publish-Ing.
Journal of Production Systems and Logistics
Volume 1 | Article 1
Published: July 2020

Influencing factors of the digital transformation on the supply chain complexity dimensions

Andreas Kluth[1], Martina Schiffer[1], Christian Fries[1,2], Jens König[2]

[1]*Fraunhofer Institute for Manufacturing Engineering and Automation IPA, 70569 Stuttgart, Germany*
[2]*Institute of Industrial Manufacturing and Management IFF, University of Stuttgart, 70569 Stuttgart, Germany*

Abstract

Digital Disruption - 'the world in which we live in is changing'! Next-day delivery, Click & Collect, personalization, short delivery times and full order transparency have been incorporated in our daily life. In order to stay competitive, companies must react to the shifting customer demand towards on-demand, fit-for-purpose services and other market requirements. Due to these challenges and the increasing globalization, companies are confronted with ever more complex supply chain networks. The way to deal with the strongly increasing complexity of the company itself and its environment has become a key competitive factor. The complexity within a production company is characterized by the challenges encountered in daily business processes and can be described by the four dimensions of complexity: variety, heterogeneity, dynamics and non- transparency, as well as their interrelationships. Therefore, Supply Chain Management (SCM) is evolving from simply managing a chain of suppliers and manufactures towards a complex network including complicated backflows.

New approaches in the context of digital transformation promise to support the management of such complex supply networks. Within this paper, influencing factors of the digital transformation and their effect on the four complexity dimensions are presented.

Keywords

Supply Chain Management; Advanced Complexity Management; Digital Transformation

1. Introduction

As part of the digital transformation, logistics and supply chain management are affected by major changes [1, 2]. Whether this is a disruption or “only” a rapid evolution, is a matter of opinion. Nevertheless, only those companies that will accept and use this digitization process to their advantage will remain competitive.

The traditional model of the manufacturing industry is outdated. Driven by an on-demand, fit-for-purpose service philosophy, the manufacturing industry has to deal with increasingly complex supply networks [1, 3, 4]. Managing the resulting complexity is therefore one of the biggest challenges of supply chain management [4–7]. The consumer goods industry is playing a pioneering role in using digitalization solutions to master complexity. Thus, the ordering process here is usually already completely digitized and the customer already knows before ordering when the product will arrive at his location of choice. However, this is still not the case for the manufacturing industry. For one thing, the technological advances of the past few years have been so rapid that technologies became suddenly affordable that were previously not. On the other hand, integrated networking requires that information and thus knowledge must be shared with potential competitors [1, 3].

This Paper has been reviewed by the Certified Reviewer Community of publish-Ing. – 2 reviews – single blind

In order for a company to remain competitive, it is important to reach every link in the value chain and create a supply network that is far more accessible, transparent and agile so that it can respond immediately and flexibly to changes and turbulences. The key competitive factors are: cost, time, quality and flexibility [8, 9] as well as a significantly increased level of data analysis options [10, 11].

Due to these challenges and the increasing globalization, companies are confronted with ever more complex supply chain networks [12]. Dealing with this strongly increasing complexity has become a key competitive factor. The complexity within a company is characterized by the challenges encountered in daily business processes and can be described by the four dimensions of complexity: variety, heterogeneity, dynamics and non-transparency, as well as their interrelationships [13–16]. New approaches in the context of digital transformation promise to support the management of complex supply networks. This paper therefore presents a top down approach for deriving influencing factors for the supply chain enabled by the digital transformation. In a first step, technologies enabling the digital transformation are presented and structured. In a second step, these technologies are applied on the supply chain processes and their potential impact on the respective processes is evaluated. In a last step, an evaluation model of complexity management systems is established from which the fields and dimensions of complexity are derived. This paper concludes with an evaluation of the digital influencing factors regarding their potential to influence the complexity dimensions.

2. Influencing Factors of the Digital Transformation

Megatrends such as mobility, urbanization, ecology and digitization cause increased environmental (external) complexity [17, 18]. These effects are reinforced by ever shorter product lifecycles and increasing product variance [19]. Besides increasing the complexity, digitization creates new possibilities for networking and cooperating between different actors and stakeholders within a supply network. Furthermore it enables complex analyses of machines, processes or performances [20, 21].

