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Towards the data-driven circular and embedded supply chain: Considerations from an ICT perspective

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Abstract

In the academic literature on Supply Chain Management the vision of a paradigm change from linear pipelines toward circular, postfossil, servitized and degrowth supply chains is drawn. Modern information and communication technologies are a key enabler for the realization of this vision. However, the literature remains vague on how these technologies can support the transformation. This publication aims to contribute to closing this gap. It provides an overview of relevant trends, technologies, and concepts, presents a visionary scenario for a data-driven and platform-based circular SCM, and identifies essential steps for its realization. Methodologically, the study is based on a literature review and a single case study in combination with an action research approach.

Keywords: supply chain management, circular economy, platforms, business ecosystems

1. Motivation

Over the last decades, the concept of Supply Chain Management (SCM), understood as "management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less costs to the supply chain as a whole" (Christopher, 2016, p. 3) has become standard in the multi-stage and international value chains of our economy. Currently, SCM departments follow a linear pipeline-oriented supply chain model that includes the extraction of raw materials from nature, their refinement, the production of supplier parts or intermediate products, the manufacturing of a final product, its distribution, use, and disposal. The product manufacturer, as the focal company at the center of the supply chain, cooperates with a multi-tier supply network and distribution partners to provide products and product-related services to the ultimate customer at the end of the supply chain (Stevens and Johnson, 2016). Today, global supply chains are primarily strived for growth, efficiency, and the control of limited market dynamics. In contrast, for practitioners, resilience to short-term external disruptions and sustainability have been of comparatively minor importance so far.

Given the increasing volatility of supply chains, SCM practices developed in and for a politically and economically stable world are increasingly reaching their limits (Bennet and Lemoine, 2014). Disruptions such as the COVID 19 pandemic or the war in Ukraine are barely manageable. Scholars are calling for a new mental model of SCM. Christopher and Holweg (2011, 2017), for example, call for a model that creates the structural flexibility needed to cope with disruptive disturbances. Wieland (2021) goes a step further and postulates a transformational SCM, which responds to phenomena not only at the supply chain but also at the political-economic and planetary level and pursues the vision of a "circular, postfossil, servitized and degrowth" supply chain (Wieland, 2021, p. 70). Richey at al. (2022) emphasize responsiveness driven by flexibility, agility, adaptability, resilience, and improvisational capabilities as the main characteristic of the supply chain of the future. There is no doubt that modern information and communication technologies (ICT) are key enablers for the implementation of the vision mentioned above (Christopher and Holweg, 2017). Stank et al. (2019) even propose a "Digitally Dominant Paradigm" (DDP) as the basis for future research in SCM. However, the scientific literature has so far failed to provide an answer to the question of what the ICT-support must ultimately look like.

Therefore this contribution aims to answer the following questions in the context of the above-mentioned vision of a circular, postfossil, servitized and degrowth supply chain: Which technological building blocks are relevant for realizing the vision? What overall picture results from the combination of these

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building blocks? What steps are required during the transformation process? Methodologically, our work is based on a single case study following an action research approach (Näslund et al., 2010).

The remainder of the study is as follows: Chapter two presents the conceptual background, detailing relevant literature and introducing the building blocks of our conceptual framework for a data-driven circular SCM. In chapter three, we outline the method employed in our research. Chapter four presents the results of our study. Chapter five offers a roadmap for transitioning from the traditional pipeline-oriented SCM to a data-driven circular SCM. Concluding remarks, including the theoretical and practical contributions of this work, its limitations, and suggestions for future research, are presented in chapter six.

2. Conceptual background

In this section, we develop a conceptual framework for our study. Drawing from the literature, we identify key building blocks of a future-oriented SCM and integrate them into a coherent framework. Our interdisciplinary expertise further supports this process, facilitating the identification of these building blocks.

Figure 1 gives an overview of the global supply chain related trends, information and communications technologies and solutions as well as overarching business concepts derived from the extant literature that are decisive, at least from the authors' viewpoint, for the future development of the SCM concept.

