Guest editorial

Supply chain management and Industry 4.0: conducting research in the digital age

Introduction

In essence, Industry 4.0[1] enables an automated creation of goods and services as well as supply and delivery, which functions largely without human intervention. Industry 4.0 is happening now (Vogel-Heuser and Hess, 2016, Sprovieri, 2019) and describes the trend toward automation and data exchange in manufacturing technologies and processes which include among others cyber-physical systems (CPS), industrial Internet of Things (IIoT), cloud computing, cognitive computing and artificial intelligence (AI). Decision making is predominantly decentralized, and system elements (e.g. production plants or transport vehicles) make autonomous, targeted decisions. A digital manufacturing enterprise is not only interconnected, but also communicates, analyzes and uses information to further drive intelligent actions back into the physical world.

Industry 4.0 will change how supply chains are designed and operated, yet research on promises and impacts of Industry 4.0 on supply chain management (SCM) is still scarce (Holmström and Partanen, 2014; Hofmann and Rüsch, 2017). We refer to SCM in the new era of Industry 4.0 as "SCM 4.0." In SCM 4.0, the digital and autonomous linkages within and between companies become a focal point of SCM (Stölzle *et al.*, 2017). SCM 4.0 represents a new stage of development in SCM, in which the coordination of materials, information and financial flows in corporate networks is largely automated and permeated with digital technologies.

This Special Issue is thus dedicated to exploring the abundant research opportunities associated with SCM 4.0 and laying down a foundation for future research on this important emerging topic. The idea is to fill gaps in the existing supply chain theory and explore the areas that are likely to be impacted by the combination of knowledge, traditional and emerging technologies. SCM 4.0 will over time manifest substantially different from conventional SCM.

Industry 4.0 components and SCM 4.0 characteristics

Industry 4.0 typically is declared as consisting of the following components and effects (based on Vogel-Heuser and Hess, 2016):

- service orientation based on CPS and the internet of services;
- CPS and multi-agent systems making decentralized decisions;
- interoperability between machine and human and virtualization of all resources;
- ability to flexible adaptation to changing requirements (cross-disciplinary modularity);
- Big data algorithm and technologies provided in real-time (real-time capability);
- optimization of processes due to flexible automation;
- data integration cross disciplines and along the life cycle; and
- access to data securely stored in a cloud or distributed data storage (e.g. blockchain).

To date, scientific literature on supply chain digitalization has often focused on specific topics and technologies such as cloud computing, big data analytics or applications in selected industries (e.g. Ivanov and Sokolov, 2012; Jede and Teuteberg, 2015; Kache and Seuring, 2017;

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Papert and Pflaum, 2017; Vendrell-Herrero *et al.*, 2017). Supply chain digitalization is emphasized as "the new interconnected business system which extends from isolated, local, and single-company applications to supply chain wide systematic smart implementations" (Wu *et al.*, 2016, p. 396).

The diversity of terms in both gray and academic literature reveal that a consistent understanding and concept of supply chain digitalization appears to be missing, yet many of those definitions and descriptions share common themes. The following aspects are prominent to outline key characteristics of the supply chain 4.0 (Kersten *et al.*, 2017; Schmidt *et al.*, 2015; Wu *et al.*, 2016):

- Customer-centric: design, produce (lot size one) and sell individualized products via omni-channel approach by means of innovative manufacturing technologies such as additive manufacturing.
- Interconnected: customers, suppliers and partners (e.g. logistics service providers) communicate and collaborate real-time based on shared and standardized data via platforms in a network of companies.
- Automated: increase efficiency based on flexible automation of physical processes via robotics.
- Transparent: GPS and CPS enable increased visibility into the diverse aspects of the supply chain (e.g. bottlenecks, delays) as well as traceability of products (e.g. location of materials, proof of provenance).
- Proactive: decision makers react anticipatorily to changing conditions and unexpected events based on real-time data analytics, machine learning and AI.

As supply chains are increasingly digitalized by adopting the Industry 4.0 approach, they increasingly will evolve to supply chain ecosystems (Ketchen *et al.*, 2014), where a business ecosystem consists of a set of organizations that are interdependent, coordinate activities and share some common adaptive challenges. According to Pidun *et al.* (2019), a business ecosystem is a specific governance model that competes on a modular, customized, multilateral and coordinated basis. This governance model is characterized by a specific value proposition (the desired solution) and by a defined, albeit changing, group of actors with different roles (such as producer, supplier, orchestrator, complementor). A new role in such supply chain ecosystems will play the technology providers and intermediaries supplying any kind of Industry 4.0 solutions. Given this introduction to Industry 4.0, we will now proceed to the contributions of the papers included in this special issue.