2.1 Digital Transformation

The raise of computers, sensors and robots facilitated industrial machines to operate independently from human interaction. One of the most important milestones within the process of the digital transformation is the invention of the programmable logic controller (PLC-Control) in 1969, were for the first time machines were controlled by computers. Since then, digital technologies dramatically reshaped industry after industry.

In recent years, companies across different industries and branches have started to further explore and implement digital solutions into their business processes in order to exploit their benefits [22, 23]. And even despite the barriers of complex company structures and long ROIs, digital solutions are forecasted to increase rapidly in the upcoming years [24]. Leveraging information will be a core competency for success, allowing companies to make faster, better, data-driven decisions, thus increasing productivity, value creation, and social welfare. Artificial Intelligence and Machine Learning, for example, can be used to improve service offerings and to generate revenue. In order to leverage the full potential firms are required to make major strategic commitments and to explore entirely new business models rather than implementing “traditional” hybrid-digital strategies.

2.2 Drivers and Enabling Technologies of the Digital Transformation

In order to better understand the digital transformation and its implications, the technologies enabling the digital transformation need to be evaluated. The enabling technologies can be structured using the four drivers of digital transformation according to [25]:

- **Digitalisation** is the digital access through the internet and communication systems.
- **Virtualisation** includes the collection, evaluation and representation of digital data.
- **Networking** describes the connection along the whole value chain through high bandwidth data telecommunication.
- **Autonomisation** is the resulting combination of established technologies and artificial intelligence. That driver delivers autonomous, self-organised systems.

These four drivers build up the development steps of the digital transformation and are connected to the enabling technologies. In the following section the enabling technologies are introduced and associated to the four drivers of the digital transformation. The focus is on the relationship between the enabling technologies and the above mentioned drivers.

Digitalisation:

The Enabling Technologies for the process of digitalisation are (see also [26–28])

- Service Oriented Architecture,
- High Performance Computing and
- Big Data.

Service Oriented Architecture describes a concept of being able to call up re-usable software components across a network. The technology connects different partners through integrated platform-, software-, infrastructure- and factory-architectures for the use of separated functionalities. The increase of data storage and computing power as part of the High Technology Computing describes an elementary requirement in the process of digitalisation. The Enabling Technology of the digitalisation for the capability of dealing with the rising amount of data is called Big Data.

Virtualisation:

The next step of the digital transformation is the process of virtualisation including the technologies of (see also [29–31])

- Machine Learning and
- Internet of Things.

As part of the virtualisation the use of Artificial Intelligence through Machine Learning methods is the key for a continuous and self-making learning process of the working machines and robotic systems in the production. The real-time capability and transparent data communication/networking of every component within the production and across the supply chain by the driver Internet of Things enables a business and operational intelligence.

Networking:

Regarding the networking possibilities within complex supply chains, influencing factors such as (see also [30])

- Cyber Physical Production Systems,
- Cloud Computing and
- Digital Shadow

have to be considered. The introduction of communicating and connecting workstations leads to the creation of decentralised self-organised Cyber Physical Production Systems. These systems take the leading role in the smart factory and realising the change from passive workstations and machines into active, communicating members of the production process using a self-making configuration called plug and produce. Cloud Computing is the on-demand availability of data storage, computing power or application software, for example through the internet, in an IT-infrastructure. This technology supports the integrated networking and the transparent data communication between every member of the supply chain for dealing with big data issues in real time. The development of software-based approaches for realising complex technical systems is part of the Cloud Engineering. The transformation of real processes into virtuality is always accompanied with the so called Digital Shadow. This enabling technology delivers copies of the different data along the supply chain for generating a real-time evaluation base.

Autonomisation:

The last step of the digital transformation, the autonomisation, is enabled by (see also [29])

- Real Time Network and
- Additive Manufacturing.

Real Time Network describes the standardisation of an immediate control of processes in such a way that the collected data are in an operational mode at any time. Additive Manufacturing, for example rapid Prototyping, is an autonomous manufacturing method based on digital 3D-construction data.

Using the four drivers of the digital transformation, the enabling technologies can be structured as follows in Figure 1. In the process of the digital transformation the drivers and the enabling technologies are placed on different layers. The enabling technologies are placed on the outer layer. The drivers in the inner layer are separated into the four steps of the digital transformation as they are described above.