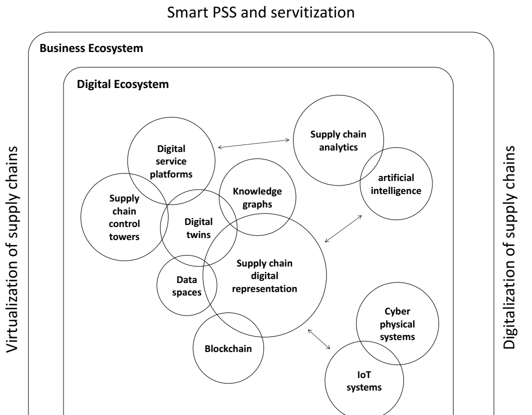

Figure 1. Relevant technologies, concepts and trends

Digitalization and virtualization of physical supply chains, servitization of product-oriented business models and the ongoing transition to sustainability will change global value creation networks significantly. Technologies like the Internet of Things (IoT), Cyber-Physical Systems (CPS), Digital Twins (DT), Data Analytics (DA) and Artificial Intelligence (AI) are considered essential enablers for a future-oriented SCM. Digital ecosystems are needed in order to integrate the different technological building blocks into data-driven solutions or services. They are the centerpiece of the overarching business ecosystems circular supply chains of the future are embedded into. The following sub-chapter describes the different trends, technologies and concepts in larger detail.

2.1. Relevant global trends

A first important trend that needs to be considered in the further development of the SCM concept is the ongoing digital transformation of product-oriented companies. Hofmann and Rüsch (2019) point out that technological innovations created in the context of Industry 4.0 are also having a strong impact on the end-to-end supply chain. Hofmann et al. (2019) summarize key activities leading to the digitalized supply chain of the future: Centering all business activities on the end customer, integration of the various actors along the value chain into a comprehensive information and communication network, flexibilization and automation of processes with the help of autonomous robots, creation of complete process transparency and end-to-end traceability for products, and proactive handling of changes and unexpected disruptions.

A second relevant development is the transition to sustainability (Pagell and Shevchenko, 2014). The climate change resulting from excessive resource consumption has reached an unacceptable state for society and politics. From a SCM perspective, the socially and ecologically sustainable procurement of materials and intermediate products is becoming increasingly important. Far beyond this, the UN and the EU are additionally calling for the transformation of traditional linear supply chains into closed-loop systems (Alcayaga et al., 2019; Allen et al., 2021; Smol et al. 2020).

A third emerging trend is the virtualization of supply chains based on additive manufacturing. Liu et al. (2014) point out that 3D printing technology has already been used for some time in the production of spare parts in aviation. Sasson and Johnson (2016) see potential applications primarily in the context of balancing manufacturing fluctuations for goods manufactured in small quantities. In principle, supply chains can be moved almost entirely into the virtual realm. Production can take place as a service close to the customer in a direct digital manufacturing supercenter (Sasson and Johnson, 2016) or by the customer on his own premises.

In addition, a progressive servitization process (Vandermerwe, 1988) can be observed in the manufacturing industry (Lightfoot et al., 2013). Smart and networked products in combination with new service-oriented and platform-based business models have the potential to fundamentally change competition between companies (Porter and Heppelmann, 2014, 2015). Physical products are increasingly becoming commodities and losing relative importance, while product-related services are gaining in relevance (Papert and Pflaum, 2017). Product-oriented companies are being forced to gradually transform themselves into service-oriented companies.

Among the trends described above, digitalization deserves special attention. It is regarded as a key enabler for the transition to sustainability (Alcayaga et al., 2017; Nobre and Tavares, 2017), the servitization of product-based business models (Porter and Heppelmann 2014, 2015) and the virtualization of supply chains (Sasson and Johnson 2016). Ultimately, it is also the prerequisite for creating responsiveness and coping with disruptive events in the supply chain (Christopher and Holweg, 2017).