Summary of articles

Toward a digitally dominant paradigm for the twenty-first century supply chain scholarship

Stank *et al.* (2019) conceptually suggest that middle-range theorizing (MRT) is an appropriate means to explore the ways in which researchers can explain supply chain phenomena in the age of digitalization, and they introduce a theoretically grounded digitally dominant paradigm (DDP) framework to help guide future SCM research. They argue that "seeing" (enhanced visibility), "thinking" (improved analytics) and "acting" (heightened operational flexibility and reduced cycle time) are core components of supply chain digitalization. This paper intends to put existing supply chain practices and concepts on to a "stress test" and checking their sustainability and required alterations in the changed context of digitalization. Stank *et al.* explicitly intend a contribution to advancing scholarly discourse and transforming (digital) SCM "[…] from a description-based research discipline to one grounded in functional theories." We may expect a plethora of new themes and challenging questions by entering the proposed context of a DDP.

Emerging procurement technology: data analytics and cognitive analytic

Handfield *et al.* (2019) employ a qualitative approach that relies on three sources of information (executive interviews, a review of current and emerging technology platforms and a small survey of chief procurement officers) to elucidate the emerging landscape of procurement analytics. This study provides specific insights into the impact of cognitive analytics and big data on procurement. Although they found that the procurement analytics landscape will continue to develop, their study revealed that there currently exist a low usage of advanced procurement analytics, and data integrity and quality issues are preventing significant advances in analytics. They suggest that it is imperative for companies to establish a coherent, systematic approach to collection and storage of trusted organizational data that builds on internal sources of spend analysis and contract databases and that current ad hoc approaches to capturing unstructured data must be replaced by a systematic data governance strategy. The study also noted the issue of complexity caused by a proliferation of available platforms that could not be all integrated. Combined with a discussion about metrics, this opens avenues for new interesting research questions on the cost and complexity of increased data availability and the resulting need for analytics.

Real-time data processing in SCM: revealing the uncertainty dilemma

Lechler *et al.* (2019) discuss the challenges of gathering relevant, timely and accurate data under volatile, uncertain, complex and ambiguous (VUCA) conditions and use a delphi study approach to investigate whether real-time data processing reduces SCM uncertainties under real-world conditions. The concept that is framed as "uncertainty dilemma" is worth noting for researchers and practitioners: on the one hand, having more real-time data may be indeed a profound means to reduce supply chain uncertainty, but on the other hand such data may also imply new uncertainties, called data-related uncertainty. Basically, this is a revival of earlier thoughts of Russell Ackoff (1967), who suggested that information systems may also become misinformation systems. Findings on real-time systems which might simulate a false security or lacking capabilities, or talents to analyze and use the information provided in real time may raise interesting issues in contrast to the typical "better world of more data" view. Organizations retain imperfect decision-making systems which are handling "messes." This dilemma calls for a more intense discussion and definition of "data uncertainty" and "data quality" that may go beyond "relevance, timeliness and accuracy." It might contain questions of "correctness" or also cost of uncertainty vs value of certainty.

Stock visibility for retail using an RFID robot

Morenza-Cinos *et al.* (2019) follow the design science methodology and use a novel algorithm to prove that an autonomous robot can perform stock-taking using RFID for item level identification much more accurately and efficiently than the traditional method of using human operators with RFID handheld readers. In their technology-centric approach, the authors present an interesting combination of robotics and RFID in pursuing "high resolution visibility," in this case for stock on the retail floor. While addressing the challenges related to data uncertainty and quality, this paper also provides interesting hints for further research in relation to the interface between humans and robots. The authors identified some unexplored potentials for their robots due to the fact that the robots for inventory taking had to follow human assisted recognition procedures. While a fully autonomous solution could provide better results, research is certainly needed to address the potential conflicts between an idealized technical and digital world and the social aspects of the human world.

Suggested research opportunities on SCM 4.0

Research opportunities suggested in the papers of this Special Issue are summarized and depicted in Table I.