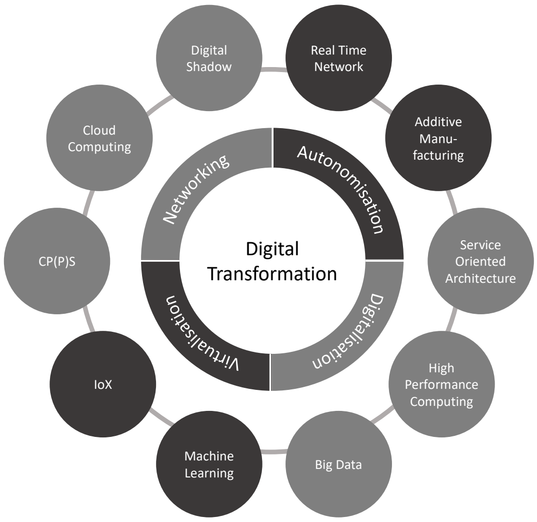

Figure 1: Drivers and Enabling Technologies for the Digital Transformation [own representation based on [25]]

3. Implications on the Supply Chain

Logistics and supply chain management will increasingly be affected by the changes of digital transformation. The extent of the changes on companies and the associated processes, products and business models is still relatively unclear. On the basis of the drivers and technologies already presented, the influence on supply chain management will be examined in the following section.

3.1 Supply Chain Management Components

Supply chain management considers the cross-company flow of materials, from the raw material to the finished product. In order to meet the increased demands of consumers, automated conveyor and storage systems were developed and information systems between individual players were implemented. The results are highly efficient, hierarchically organized value chains that provide goods worldwide just-in-time. The goal of the SCM is therefore a cost-efficient planning of the entire manufacturing and transport processes [32, 33].In the course of the digital transformation, the next development phase also begins for logistics. The previously rigid value chains are developing into increasingly complex and intelligent networks.

In order to make the influences of digital transformation on supply chain management assessable, a reference model for the description, evaluation and analysis of value chains is required. In this paper the assessment of supply chain processes across companies and sectors is based on the SCOR model. The Supply Chain Operations Reference-model (SCOR) is the product of the Supply-Chain Council (SCC). It provides a modeling language for designing supply chains and distinguishes between process elements and process types. Five process elements describe the supply chain from the local perspective of a manufacturer to its customers and suppliers (Figure 2):

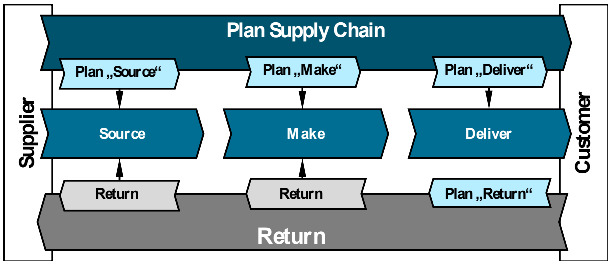

Figure 2: SCOR-Model (own representation based on [6])

The process ‘**Plan**’ describes the activities associated with developing plans for the operation of the supply chain. The planning process involves capturing requirements, collecting information about available resources, balancing requirements and resources to identify planned capabilities and gaps in demand or resources, and identifying actions to correct these limits. The process ‘**Source**’ describes the ordering and receipt if goods. It includes placing orders or planning deliveries, receiving, validating and storing goods and accepting the invoice from the supplier. The '**Make**’ processes describe the activities associated with adding value to materials or creating content for a service. The transformation of materials is more commonly used as 'production' because 'make' represents all types of material transformation, e.g. assembly, chemical processing. The ‘**Deliver**’ processes describe the activities associated with the creation, maintenance and fulfillment of customer orders. The process embodies the receipt, validation and creation of customer orders, scheduling order delivery pick, packaging and shipment and invoicing the customer. The process ‘**Return**’ describes the reverse flow of goods. It’s embodies the identification of the need to return, the disposition decision making, the scheduling of the return and the shipment and receipt of the returned goods.

Building on these five core elements, sub-elements were created within the framework of the SCOR model. For each level 1 process there are 3 or more differentiating level 2 process categories. Each level 2 process contains level 3 process elements. These hierarchical relationships provide a classification of the processes.

3.2 Impact of Enabling Technologies

In the following, the process-elements are matched with the enabling technologies. The influences on the respective supply chain processes are qualitatively evaluated with the help of experts from research and industry. The basis of the evaluation are the target dimensions of production according to ERLACH [34]. It is assumed that the efficiency of a production is basically determined by four mutually independent target dimensions. This statement can be applied to supply chain management. The four target dimensions are variability, speed, economic efficiency and quality. On a general level, these four dimensions span the broadly applicable target system of supply chain management [34].