2.2. ICT for a future-oriented SCM

The literature emphasizes that IoT technologies have high potential for the further development of supply chains (Calatayud et al., 2018; Papert et al., 2016). Simpler representatives of this group of technologies are capable of identifying and localizing physical objects along their entire life cycle. More complex ones additionally collect and process data, make decisions independently, and take over control tasks (López et al., 2011). The concept of IoT is also closely related to Industry 4.0 and Supply Chain 4.0 (Hofmann et al., 2019). Industry 4.0 places Cyber-Physical Systems (CPS) in the context of industrial production, while SCM 4.0 expands this to a cross-company perspective. At their core, IoT technologies and CPS create visibility in supply chains and enable the decentralization of control tasks.

Data provided by the IoT or CPS in combination with data from other sources like Enterprise Resource Planning (ERP) systems, the internet, etc. can be processed by Supply Chain Analytics tools (Lodemann et al., 2022) to contribute to different SCM goals. In addition to established mathematical and statistical methods, supply chain analytics (SCA) also includes AI methods (Calatayud et al., 2018). Unfortunately, up to now it is unclear, how far the automation of decision-making processes based on AI can go, (Lodemann et al, 2022).

IoT, CPS, SCA, and AI are directly linked to the concept of the Supply Chain Control Tower (SCCT; Kumar et al., 2022; Vlachos, 2021). SCCTs use these technologies in combination with cloud-based information services to establish real-time visibility across the supply chain, to predict its future behavior, to provide decision support for the user and to automate decision making to the largest possible extent. Calatayud et al. (2018) use the term "self-thinking supply chain" in order to emphasize the AI-based decision-making capabilities of SCCTs. SCCTs combine technical infrastructures, informational processes, data, new ways of working, and people to ultimately make supply chains more efficient, customer-centric, resilient, and sustainable (Kumar et al., 2022).

An important prerequisite for the successful operation of a SCCT is a digital representation of the supply chain itself. Data lakes are used to integrate functional data silos within the company, knowledge graphs (Noy et al., 2019) allow quick access to the data when needed for a specific information service. In the future, international industrial data spaces should make this possible (Otto and Jarke, 2019. However, there remains a need for clarification regarding the governance of these data spaces and the reliable exchange of data between companies, in order to ensure their widespread acceptance. As an enabling technology the blockchain has been discussed for several years (Saberi et al., 2018). Like Bitcoin, blockchains are based on a distributed ledger approach and do not require a central authority. Corresponding solutions are trustworthy per se and are particularly suitable if trust cannot be built up in the conventional way.

Data spaces are closely linked to the concept of the Digital Twin (DT). According to Wang (2022), DTs are holistic digital representations of physical entities and processes that are continuously updated to perfectly represent reality at any point in time. On the one hand, digital twins use historical and real-time data to simulate the past, present, and future behavior of a real system. On the other hand, digital twins are able to detect and react intelligently to sudden disturbances using predictive and prescriptive data analytics. In the academic literature on SCM, digital twins are discussed especially in the context of novel risk management solutions (Ivanov and Dolgui, 2021).

Data is also the most important resource for the platform economy (van Alstyne, 2016). Digital marketplaces for procurement, contract manufacturing, trade and transport services have already become an integral part of SCM practice. In addition, digital visibility platforms integrate and process data from different sources across companies in order to provide a high degree of transparency. They anticipate disruptive events, and support supply chain risk management processes. In addition, digital service platforms have also been discussed in connection with the realization of circular supply chains for physical products (Berg and Wilts, 2019). Finally, digital service platforms are an essential tool for the implementation of Industry 4.0 and Supply Chain 4.0 concepts (Hofmann and Rüsch, 2017). Ivanov et al. (2022) even go one step further and assume that entire supply chains can be orchestrated via digital service platforms. They use the term "supply-chain-as-a-service paradigm" to emphasize the importance of such an approach.