Although the list of research suggestions in Table I is far from being an exhaustive or even comprehensive research agenda for SCM 4.0, these mentioned research ideas do cover a range of important topics in the key aspects of SCM 4.0: customer-centric, interconnected, automated, transparent and proactive. More importantly, specific research directions provided by the articles in this Special Issue center on several key areas that warrant SCM researchers' particular attention, and we offer some discussion below.

In the area of machine learning (an application of AI) in supply chain processes, the focus is on prediction rather than explanation based on existing theories, as evidenced in that fields leading journals. Machine learning implies that a system or algorithm is learning without being explicitly programmed and in practice can detect patterns that enable prediction. Handfield *et al.* (2019) point out the need for supply chains to go from optimization toward prediction, and supply chain researchers should embrace the challenge. This is likely to mean a shift toward more inductive research methods in SCM. Focusing more on rigorous development and use of inductive methods, as pointed

Article authors	Suggestions for future research	Addressed characteristics of Industry 4.0
Stank *et al.* (2019)	Explore ways that digitalization will alter current supply chain models and frameworks Following the digitally dominant paradigm (DDP) to study how established concepts and relationships in SCM are impacted Guiding the use and appropriateness of inductive methods and design science approaches to establish new insights on supply chain concepts and theory	Customer-centric, interconnected, automated, transparent, proactive
Handfield *et al.* (2019)	Explore the role of analytics centers and how they could serve specific functional analytic needs (like in procurement) Investigate ways to balance the trade-off between increased supply chain transparency and information leaks to competitors Addressing the human-machine role division in supply chains, i.e., elaborate on who makes what decision and what competence do humans working with machine outputs need Research on the change in objective of decision support systems, from supply chain optimization toward prediction	Automated, transparent, proactive
Lechler *et al.* (2019)	Investigate the contingency variables when real-time systems do not influence supply chain uncertainty Explore and evaluate additional emerging aspects of real-time data-processing applications in SCM, as well as empirical justification in real-world contexts	Transparent, proactive
Morenza-Cinos *et al.* (2019)	Contrast the performance and value of different RFID robots in the supply chain Explore the performance and value of a fully autonomous solution to the human assisted recognition procedure in SCM Create operational guidelines for robot operations in the SCM context	Automated, proactive

Table I.
Summarized future research suggestions of the Special Issue papers

out by Stank *et al.* (2019), is likely to answer some of the recent calls for more managerial relevance of supply chain research.

Big data in supply chains still represents a big opportunity for future research (Richey *et al.*, 2016; Hofmann and Rutschmann, 2018). Researchers are advised to look in new places for data. Sanders *et al.* (2019) points to crowdsourced data as one of many potential novel data sources that supply chain researchers can access, though very few samples have been published to date (Sternberg and Lantz, 2018). Given the push for predictive methods, data accuracy becomes more important, as outlined by Lechler *et al.* (2019). It also accelerates the need for algorithms that can handle data sets not collected for the purpose of scientific analysis, e.g., containing missing data points and inaccuracies.

Automation in inter-organizational operations fosters the idea of self-steering supply chains. Cost pressure urges companies to make processes more efficient and unlock saving potentials. Whereas companies started to automate their (standardized) production processes during the 1970s (Kagermann, 2015), processes such as goods handling and delivery are still mainly done manually. Supply chain managers can either semi-automate these non-standardized processes by equipping employees with supportive technologies or completely automate processes with robotic solutions. Besides automated manufacturing and intra-logistics, external freight transportation and delivery is increasingly considered to be automated. Whereas the introduction of fully autonomously driving trucks is still facing technological and regulatory challenges (Flämig, 2016), automated solutions for last mile delivery (e.g. autonomous drones or delivery robots) are already tested in pilot projects, both underlining the need for future research efforts (Jennings and Figliozzi, 2019). The paper of Morenza-Cinos *et al.* (2019) is a good example for the automation of intra-logistics process via robots. In this regard, a critical part will be the design of the human–machine interaction (Gorecky *et al.*, 2014).

Several of the papers in this issue have touched on the human factor in the digital age, emphasizing the importance of empowering supply chain workers and/or managers and ensuring they have the right skills to work effectively with machines. For example, in their recent paper Klumpp and Zijm (2019) outline the risk of a potential artificial divide in the human workforce as an issue for social sustainability. A goal could be a human-centered automation that efficiently combines the sensorimotor and cognitive capabilities of humans with the benefits of robotic systems resulting in highly flexible automation solutions (Pinzone *et al.*, 2018).