Table 1: Impact of enabling technologies on SC processes

	Subelement SOCR	Digitalisation			Virtualisation		Networking			Autonomisation	
		SoA	HPC	BD	ML	IoX	CP(P)S	CC	DS	RTN	AM
Plan	Identfiy, Prioritize and Aggregate SC Requirements	x	x	x	x	x		x	x	x	
	Identfiy, Prioritize and Aggregate SC Resources	x	x	x	x	x		x	x	x	
	Balance SC Resources and Requirements			x	x	x		x	x		
	Establish SC Plans	x		x	x	x		x	x	x	
Source	Schedule Product Deliveries	x		x	x	x		x	x	x	
	Receive Product					x	x		x	x	
	Verify Product	x		x	x	x	x	x	x		
	Transfer Product					x	x		x	x	
	Authorize Supplier Payment	x	x	x		x		x	x	x	
Make	Schedule Production Activities	x		x	x	x		x	x	x	
	Issue Material			x		x	x	x	x	x	
	Produce and Test	x		x		x	x	x	x	x	x
	Package	x		x		x	x	x	x	x	
	Stage Product	x		x		x	x	x	x	x	
	Release Product to Deliver	x				x	x		x	x	
Deliver	Process Inquiry and Quote	x		x	x	x		x	x	x	
	Receive, Configure, Enter and Validate Order	x		x	x	x	x	x	x	x	
	Reserve Inventory and Determine Delivery Date	x		x	x	x		x	x	x	
	Consolidate Orders	x		x		x		x	x	x	
	Build Loads	x		x	x	x	x	x	x	x	
	Route Shipments	x	x	x	x	x		x	x	x	
	Select Carriers and Rate Shipments	x	x	x	x	x		x	x	x	
	Receive Product from Source or Make	x		x		x	x	x	x	x	
	Pick and Pack Product					x	x		x	x	
	Load and Ship Product	x				x	x		x	x	
	Receive and verify Product by Customer			x		x	x	x	x	x	
	Install Product and Invoice	x				x	x		x	x	
Return	Identify Product Conditions	x	x	x	x	x	x	x	x	x	
	Disposition Product	x	x	x	x	x		x	x	x	
	Request Product Return Authorization			x	x	x		x	x	x	
	Schedule Product Shipment	x	x	x	x	x		x	x	x	
	Return Product	x				x	x		x	x	

Artificial intelligence technologies include machine learning, deep learning and predictive analytics. Machine learning algorithms are able to quickly analyse large, diverse data sets to improve the accuracy of demand forecasting or to detect anomalies in manufacturing accuracy. Reducing freight costs and improving delivery performance are advantages of machine learning in collaborative supply chain networks. Large amounts of data are required to utilize artificial intelligence. Big Data applications enable, among other things, a better exploitation of synergies and at the same time an increase of the planning information basis. It is also possible to avoid empty runs and dynamically optimize routes in real time, for example by taking into account the current traffic situation, the current cost structures prevailing on the market or changed delivery sequences. Service oriented Architecture has a further positive influence on the supply chain. Producer can use one of several strategies to aggregate customers' orders before it processes them and to accumulate suppliers' quotes before it decides on a particular supplier. The use of a Service Oriented Architecture can substantially improve the efficiency of a supply chain [35].

As it has been presented, different drivers have a potential influence on the Supply Chain Management of a single company and its value network. Supply Chain Management can be seen as a certain part or field of the company`s structure. SCM can be seen as a single element of the overall system "company". So in order to derive possible effects of the mentioned drivers on the element SCM, the Supply Chain Management as a specific field has to be elaborated in a further way. Elements in an overall system have their own complexity and behaviour, so it can be stated that also a supply chain has its own complexity and the influences of the digital drivers have effects on this complexity.

4. Advanced Complexity Management in Supply Chains

4.1 Complexity Management Model

At the Fraunhofer-Institute for Manufacturing Engineering and Automation IPA a new approach for dealing with complexity in production systems was developed in the recent years. In this overall context, advanced Complexity Management is the target-oriented and value-added utilization of available resources in order to harmonize internal and external complexity, using appropriate manipulating, coping or pricing strategies. Thus, it leads to the right level of complexity in order to be successful on the market and react optimally to external complexity [15]. The main principles of this approach are (1) to divide complexity in external and internal. Furthermore, (2) complexity can be spanned into the four complexity dimensions: *variety, heterogeneity, dynamics and non-transparency*[16].