2.3. The concept of business ecosystems

The digitalization of companies and supply chains, the servitization of product-based business models and the virtualization of value creation processes presented in section 2.1 based on the technological building blocks introduced in section 2.2, requires new roles that are not represented in existing SC models. In order to solve this problem, researchers from the SCM community are discussing the concept of business ecosystems introduced by Moore in 1996.

Today, the term business ecosystems can be understood as "loosely connected business community made up of different levels of organizations that share a common goal and co-evolve with each other" (Rong et al., 2015). Letaifa (2014) illustrates the challenges of transforming a traditional supply chain into a business ecosystem in the context of the information and telecommunications industry. Prockl et al. (2017, p. 137) point out that both terms, supply chain and business ecosystem, have different and contrasting characteristics and that both concepts have their justification: "While SCM has the holistic, integrated flow as a consistent theme and thus aims more at a tight integration of the supply chain, ecosystem approaches put an emphasis on the diversity of loosely connected and emerging structures and their dynamics beyond the dyadic integration.". Nevertheless, it makes perfect sense to look at traditional supply chains from a business ecosystem perspective in order to open up promising new research streams (Prockl et al., 2017). From our point of view, the business ecosystem approach can also be helpful in the context of developing the transformational supply chain management outlined by Wieland (2021).

Digital ecosystems can be understood as a special type of business ecosystem focusing on the data value chain (Selander et al., 2013). In the context of tomorrow's SCM, digital ecosystems should provide information services that create, transfer, integrate, process, and analyze data along the supply chain and share the results with interested actors. The objectives would then be to increase efficiency, improve customer orientation, better deal with market dynamics, as well as create responsiveness and sustainability. So far, the academic literature provides limited guidance on how digital ecosystems for SCM could look like and how they should be developed. An exception is the literature on digital ecosystems for the IoT. Papert and Pflaum (2017) for example, describe the main roles within an IoT ecosystem and develop a comprehensive model based on a grounded theory approach. They point out that digital platforms play a key role in IoT ecosystems. Koren et al. (2023) explain what happens when two platform-based IoT ecosystems address the same customers. Based on a longitudinal case study in agriculture, they show that under certain circumstances the platform companies are not only willing but also able to share the same data base and to co-create additional value for their common customers.

2.4. The resulting framework

Figure 2 shows the theoretical framework for an IT system supporting the data-driven circular SC of the future developed on the results presented above. We understand the term “circular SCM” as “the coordinated forward and reverse supply chains via purposeful business ecosystem integration for value creation from products/services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organizations” (Batista et al., 2018, p. 446).

The center of the model is a comprehensive data space based on knowledge graphs and blockchain technology, which integrates data sources of different supply chain actors and thus contains a complete digital representation of the circular supply chain. Structures, processes, products, and services are addressed equally. In addition to historical and current data, the representation also contains forecast information. In principle, the individual actors retain sovereignty over their own data. Based on an alliance-driven digital service platform, information services can be made available by different actors, which are used during design, operation, and optimization of the circular supply chain. The data space mentioned above provides the information needed by individual services. Mathematical, statistical and AI methods used by the services are in turn developed, maintained, and made available via a data science and machine learning (DSML) orchestration platform or “machine room”.

In combination, the service platform, the data room, and the machine room form a digital ecosystem that also integrates the physical processes in the supply chain via IoT technologies and CPS. The digital ecosystem and the physical supply chain are in turn embedded in a higher-level business ecosystem.

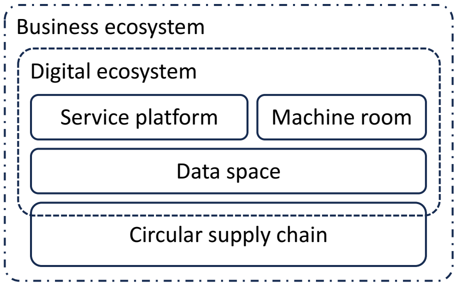

Figure 2. Conceptual framework

3. Method

We conducted a single-case study in combination with an action research approach (Näslund et al. 2010; e.g., Sundarakani et al., 2021). We contend that action research is suitable for achieving our research objective, as it emphasizes changes or transformations. Table 1 provides a brief overview of the method applied, categorizing into three major categories: design, data collection, and data analysis (Näslund et al., 2010).

