Supply Chain Resilience and Digitalization: A multi-theory lens for driving future research

Supply Chain Resilienz und Digitalisierung: Eine Sichtweise multipler Theorien zur Unterstützung zukünftiger Forschung

Florian Stöfer*†
*FOM Hochschule, Essen, Germany
†Universidad Católica San Antonio de Murcia (UCAM), Murcia, Spain, fpstofer@alu.ucam.edu

Abstract — During recent years, global supply chains (SC) have been exposed to an unprecedented series of disruptions, subsequently facing tremendous challenges and suffering severe performance losses. The sources and types of disruptions are diverse, for example the COVID-19 pandemic, natural catastrophes exacerbated by climate change, the war in Ukraine, inflation and surging energy prices in Europe, political conflicts like the trade war of USA vs. China or Brexit. This development has drawn the attention of academia and business practitioners to the concept of supply chain resilience (SCRES) as strategic priority to maintain sustainable competitive edge. At the same time, supply chain digitalization (SCD) and rapid advancements in information and communication technologies represent another disruptive force of the contemporary business environments. This paper conceptualizes a promising and novel research area at the intersection of SCRES and SCD. Further, it presents a series of applicable theoretical lenses to inform future research about the interrelationship of SCRES and SCD.

Zusammenfassung — In den letzten Jahren sind globale Lieferketten (SC) einer beispiellosen Reihe von Disruptionen ausgesetzt, die sie vor große Herausforderungen stellen und zu starken Leistungsverlusten führen. Die Ursachen und Arten der Disruptionen sind vielfältig, z.B. die COVID-19-Pandemie, Naturkatastrophen die durch den Klimawandel weiter verschärft werden, der Krieg in der Ukraine, Inflation und steigende Energiepreise in Europa, politische Konflikte wie der Handelskrieg zwischen den USA und China oder der Brexit. Diese Entwicklungen haben die Aufmerksamkeit von Wissenschaftlern und Wirtschaftsexperten auf das Konzept der Lieferkettenresilienz (SCRES) als strategische Priorität gelenkt, um nachhaltig Wettbewerbsvorteile zu generieren. Gleichzeitig stellen die Digitalisierung der Lieferkettenmanagements (SCD) und die rasanten Fortschritte in der Informations- und Kommunikationstechnologie eine weitere disruptive Kraft im heutigen Geschäftsumfeld dar. In diesem Beitrag wird ein vielversprechender und innovativer Forschungsbereich an der Schnittstelle von SCRES und SCD konzeptualisiert. Darüber hinaus wird eine Reihe von anwendbaren Theorien vorgestellt, um zukünftige Forschung über die Wechselbeziehung von SCRES und SCD theoretisch zu bereichern und fördern.

I. Supply Chain Management and Disruptions

A SC represents a network of connected and interdependent organizations which cooperatively manage and improve the flows of materials, services, finances and information across different value-adding stages from suppliers, manufacturers and other involved parties like service providers to final customers [1, 2]. Supply chain management (SCM) is concerned with the management of SCs and defined as "the integration of business processes from end user through original suppliers that provides products, services, and information that add value for customers" [3, p. 504]. The concept of SCM emerged in the 1980s as a strategic, systematic and multidisciplinary approach with the primary goal of integrating different functions (e.g. procurement, manufacturing, logistics) and companies that were previously regarded as fragmented entities [4, 5, 6, 7, 8]. In addition, SCM can be viewed as general management philosophy [2] and also deals with the intangible assets of SCs like behaviors and relationships within and across organizational boundaries [1, 9] with the ultimate goal of improving performance or decreasing cost [10]. Since the early 2000s, numerous scholars have repeatedly indicated several trends and reasons that have increased the vulnerability of SCs, e.g. [1, 10 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]:

- Focus on lean and efficient SCs, i.e. downscaled inventory buffers and just-in-time deliveries, focused factories and centralized distribution
- Advanced globalization and geographically dispersed SC networks
- Increased outsourcing of SCM activities
- Reduced supplier base, single sourcing and increasing dependence on suppliers
- Extended interconnectedness and intertwined, complex processes across organizations
- Shortened product life cycles, accelerated time-to-market and higher product variety
- Capacity limitations
- Increased customer requirements and demand volatility
- External risks such as natural (e.g. pandemics, storms, floods, earthquakes) or man-made disasters (e.g. wars, strikes, accidents)
- Political upheavals or regulations

SC disruptions are unanticipated events that disrupt the flow of goods and services within a SC [21]. The financial, performance-related and reputational consequences of SC disruptions are severe and can substantially threaten the competitiveness and survival of companies. Some frequently cited cases in literature include Ericsson´s loss of $400 million after a fire at one of their common suppliers [13], Land Rover almost shutting down production lines due to a bankrupt supplier [22], Toyota losing 17% of stock value, temporarily closing all 12 assembly plants and cutting domestic vehicle production by 78% year-on-year after the 2011 earthquake [23, 24], an explosion at a site of automotive supplier Evonik that led to a shortage of special resin used in the production of many core components in the automotive industry [25] or the most recent comprehensive semiconductor shortage leading to a global production shortfall of almost 10 million vehicles in 2021 [26, 27]. Other examples of tremendous supply and demand disruptions that caused financial losses, sometimes exceeding the billion-dollar level, include companies like Cisco, Nike, Bosch, Pfizer, Dell, Boeing or Mattel [13, 28, 29, 30]. In tightly linked automotive SCs, disruptions can cause losses of over US$ 100 million per day [31].