When dealing with complex problems and situations, and before developing specific strategies, it is important to distinguish between several terms, which are often used in the same content, although they have different meanings and definitions. In this case the terms complicacy and complexity are often used in the same way [36]. Complicated issues or systems can be described and controlled using causal interrelationships between the corresponding system's objects. Contrary to that, complex issues and systems cannot be predicted or controlled in such a context, because such problems also include non-causal, but surprising interrelationships. The main difference between complicacy and complexity, according to the advanced Complexity Management Model, is the characterization by so called complexity dimensions. Complicated issues are described just by the two dimensions variety and heterogeneity [37], whereas complex issues include also the dimensions dynamics and non-transparency [14]. That means, as soon as dynamic aspects or factors concerning non-transparency are involved, the problem/issue is related to complexity. Although there is no academic consensus about a consistent definition, within this paper it can be summarized, that complexity can be seen as the combination of a various and heterogenic system elements as well as their interrelationships that are changing dynamically and not clearly comprehensibly.

As mentioned above progressively increasing external complexity - describes the market perspective, which is characterized by so called changeability and flexibility drivers such as population growth and demographic change, increasing consumption of resources or digitalization - can only be met with an equivalent internal complexity. Therefore, complexity has to be adjusted within the supply chain to the required external complexity and cannot be concerned in isolation [15, 38]. In this context, internal complexity represent complexity inside a supply chain, external complexity describes complexity of the supply chain environment [39]. Internal complexity is ideal if it corresponds to the respective external complexity [40] with the right level. If internal complexity is low, external complexity cannot be met sufficiently and therefore the complexity management is not effective. If internal complexity is too high, unnecessary expenses incurred in the supply chain, so that the management of complexity is not efficient [14].

4.2 Supply Chain Complexity Dimensions

As mentioned before, internal complexity of a supply chain (company perspective) can be described in principle by the four dimensions of complexity: variety, heterogeneity, dynamics and non-transparency.

Variety describes the number of distinguishable states and configurations / distinguishable elements and relations of a system. The more elements that exist in a system, the greater its complexity. The same applies to the number of interrelations between the individual elements. In case of supply chain this could be the number of stakeholder/actors (such as suppliers, manufacturers or customers) as well as for example the amount of products, that have to be covered by the whole value network.

Heterogeneity describes the second quoted dimension of complexity, indicating, on the one hand, the differences between the individual elements and, on the other, describing the proportion of opposing relationships / relations between the elements [41]. Similar to the variety, heterogeneity in supply chains can be related to the difference of products and suppliers, but also variable possibilities of transportation ways within the value network.

Dynamics describes the changeability over time as well as possible turbulence effects of the system. Accordingly, additional complexity arises when the framework conditions, influencing factors, system elements and their relations frequently change or their characteristics fluctuate greatly [41]. Within a supply chain dynamic can occur due to fluctuations in customer demands, or changing supplier requirements etc.

Non-transparency is characterized by the knowledge about the system and its interdependencies in terms of lack of definitions or fuzziness. The less a company knows about the elements and its interactions within a system (supply chain), the higher is the non-transparency and thus increases the complexity [42].

In general, it can be stated that higher degrees of each single dimension lead to an increasing complexity of the overall system.

By using these dimensions, the impact/influence of the described SC processes, and therefore also of the enabling technologies on the supply chain complexity can be elaborated (such as an example is shown in Figure 3).