Table 1: Action research approach.

Category/aspects	Implementation in our study
Design Aspect 1: Research Question	• RQ1: What overall picture results from our conceptual framework for a circular and data-driven supply chain management? • RQ2: What steps are required during the transformation process?
Design Aspect 2: Change: Science and Practice	• Contribution to the practical challenges faced by a company and advancements in SCM research • Formulation of the SCM strategy for a medium-sized automotive supplier
Design Aspect 3: Action Research Discussion/Motivation	• The authors have accompanied the development of an SCM strategy and the formulation of a corresponding transformation process for a company over a one-year period
Design Aspect 4: Unit of Analysis, Context of Case	• Unit of analysis: SCM unit • Context: Automotive industry
Data Collection Aspect 1: Methods, Triangulation 1 and 2, Field Notes	• Four content-based, sequential workshops • Seven interviews conducted with company representatives • On average, 5 employees of the company's SCM and digitalization departments participated • Company provided presentations and business reports
Data Collection Aspect 2: Researcher Role, Team-Based Approach	• The study draws from the professional work of the authors • Authors scientifically accompanied the development of the SCM strategy
Data Collection Aspect 3: Access and Trust	• The authors were granted access to sensitive and confidential information pertaining to SCM and other relevant business units • The authors were invited to share their findings with executives outside of the project
Data Analysis Aspect 1: Structure: Categorization and Pattern Matching	• Comprehensive coding of the qualitative data • The conceptual framework (depicted in Figure 2) served as the foundation for categorization
Data Analysis Aspect 2: Cyclical Process, Project Reviews	• Sequential workshops and interviews were conducted throughout the project • Findings were regularly discussed with key stakeholders from the company
Data Analysis Aspect 3: Presentation: Logical Chain, Frameworks, Contributions to Science and Practice	• The results were comprehensively documented and shared with the leadership team • The results outline a transformation process for the company to execute its data-driven SCM strategy
Data Analysis Aspect 4: Rigor and Validity	• Throughout the project, qualitative data were collected by multiple researchers • Regular meetings with key stakeholders facilitated discussions of insights • The results and the current status of work packages were consistently reviewed within the research team

4. Results of the case study

Through the study, we developed a data-driven and circular supply chain management system vision at a high level. Additionally, we identified several transformative steps that are necessary to attain this vision.

4.1. State of the Art: Traditional SCM

The concept of the supply chain is currently understood as a linear construct following a clear path including the extraction of raw materials from nature, the refinement of these materials, the manufacture of intermediate and final products, their consumption, and the disposal of the product or residual waste at the end of the lifecycle. The academic discipline of SCM usually views such supply chains from the perspective of the focal company, which is connected upstream with a network of supplier companies and downstream with a distribution network. The chain is hierarchically organized, suppliers and service providers are strictly evaluated before cooperation, and cooperation is comparatively long-term and stable. Changes are considered time-consuming and expensive.

The main goals of today's SCM are still reducing costs along the whole supply chain, increasing customer value, and mastering limited market dynamics on the distribution side. Everyday risks and disturbances are addressed with more or less developed Supply Chain Risk Management (SCRM) systems. More serious disruptions on the other hand are challenging and require a certain amount of improvisation, which is at odds with companies' efforts to standardize and scale processes. In comparison to the goals mentioned above, dealing with social and ecological sustainability have had much less management attention in the past. However, with the increasing volatility of supply chains, the increasing criticality of disruptions, and the new demands for sustainability in society and politics, the situation is beginning to change. Resilience and sustainability goals are gaining importance.

