model and competition between companies and supply chains.	How do the potential effects on companies' roles and on supply chain configuration differ from each other within different industries?
	CPS applications are nothing else but building bricks for the digital transformation of companies and, with a broader scope, of supply chains.	Which models, procedures, methods and tools can be applied to transform todays' companies and supply chains into their digital counterparts?

RT: Research theme

Table 5: Research agenda regarding CPS implementation within SCM

Following the impressions of the conducted workshops, future research should therefore emphasize on the differences between industries and value creation stages, as far as the state of play and application roadmaps are concerned. Due to the in-principle character of CPS implementation within supply chains, comprehensive costs-benefit-models allowing to carry out economic feasibility studies for the different applications become necessary. Another promising subject is the detailed analysis of decision-making within the "supply chain of the future". Due to their functional profile, CPS have the capability of autonomous decision making without consulting a human or of creating data and information, that might change the decision behavior of human operators. Apart from that, CPS utilization drives digital transformation. It can be observed, that data is recently understood as a value carrier in supply chains, that data-driven services are becoming more and more important for the customer and that CPS implementation not only changes business models, but also competition and supply chain configuration in general. At this point, further research on these changes becomes necessary. Qualitative as well as quantitative research is required in order to completely understand the effects of CPS implementation on companies and their supply chains. Furthermore, scientific research on the "data-driven enterprise" might also lead to new theoretical perspectives. Finally, the CPS implementation should be regarded as an interdisciplinary issue. Researchers from economic and social sciences, psychology and information systems research therefore need to cooperate intensively in order to solve the most relevant problems.

6 Conclusion

During the course of investigations on which this paper is based, a more detailed understanding of the CPS term, based on a broad concept-centric literature review, was developed, advanced and refined all the way to a generic, generally applicable and consistent definition of the terminology. The conducted modified matrix analysis in this course furthermore led to the elaboration of core functions and characteristic attributes of CPS. Both aspects are addressed within section 3 of this paper and answer RQ1 to a satisfactory extent. By means of an ensuing series of focus group workshops, conducted with companies from different segments of the German metal and electrical industry, different fields of application for CPS within supply chain processes along the lifecycle of a company's products as well as potential thereof resulting benefits have been identified in order to answer RQ2. As an additional outcome from the post-processing and aggregation of these workshops, a total of 14 specific problem solutions has been identified. With respect to these CPS-based solutions, a more detailed classification into machine-, process-, human- and product-centric applications can be made. Their evaluation furthermore demonstrates, how CPS utilization contributes to cost reduction, additional customer value, velocity, visibility, as well as responsiveness within supply chains and as a consequence to enhanced SCM. Thereby, RQ 3 has been answered to full extent. Since RQ2 and RQ3 are closely related and interlinked with each other, they were treated coherently within the fourth section of this paper. Within the subsequent fifth section, an outline for future research to be conducted with respect to the realization of the "supply chain of the future" was compiled. This identification of further developments and necessary improvements with regard to the status quo, in the sense of an accompanying research agenda, is targeted to help the scientific SCM community "catch up" with the needs of economic practice and thereby answers RQ4. Generally recapitulated and condensed, identified research questions refer to decision-making, cost-benefit relations, as well as to the digital transformation of companies and related supply chains.

The presented generic CPS definition and the identification of relevant research questions concerning the future implementation of CPS within industrial supply chains are predominantly of particular value for the scientific SCM community. Nevertheless, practical implications can be identified as well. The revealed positive link between CPS utilization and objectives of enhanced SCM might not only trigger a broader scientific discussion on the topic but also a proceeding cognitive process in the minds of managers concerning the value of CPS for the digital transformation of supply chains. Additionally, decision makers can use the set of problem solutions specified within this paper as a starting point for generating their own CPS application roadmap. With respect to research limitations, one constraint might be rooted in the primarily German perspective and the focus on the mechanical and electrical industry. Even though that conclusions drawn from the observation of one of the largest economies in the world with a variety of global market leaders, not least within the industry under observation, should provide at least a certain amount of international and cross-industrial applicability, further research needs to be expanded by especially these perspectives. The fields of application, as well as the potential benefits and most notably the specific problem solutions, identified and described during the focus group workshops, can moreover only be regarded as an initial "snapshot in time", explicitly without any claim to completeness. It can be stated, that a broad variation of additional scenarios is emerging consecutively, but the results achieved so far do nevertheless already illustrate the massive potential of the in-principle innovation CPS. Generally spoken, as CPS still have to be considered as an emerging technology, results have to be reviewed and revised with ongoing technological improvements, if necessary. With respect to a generic, generally applicable and consistent understanding of the CPS terminology, the focus on scientific literature, in terms of journal publications, might be questioned. It therefore potentially promises further insights to extend the underlying research framework towards other data sources, such as working papers, technical reports, or more practical-oriented literature in general. A last limitation might reside within the strong SCM perspective of the research on which this paper is based. Since the sustainable implementation of CPS along entire product lifecycles is an interdisciplinary task, results have to be combined with knowledge from other scientific disciplines and embedded into an overall context. Conclusively, future endeavors in CPS research should also target towards the further conceptual integration into the IoT and therefore as well within the scientific field of digitalization, understood as "the transformation of socio-technical structures that were previously mediated by non-digital artifacts or relationships into ones that are mediated by digitized artifacts and relationships." (Yoo et al. 2010, p. 6).