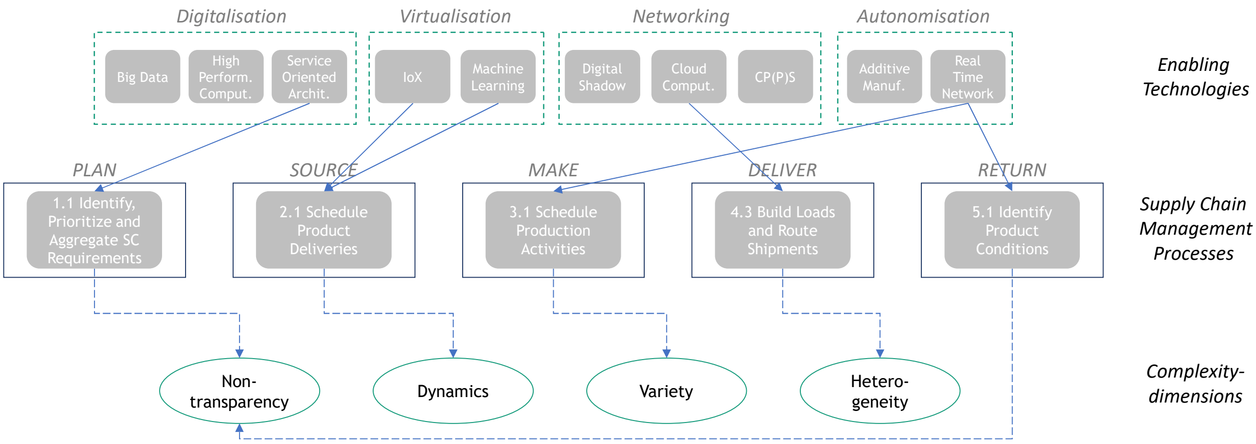

Figure 3: Exemplary influences of selected enabling technologies on SC complexity dimensions

As described in Table 6, “Service Oriented Architecture” has an impact on the SC process “Identify, Prioritize and Aggregate SC Requirements”. Concerning the complexity dimensions, it can be stated that this process has an effect on the non-transparency of the supply chain, because if you cannot identify, specify and communicate such SC requirements, the complexity arises. Another example is the impact of “Cloud Computing” on the SC process “Build Loads and Route Shipments”, which has an effect on calculating and analysing the heterogeneity of all possible transportation routes within the overall supply chain.

5. Conclusion

Within this paper a first approach is shown, how to connect the three separated topics “digitalization”, “supply chain management” as well as “complexity management” and how to identify possible interlinkages between these scientific fields. The basic question was: “Do digital drivers have influence on supply chain management and can it be interpreted in terms of complexity issues?”. As presented in this paper, specific enabling technologies from the so called Digital Transformation can be clustered using the drivers:

digitalisation, virtualisation, networking and autonomisation. Further it can be stated that these enabling technologies can have a certain impact on the activities and processes within a supply chain network. In many cases one single enabling technology can influence more than just one SC process. An approach for describing complex systems like supply chains using so called complexity dimensions (variety, heterogeneity, dynamics and non-transparency) was presented. Each of the described SC processes refers to one or more of these complexity dimensions. That means each process has a specific effect on the single dimensions, and thus on the SC complexity in general. So by using the presented influence of the enabling technologies on the SC processes, and further the mentioned impact of each SC process on the complexity dimensions, a specific connection between the enabling technologies and the complexity dimensions of a supply chain can be elaborated.

References

[1] C. Engelhardt-Nowitzki, O. Nowitzki, and H. Zsifkovits, Eds., Supply Chain Network Management. Wiesbaden: Gabler, 2010.

[2] S. Berman and A. Marshall, "The next digital transformation: from an individual-centered to an everyone-to-everyone economy," Strategy & Leadership, vol. 42, no. 5, pp. 9–17, 2014, doi: 10.1108/SL-07-2014-0048.

[3] A. Busch and W. Dangelmaier, Integriertes Supply Chain Management. Wiesbaden: Gabler Verlag, 2004.

[4] C. Bode and S. M. Wagner, "Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions," Journal of Operations Management, vol. 36, no. 1, pp. 215–228, 2015, doi: 10.1016/j.jom.2014.12.004.

[5] S. Chopra and M. S. Sodhi, "Managing risk to avoid supply-chain breakdown," MIT Sloan Management Review, vol. 46, pp. 53–61, 2004.

[6] C. W. Craighead, J. Blackhurst, M. J. Rungtusanatham, and R. B. Handfield, "The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities," vol. 38, no. 1, pp. 131–156, 2007, doi: 10.1111/j.1540-5915.2007.00151.x.

[7] P. Trkman and K. McCormack, "Supply chain risk in turbulent environments—A conceptual model for managing supply chain network risk," International Journal of Production Economics, vol. 119, no. 2, pp. 247–258, 2009, doi: 10.1016/j.ijpe.2009.03.002.

[8] H. Werner, Supply Chain Management. Wiesbaden: Springer Fachmedien Wiesbaden, 2017.

[9] H. Arndt, Supply Chain Management. Wiesbaden: Gabler, 2008.