From an IT perspective, SCM departments in companies are supported by supply chain software tools. These tools help the human decision maker with demand forecasting as well as with demand and supply planning at various levels and time horizons. They also enable data exchange and collaboration with partners and integrate tracking and tracing modules in order to increase supply chain visibility. The more traditional Advanced Planning and Optimization (APO) tools are more and more being replaced by Supply Chain Planning (SCP) platforms. Market leaders already use knowledge graphs in order to digitally represent the supply chain. However, the performance of SCP platforms is limited due to the granularity and quality of the available data. In fact, partners in the supply chain usually do only provide access to data they have contractually agreed on. In addition, advanced analytics methods and artificial intelligence processes are already being used for simpler applications.

4.2. Step 1: SCCT-based SCM

In this first step, companies are aware of the potential of technologies like IoT or AI for SCM. The structure of the traditional supply chain described in the last section is supplemented by a supply chain control tower (SCCT). In principle, an SCCT is a piece of software which builds upon the already existing IT infrastructure. Monitoring, forecasting, planning and control functions that were previously performed by ERP systems are transferred to the SCCT.

The main goal for implementing an SCCT is to increase flexibility, agility and resilience and thus enhance the responsiveness of the existing supply chain. With the help of a SCCT companies are able to react much faster to everyday disturbances and dynamic market behavior. Nevertheless, challenges driven by more critical short-term disturbances of the supply chain still remain. A SCCT does not provide the structural flexibility which is needed to cope with this type of disturbances.

The introduction of the concept of the SCCT is associated with a paradigm shift in SCM. The basic principle is no longer to use IT in order to support the human decision-maker with better information, but to automate decision-making processes to the largest possible extent and thus to realize the concept of the "self-thinking supply chain" proposed by Calatayud et al. (2018). The automation of decision processes promises faster reactions and less friction losses in case that a supply chain disturbance occurs. How far this automation can go depends on the performance of the ICT that are used.

Automation is achieved primarily through the application of modern data analytics and AI methods including ML and Natural Language Processing (NLP). The different methods are made available and permanently maintained by data science and ML orchestration platforms (DSML, Krensky et al. 2020). Primary data sources are ERP systems and other software packages used by the company. Data lakes and knowledge graphs are employed in order to integrate functional data silos. Additionally, IoT based tracking and tracing platforms, operated by third parties or the company itself enhance the granularity and the quality of the data. SCCTs are also connected to digital cloud-platforms creating visibility and supporting risk management in the end-to-end supply chain. Despite the meanwhile very powerful data integration and DSML tools, the possibilities for automation are still limited. On the one hand the limited quality of data in the IT-systems requires extensive data augmentation processes and prohibits fully automated solutions. On the other hand there is the restricted willingness to share data beyond the contractually agreed level.

In principle, SCCT support the different SCM functions already mentioned in the description of the state of the art in sub-chapter 3.1. In addition, SCCTs integrate platform-based services which improve process visibility and help to identify and manage potential risks after they have occurred. Moreover, SCCTs connect to the world wide web in order to gather additional valuable information then used to create supply chain insights for management on different organizational levels. Information for the user is usually prepared graphically and presented via a dashboard.

4.3. Step 2: Platform-based SCM

In the second step, the SCCT-based "self-thinking supply chain" can be embedded into the platform economy. Platforms generally act as intermediaries and bring producers and consumers of goods and services together. Modern cloud-based platforms use innovative data analysis techniques to create the best possible fit between the consumer's requirements and the producer's performance characteristics.

Cloud-based platforms can be used to create adaptability within supply chains. For example, digital marketplaces for contract manufacturing enable the rapid identification and integration of an alternative partner if a supplier is no longer able to deliver. Thus, the supply chain would be able to handle not only day-to-day but also more critical short-term disruptive events. In principle an entire supply chain could be built on matching platforms for manufacturing, transportation, and distribution services. To what extent such an idea can be implemented certainly depends on industry-specific framework conditions.

In a platform-based supply chain the orchestration of resources is no longer done by the company itself but fully or at least partially delegated to one or more platform operators. The extent to which tasks along the supply chain are delegated to digital platforms is a strategic decision. Possible decision criteria might be the technological expertise and the domain-knowledge of the platform provider. Other criteria have, from the authors' point of view, still to be identified and described by the scientific community.