As outlined by Stank *et al.* (2019), we do need a new set of tools to address the emerging DDP in supply chains. The quick development and the high number of issues on novel technologies in supply chain journals emphasize the need for supply chain scholars to stay up to date. Upcoming (special) issues on the theme of blockchain (Rao *et al.*, 2017), the technology management in a global context (Heim and Peng, 2019) or disruptive technologies with focus on reconciling humans and machines (Kumar *et al.*, 2019) will provide future research ideas on those technologies and their role in SCM.

Industry 4.0 and SCM theory development

The SCM field has been emphasizing the importance of theory-driven research for a long time. Applying appropriate theories not only helps us better understand and explain SCM phenomenon and elements, it also offers much needed theoretical lens to explore emerging SCM strategies and practices. Conducting research on SCM topics associated with Industry 4.0 can be challenging due to limited availability of information and data, but this makes theory application even more important because it provides necessary guidance and structure. The papers in this Special Issue make valuable theoretical contributions. Stank *et al.* (2019) used MRT to introduce a theoretically grounded DDP. Handfield *et al.* (2019) used theoretical constructs in their interviews with company executives and developed a framework to guide future research on procurement analytics. Lechler *et al.*'s (2019) delphi study specifically addresses an important theoretical SCM research gap: gathering relevant, timely and accurate data under VUCA conditions. While Morenza-Cinos *et al.* (2019) did not apply any specific theory in their rather technical study on using autonomous robots to perform RFID stock-taking tasks, their study does present a critical theoretical implication for future research – how to address the interface between an idealized technical and digital world and the social aspects of the human world.

In total 26 papers were submitted to the Special Issue, with topics such as: autonomous logistics business models, big data, cloud logistics, autonomous vehicles, blockchains (several papers), direct manufacturing, physical internet and traceability. As can be taken from the enumeration, topic relevance was not the reason why most papers did not get published (though some topics not mentioned above were clearly outside the scope), as most topics clearly relate to core components and implications of SCM 4.0. So why did the reviewers recommend against publication of such interesting themes?

Several manuscripts lacked a significant contribution to the field. Given the novelty of supply chain digitalization and SCM 4.0 and the speed of the technological development, there are several opportunities to make contributions, yet many papers failed to provide additional insights. Conceptually describing a new technology and what implications it hypothetically might have, based on marketing material from technology providers, is unlikely to represent a significant scientific contribution to the field and many papers lacked proper application of methodology and relevant data. Conceptual papers, not using empirical data, need to be very well written and present a new phenomenon or research direction. Stank *et al.* (2019) in this Special Issue represent a good sample of how to conceptually advance the field in a new direction. For papers using such a purely conceptual approach, a literature review needs to do more than just compile presented insights, it needs to contribute to the theoretical understanding of the phenomena reviewed and present a forward-looking research agenda.

Plenty of research look at the potential effects of novel technologies and concepts, but research is scarce on the mechanism of supply chain adoption (Pattersson *et al.*, 2003, Autry *et al.*, 2010). As previously outlined, several of the papers addressing novel technologies fail to incorporate the basic question: Will this novel technology actually be adopted or not (Venkatesh *et al.*, 2003)? Radical novel technologies do not come into existence by aggregating small changes in earlier technologies, they are the result of combinatorial evolution, i.e., evolution implies that inventions are the result of intentional combinations of existing technologies through a process that involves interplay between experience and knowledge – driven by need (Arthur, 2009). Holmström and Partanen (2014), for instance, have applied combinatorial technological evolution to examine digital transformation in supply chains.

Furthermore, the (inter-)organizational ambidexterity theory (Gibson and Birkinshaw, 2004) could serve as a theoretical lens. Ambidexterity allows organizations to simultaneously integrate and reconcile exploratory and exploitative activities in trade-off situations (Raisch and Birkinshaw, 2008). Accordingly, an ambidextrous SCM 4.0 approach would be able to simultaneously exploit current SCM capabilities and resources along the supply chain as well as explore new technological opportunities coming along with Industry 4.0 components and manage the tensions arising from pursuing both.