[10] M. A. Waller and S. E. Fawcett, "Data Science, Predictive Analytics, and Big Data: A Revolution That Will Transform Supply Chain Design and Management," J Bus Logist, vol. 34, no. 2, pp. 77–84, 2013, doi: 10.1111/jbl.12010.

[11] S. Tiwari, H. M. Wee, and Y. Daryanto, "Big data analytics in supply chain management between 2010 and 2016: Insights to industries," Computers & Industrial Engineering, vol. 115, pp. 319–330, 2018, doi: 10.1016/j.cie.2017.11.017.

[12] C. Harland, R. Brenchley, and H. Walker, "Risk in supply networks," Journal of Purchasing and Supply Management, vol. 9, no. 2, pp. 51–62, 2003, doi: 10.1016/S1478-4092(03)00004-9.

[13] J. Jäger, A. Kluth, A. Schatz, and T. Bauernhansl, "Complexity Patterns in the Advanced Complexity Management of Value Networks," Procedia CIRP, vol. 17, pp. 645–650, 2014, doi: 10.1016/j.procir.2014.01.070.

[14] J. Jäger, A. Kluth, M. Sauer, and A. Schatz, "Advanced Complexity Management – The new management discipline in production and Supply Chain," ZWF Journal of economic Factory Operation, no. 108, pp. 341–343, 2013.

[15] A. Kluth, J. Jäger, A. Schatz, and T. Bauernhansl, “Evaluation of Complexity Management Systems – Systematical and Maturity-based Approach,” Procedia CIRP, vol. 17, pp. 224–229, 2014, doi: 10.1016/j.procir.2014.01.083.

[16] A. Kluth, J. Jäger, A. Schatz, and T. Bauernhansl, “Method for a Systematic Evaluation of Advanced Complexity Management Maturity,” Procedia CIRP, vol. 19, pp. 69–74, 2014, doi: 10.1016/j.procir.2014.05.041.

[17] M. Hoppe, A. Christ, A. Castro, M. Winter, and T.-M. Seppänen, “Transformation in transportation?,” Eur J Futures Res, vol. 2, no. 1, p. 1, 2014, doi: 10.1007/s40309-014-0045-6.

[18] V. Laval, “Impact of Recent Megatrends on the Controlling Role Model,” Procedia Economics and Finance, vol. 27, pp. 54–63, 2015, doi: 10.1016/S2212-5671(15)00971-5.

[19] S. Kara and B. Kayis, “Manufacturing flexibility and variability: an overview,” Jnl of Manu Tech Mnagmnt, vol. 15, no. 6, pp. 466–478, 2004, doi: 10.1108/17410380410547870.

[20] D. Schallmo and A. Rusnjak, “Roadmap zur Digitalen Transformation von Geschäftsmodellen,” in Digitale Transformation von Geschäftsmodellen, D. Schallmo, A. Rusnjak, J. Anzengruber, T. Werani, and M. Jünger, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2017, pp. 1–31.

[21] S. Hippmann, R. Klingner, and M. Leis, “Digitization – Areas of Application and Research Objectives,” in Digital Transformation, R. Neugebauer, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2019, pp. 9–17.

[22] C. Matt, T. Hess, and A. Benlian, “Digital Transformation Strategies,” Bus Inf Syst Eng, vol. 57, no. 5, pp. 339–343, 2015, doi: 10.1007/s12599-015-0401-5.

[23] K. Schwertner, “Digital transformation of business,” TJS, vol. 15, Suppl.1, pp. 388–393, 2017, doi: 10.15547/tjs.2017.s.01.065.

[24] C. Ebert and C. H. C. Duarte, “Digital Transformation,” IEEE Softw., vol. 35, no. 4, pp. 16–21, 2018, doi: 10.1109/MS.2018.2801537.

[25] B. Bloching et al., Die Digitale Transformation der Industrie. [Online]. Available: https://bdi.eu/media/user_upload/Digitale_Transformation.pdf

[26] C. Schawel and F. Billing, Top 100 Management Tools: Das wichtigste Buch eines Managers : von ABC-Analyse bis Zielvereinbarung, 6th ed. Wiesbaden: Springer Gabler, 2018.

[27] R. Neugebauer, Digital Transformation. Berlin, Heidelberg: Springer Berlin Heidelberg, 2019.

[28] V. Wittpahl, Digitalisierung. Berlin, Heidelberg: Springer Berlin Heidelberg, 2017.