In principle, digital platforms for SCM use the same technologies that have already been described in 3.2. Information about possible value creation partners is the essential resource platforms create value from. It can be gathered automatically via the world wide web. The matching procedures used on the platforms are increasingly supported by AI and NLP. A severe problem arises in case that different platforms have to be integrated into an overall supply chain solution. Most of the existing platforms still use proprietary connectors and a common interface is still missing.

Existing platforms for SCM support the identification, evaluation and selection of suppliers, contract manufacturers including additive manufacturing providers, transportation service providers, warehousing providers etc. Others deliver visibility services or market insights. Still others support supply chain risk management processes for the different supply chain actors. Most existing platforms on the market focus on a specific function within the supply chain to reduce complexity and thus provide a high-quality and reliable service. Different cloud-platforms can be combined in order to create a “supply chain as a service” solution. Here it has to be mentioned, that the platform based SCM concept has a certain similarity with the 4PL concept. However, there are some differences. First, the platform based SCM concept builds significantly on innovative digitalization technologies like IoT and AI including NLP. Second, it does not only focus on logistics processes for physical processes, but also includes servitization aspects and the management of value creation systems for PSSs.

4.4. Step 3: Smart circular SCM

In the third step, the traditional linear supply chain is transformed into a circular value creation system embedded in an open and alliance-driven business ecosystem. The circular supply chain combines traditional value creation processes with sustainability activities and various circular strategies, commonly referred to as "R" strategies, leading to smarter product use and manufacturing, extended life of the product and its parts, and wise use of materials (Potting et al., 2017; Kristoffersen et al., 2019). In addition to the actors of the traditional supply chain, further cooperation partners for the return of goods, their repair and reprocessing, etc. are needed.

The main idea behind circular SCM is to increase sustainability of supply chains by reducing the amount of raw materials taken from nature, residual waste, landfill, and incineration to the absolute minimum. Additionally, circularity can contribute to supply chain resilience because manufacturing companies gain sovereignty over their own products and materials and are thus less dependent on supplies from abroad. In order to realize these benefits products have to be smart and networked and traditional product-oriented business has to be transformed into “as a service” business.

The circular supply chain is no longer coordinated by a corporate control tower or several networked digital platforms, but by a comprehensive alliance-based business ecosystem. The fundamental changes associated with the realization of a circular and future-oriented SCM can only be successfully managed if all actors involved are guided by a common vision. Co-evolution and co-creation is key. All companies have to agree with the governance structures and measurable value has to be generated for each of them.

The necessary ICT infrastructure is provided by a digital ecosystem. The core of this ecosystem is a comprehensive digital representation of the circular system (“data space”) describing its structure, the value creation process, and the life cycles of individual products in a high level of detail. The products themselves have a unique identity and are permanently connected to the digital representation via the Internet of Things. In the future the physical products will be represented by the digital product passport which is currently under development. Service providers within the digital ecosystem can offer data-driven services based on the digital representation. The algorithms which are needed in order to create value are provided by DSML orchestration platforms.

In order to design, operate and optimize a circular supply chain continuously a set of data-driven services are needed. These include, for example, services that support design for circularity or services that map the current state of the system using descriptive methods. Other services might use ML techniques to forecast future demands, the volume of returned products, the remaining lifetime of products already in the field etc. based on historical information. Still others may use mathematical optimization methods to optimally plan future resource deployment based on the forecasts. 3D printing services and product-specific services like predictive maintenance etc. might also be offered in the digital ecosystem.

4.5. The roadmap at a glance

Table 2 summarizes the development steps described in the last sections. The focus of the transformation from traditional SCM to SCCT-based SCM is on increasing the traditional supply chain's flexibility and agility through the digitalization of internal processes and the use of IoT and AI technologies. The transition from SCCT-based SCM to platform-based SCM, in turn, strives for structural flexibility or adaptability by incorporating digital cloud platforms from outside the supply chain. Finally, increasing resilience and sustainability are the main goal of the transformation from platform-based to smart circular SCM.