It can recapitulatory be registered, that this paper only scratches the surface of the potential for CPS-related research. Alongside with future research endeavors, scientific agendas, frameworks, application roadmaps and other aspects will be refined and adapted on a regular basis. With regard to the former, particular research questions will become more specific with completely new ones arising as well. This paper nevertheless already provides several relevant insights into a still comparatively new, emerging field of interest bearing the potential of significantly supporting the establishment of a prospective broad research stream and also of triggering a broader discussion on SCM related aspects of CPS. Even though the actual technical concept itself has meanwhile gained considerable momentum as a subordinated part of other – mainly practice-driven – discussions of broader subject areas, such as Industry 4.0 and the Industrial Internet (of Things), it nevertheless appears to be worthwhile to simultaneously pursue a consistent scientific approach towards this topic.

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7 References

**Indicates the paper is included within the literature review. However, only those publications from the review, carrying out a specific definition of CPS, are listed below. A full set of bibliographic details is available upon request.*

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8 Appendix

Author(s)	Integration	Sensors	Information and data processing	Automation and control	Networks	Actuators	Adaptability
Akella et al. (2010)	X		X				
Alcaide et al. (2013)	X		X				
Al-Hammouri (2012)	X	X	X	X	X	X	
Burmester et al. (2012)	X	X		X	X		
Chen et al. (2012b)	X		X				
Cheng et al. (2012)	X	X	X	X	X	X	
Coronel and Simó (2012)	X						
Crenshaw (2013)		X		X			
Denker et al. (2012)	X	X		X		X	
Du et al. (2012)	X	X	X	X	X		

Author(s)	Frazzon et al. (2013)	Garone et al. (2012)	Gelenbe and Wu (2012)	Gupta et al. (2011)	Haque and Aziz (2013)	Ivanov and Sokolov (2012)	Jianjun et al. (2013)	Lai et al. (2011)	Lee (2009)	Lei et al. (2013)
Integration	x			x	x	x	x	x	x	
Sensors		x	x	x	x					x
Information and data processing	x			x	x			x	x	
Automation and control	x	x	x	x	x	x				x
Networks	x		x		x				x	x
Actuators										x
Adaptability					x	x				

Author(s)	Sahingoz (2013)	Rovers and Kuper (2013)	Pasqualetti et al. (2013)	Parvin et al. (2013)	Park et al. (2013)	Mitchell and Chen (2013)	Meseguer (2012)	Magure-anu et al. (2013)	Lun and Cheng (2011)	Lien et al. (2012)
Integra-tion	X	X	X	X	X	X	X	X	X	
Sensors	X			X		X	X	X		X
Infor-mation and data processing	X	X	X	X	X			X		X
Automa-tion and control	X			X		X		X	X	X
Networks	X		X	X	X			X	X	X
Actuators	X					X	X	X		X
Adapta-bility										

Author(s)	Integration	Sensors	Information and data processing	Automation and control	Networks	Actuators	Adaptability
Sangiovanni et al. (2012)	×	×	×	×	×	×	
Schneider et al. (2013)	×	×	×	×	×		
Tang et al. (2013)	×	×	×	×	×		
Verl et al. (2012)	×	×	×	×		×	×
Wan et al. (2011)	×		×	×	×		
Wang et al. (2011)	×	×	×	×	×		
Zhang et al. (2013a)	×			×			
Zhang et al. (2013b)	×		×	×	×		

Appendix 1: Distribution of CPS functions over the literature sample