[29] T. Bauernhansl, M. ten Hompel, and B. Vogel-Heuser, Industrie 4.0 in Produktion, Automatisierung und Logistik. Wiesbaden: Springer Fachmedien Wiesbaden, 2014.

[30] B. Vogel-Heuser, T. Bauernhansl, and M. ten Hompel, Handbuch Industrie 4.0 Bd.3. Berlin, Heidelberg: Springer Berlin Heidelberg, 2017.

[31] C. Wolf and E. M. Halter, Virtualization: From the Desktop to the Enterprise. Berkeley, CA: Chris Wolf and Erick M. Halter, 2005. [Online]. Available: http://dx.doi.org/10.1007/978-1-4302-0027-7

[32] I. Lapinskaitė and J. Kuckailytė, “THE IMPACT OF SUPPLY CHAIN COST ON THE PRICE OF THE FINAL PRODUCT,” Business, Management and Education, vol. 12, no. 1, pp. 109–126, 2014, doi: 10.3846/bme.2014.08.

[33] S. Winkelhaus and E. H. Grosse, “Logistics 4.0: a systematic review towards a new logistics system,” International Journal of Production Research, vol. 58, no. 1, pp. 18–43, 2020, doi: 10.1080/00207543.2019.1612964.

[34] K. Erlach, Wertstromdesign: Springer Berlin Heidelberg, 2010.

[35] X. Liu, Z. Zhang, T. Lu, and W. Fan, “Optimizing Supply Chains through Service-Oriented Architecture,” in IFIP — The International Federation for Information Processing, Research and Practical Issues of Enterprise

Information Systems II Volume 1, L. D. Xu, A. M. Tjoa, and S. S. Chaudhry, Eds., Boston, MA: Springer US, 2008, pp. 405–414.

[36] W. ElMaraghy, H. ElMaraghy, T. Tomiyama, and L. Monostori, "Complexity in engineering design and manufacturing," CIRP Annals, vol. 61, no. 2, pp. 793–814, 2012, doi: 10.1016/j.cirp.2012.05.001.

[37] R. Denk and T. Pfneissl, Eds., Komplexitätsmanagement. Wien: Linde, 2009.

[38] Ashby W. Ross, An Introduction to Cybernetics. London: Champman & Hall, 1970.

[39] G. Schuh, Produktkomplexität managen: Strategien ; Methoden ; Tools, 1st ed. s.l.: Hanser, 2014. [Online]. Available: http://dx.doi.org/10.3139/9783446443549

[40] P. Kappelhoff, Complexity Theory: New Paradigm for Management Research: In: Schreyögg, G.; Conrad, P. (pub.): Management Research 12.: Theories of management. 1st edition. Wiesbaden: Gabler, 2002.

[41] M. Gießmann, "Komplexitätsmangement in der Logistik : kausalanalytische Untersuchung zum Einfluss der Beschaffungskomplexität auf den Logistikerfolg," Dissertation, Wirtschaftswissenschaften, Lehrstuhl für Betriebswirtschaftslehre, Technische Universität Dresden, 2010.

[42] U. Schwenk-Willi, "Integriertes Komplexitätsmanagement : Anleitungen und Methodiken für die produzierende Industrie auf Basis einer typologischen Untersuchung," Dissertation, Wirtschaft-, Rechts- Und Sozialwissenschaften, Hochschule St. Gallen, 2001.

Biography

Andreas Kluth (*1982) is working as a Project Leader and Senior Consultant at Fraunhofer IPA since 2009. He is member of the working group Production Planning and Control. His main fields of scientific working are advanced Complexity Management, order management, production planning. He has already published several scientific articles at national and international conferences and journals.

Martina Schiffer (*1984) is a research associate at the Fraunhofer-Institute for Manufacturing Engineering and Automation IPA. Her research focuses on supply chain management and production planning and control. Before joining the Fraunhofer IPA, she worked 3,5 years as a Process Engineer for a plant manufacturer for metallurgical and rolling mill technology.

Christian Fries (*1992) is a research associate at the Fraunhofer-Institute for Manufacturing Engineering and Automation IPA and at the Institute for Industrial Manufacturing and Management IFF at the University of Stuttgart. His research focuses on supply chain management and future production methods.

Jens König (*1995) is a student assistance at the Institute of Industrial Manufacturing and Management (IFF) at the University of Stuttgart since 2019.