5. Conclusion

So far, the academic literature has not provided any concrete indications on how a "circular, postfossil, servitized and de-growth " (Wieland 2021: 70) SCM, can be supported by ICT and what a roadmap to this new form of SCM might look like. This contribution presents initial indications in this regard and thus provides a starting point for further scientific work. A fruitful future avenue, for example, would be the development of a maturity model for a future oriented SCM and its use in practice for an initial classification of companies.

Nevertheless, this research work has some limitations. First, the development of the vision and the roadmap are based on a single case study. A more comprehensive empirical survey based on a larger number of interviews with experts from the SCM community would certainly help to further sharpen and generalize the results. Secondly, the company addressed in the case study belongs to the automotive industry. We expect that additional case studies focusing on other industries might generate further interesting results. Third, the structure of the summarizing Table 2, which has been developed quite pragmatically during our research work merits some theoretical grounding. The application of data life cycle models from literature in combination with ecosystem theory would certainly be helpful and provide further insights.

Table 2: Roadmap for the further development of the traditional SCM concept.

Phase	0	1	2	3
Type	Traditional SCM	SCCT-based SCM	Platform-based SCM	Smart circular SCM
Supply Chain	Traditional, hierarchically organized, static supply chain with a focal actor at the center	Traditional supply chain, enhanced by an SCCT with self-thinking capabilities.	Self-thinking supply chain embedded into a global platform economy	Circular supply chain embedded in an open alliance-driven business ecosystem
Objective	Reducing costs along the whole supply chain, increasing customer value, and mastering limited market dynamics	Increasing flexibility, agility, and resilience in order to react faster to everyday disturbances and dynamic market behavior.	Creation of structural flexibility or adaptability especially with regard to short-term and disruptive events in the supply chain	Increasing sustainability and resilience of the supply chain with regard to limited planetary resources
Coordination principle	Use of decision support systems for decisions made by human actors	Data-based and largely automated decision-making through AI	Shifting AI-based decision making to digital platforms outside the supply chain	Ecosystem governance through the alliance of ecosystem actors
IT Support	APO, SCP, data lakes, knowledge graphs	IoT, AI, DSML Orchestration Platforms	IoT, AI, and DSML enabled cloud platforms	Digital federated business ecosystem
Data basis	In-house data sources including data from partners defined in bilateral cooperation contracts	Inhouse data, additional data from IoT-based tracking platforms and the world wide web	Delegation of cooperation decisions to digital platforms with their own database	Cross-company federated and ecosystem-centric data spaces
Services	Supply chain design, forecasting, planning and optimization, tracking and tracing, cooperation etc.	Services as in traditional SCM but with a stronger focus on cross-functional tasks, risk management	Matching services for different resources, visibility and market insights, supply chain as a service	Design, operation and optimization of circular supply chains, 3D printing, product-specific services

Finally, some interesting challenges for the scientific SCM community arise from this contribution. In the context of SCCT-based SCM questions concerning the technical architecture, the specific services, the embedding of the tower into the socio-technical system "company" need to be answered. From the authors' point of view the implementation of a SCCT creates the capability to share data on a larger scope and scale and is thus the prerequisite for the next step on the transformation roadmap. Up to now, the use of digital cloud platforms in SCM has only been rudimentarily investigated. An important step would be to identify the most important platforms on the market, to build clusters and to find out, which of these clusters are used in which industry. A second step could be to learn more about successful configurations of different types of platforms in different industries. Furthermore, the idea of the "supply chain as a service" merits some more attention. A central challenge concerning the realization of the smart circular supply chain is the design of the circular process itself. Essential ecosystem roles have to be described. Relationships between them have to be analyzed. In particular it must be clarified how the governance of the digital ecosystem and the overarching business ecosystem has to be designed in order to successfully operate the circular supply chain. Only, if the main actors within the alliance see a reason behind their joint activities and are willing to share data, the transformation of traditional supply chains into circular structures has the chance to succeed.

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