Regarding SCM4.0 and big data applications (like Lechler *et al.*, 2019; Sanders *et al.*, 2019), a further question arises: How to handle the huge amount of data in real-time circumstances in order the achieve transparency along the supply chain? An answer could deliver the (inter-organizational) information processing theory. Based on this theory, firms must organize and use information effectively, especially when they execute tasks that involve high levels of uncertainty (Galbraith, 1974). According to Galbraith, firms should either reduce their needs for information through "mechanistic" organizational means, or increase their information processing capacities. Regarding the latter, firms can increase its information processing capacity by investing in vertical information systems (Srinivasan and Swink, 2015). Vertical information systems enable organizations to process data efficiently and "intelligently," addressing some of the key characteristics of the supply chain 4.0 interconnected, transparent and proactive, as described above.

Toward an agenda of SCM 4.0 research

Clearly, Industry 4.0 represents a great shift in how supply chains are managed and call for SCM 4.0 research (Hofmann and Rüsch, 2017). In addition to several highly relevant and interesting venues for future research suggested by the included papers, plenty remains. Min *et al.* (2019) suggested four main directions for supply chain research: strategic nature of SCM, customer value creation as the whole purpose of SCM, supply chain orientation[2] as an essential facilitator and interorganizational collaboration at the center of SCM. Based on the papers in this issue and the current development and characteristics of SCM 4.0, we are suggesting a fifth category of human-centric supply chain. Our aim is to inspire scholars doing research in the field of SCM 4.0 by the suggested topics in Table II.

Category	Future research venue
Supply chain strategy	Explore how the digital transformation is forcing organizations to re-think their business models and roles within their supply chains (adopt vs transform) Investigate the relationship between supply chain strategy and adoption of novel technologies Examine whether the governance model "supply chain ecosystems" will prevail, and if so, which of the established actors will be disintermediated Investigate the effects of digitalization on the strategic objectives of supply chain management (network value)
Customer value creation	Elaborate how supply chain digitalization can lead to new business models based on novel combinations of existing technologies to meet current and future needs Explore digitally enabled circular business models, creating value and improving environmental sustainability Study how to proactively detect, translate and incorporate customer needs and wants into supply chain strategies and processes through emerging technology tools Examine the effects of data driven services on supply chain thinking and supply chain management activities
Supply chain orientation	Study how SCM will be positioned in the organization after a transformation toward SCM 4.0 Analyze the benefits and drawbacks of owning vs "renting" the technological infrastructure of the supply chain (license-and-install vs as-a-service) Study how some technologies can help to deal with some of today's prevalent supply chain challenges and become integral part of supply chain processes (niche vs integrated usage)
Inter-organizational collaboration	Study whether the current understanding of supply chain partnership still hold true in a digitalized SCM context Examine whether traditional power imbalance in supply chains can be addressed through SCM digital transformation Investigate how digital technologies facilitate (or hinder) the collaboration between supply chain partners while the interdependencies increase (limited vs expanded) Investigate whether supply chain actors should join an existing platform or to build up a one (join vs own) Whereas CPS, IIoT and blockchain-based smart contracts enable decentral decision making, investigate which SCM activities to centralize in order to achieve control (centralized vs decentralized) Explore how technical standards evolve in the supply chain (wait-and-see vs orchestrate)
Human-centric issues	Determine the role of human in digitalized SCM applications and practices Explore the degree SCM should shift power and decision-rights to machine learning and AI (prescriptive vs predictive) Analyze the potential overreliance on big data and machine learning insights that could stifle innovation and collaboration efforts in the supply chain Elaborate on the appropriate leadership practices during the digital transformation of the supply chain (transactional vs transformational) Investigate how SCM and related departments can fill the talent gap in analytical and digital capabilities (train vs hire)

Table II.
An agenda of future SCM 4.0 research

Finally, we would like to encourage SCM researchers to look outside the box not only in their quest for data and the exploration of new insights (following an inductive reasoning, Mantere and Ketokivi, 2013), but also to apply and elaborate on and extend theories (following an abductive reasoning, Dubois and Gadde, 2002) to make sense of new technologies in SCM rather than echoing PR departments of technology providers. Engaged scholarship is likely to provide SCM with deeper insights (Mathiassen, 2017). Given the many challenges society today is facing, we do well in following Kurt Lewin's advice: "If you want truly to understand something, try to change it."

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Notes

1. Industry 4.0 refers to the 4th industrial revolution and is translated from German. The term "Industrie 4.0" was first used in 2011 at the Hannover Fair (Vogel-Heuser and Hess, 2016). Several definitions of the concept exist.
2. Defined by Min *et al.* (2019, p. 45) as "the recognition by an organization of the systemic, strategic implications of the strategic and tactical activities involved in managing the various flows in supply chain".

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