Hendricks and Singhal [14, 32, 33] indicate in a sequence of studies that SC disruption and excess inventory announcements are to a significant extent negatively associated with lower stock returns as a consequence of lower sales or higher cost. In their study from 2003, the authors indicate that major SC disruptions reduce the stock market value of a company on average by 10% [14]. In their study from 2005, including 827 announced SC disruptions, they conclude that the average abnormal stock returns of firms that experienced disruptions is nearly -40% relative to their industry peers [31]. Similar recent research shows that firms affected by SC disruptions caused by the Great East Japan Earthquake in 2011 lost on average 5.21% of their shareholder value during the one-month period after the event [34]. In essence, there exists evidence that capital markets negatively react to SC disruptions and thus highly value capabilities like robustness and resilience to resist or quickly recover from such incidents.

II. Supply Chain Resilience

Many scholars suggest that that risks and disruptions are unavoidable and thus form an inherent part of contemporary SCs [19, 21, 35, 36]. Based on observations that some SCs have the ability to recover more effectively than others from inevitable risk events, a discussion about SCRES has precipitated in academia and SCM practice [22, 37, 38, 39, 40]. In general, resilience is a multidisciplinary, multidimensional and hierarchical concept [16, 17, 40, 41, 42]. SCRES can be defined as "the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" [16, p. 131]. While the definition of SCRES has been subject of several literature reviews, most common aspects include anticipation, preparation, resistance, mitigation, response, coping, maintenance of control or structure, recovery, restoration, adaption, growth and performance improvement related to SC disruptions [16, 17, 18, 41, 42, 43]. This sequence of notions also reflects the temporal scale of SCRES when it is conceptualized as process during unfolding crisis events [17, 38]. However, the stated phases are rather cyclical and concurrent than strictly linear [44].

In accordance with organizational theory, SCRES can be considered a meta-capability which operationally consists of various formative elements and capabilities [45, 46, 47]. While there are substantial differences regarding the scope and causal relationships of SCRES elements in literature, the most commonly stated capabilities are SC-reengineering, SC understanding, visibility, learning agility, flexibility, redundancy, collaboration, information-sharing, integration, velocity, efficiency, cultural change, contingency planning, demand management, innovation, risk awareness, contract management, supplier management, sensing, anticipation, adaptability, security and communication [16, 17, 18, 22, 24, 37, 38, 39, 40, 41, 42, 43, 44, 48, 49, 50]. Given the recent series of SC disruptions (e.g. COVID-19 pandemic, war in Ukraine, Brexit, geopolitical conflicts, natural catastrophes, strikes, rising energy prices or port congestion), the potential of SCRES to enable companies to better anticipate, respond and recover from such evens has attracted considerable interest of academia and business practice [18, 27, 49, 51, 52]. In fact, many studies highlight the historical over-reliance on lean instead of resilient SC design and shortcomings of many organizations to address recent SC disruptions with adequate capabilities [52, 53, 54, 55, 56].

III. Supply Chain Digitalization

Significant technological progress under the umbrella of Industry 4.0 has created a positive disruption, requiring companies to rethink traditional ways of operating their SCs and contemplating how to utilize digital technologies (DT) to strengthen their competitiveness [57, 58]. The terms SC 4.0 or SCD reflect the application of the Industry 4.0 concept to SCM and the adoption of DTs in SC processes. DTs are information, computing, communication, and connectivity technologies that revolutionize business strategies, processes, capabilities, products and services [59]. In technical terms, the concept of a digital SC can be described as "(…) an intelligent best-fit technological system that is based on the capability of massive data disposal and excellent cooperation and communication for digital hardware, software, and networks to support and synchronize interaction between organizations by making services more valuable, accessible and affordable with consistent, agile and effective outcomes" [57, p. 165]. SCD is considered a holistic management approach comprising managerial and capabilities supporters, technology levers, SC processes' performance requirements and strategic outcomes [60]. While certain DTs have existed for some years and underwent continuous development, others are just emerging or will reach higher maturity and wider applicability in SCM practice during the next years. The range of DTs includes e.g. [54, 56, 57, 58, 59, 61, 62, 63, 64]:

- Cyber-Physical Systems
- Artificial Intelligence (AI) and Machine Learning
- Virtual and Augmented Reality
- Digital Twins/Simulation
- Additive Manufacturing/3D-printing
- Big Data Analytics, Business Intelligence
- Cloud Technology and Computing, Digital Platforms
- (Industrial) Internet of Things (IoT)
- Blockchain
- ERP
- Mobile Apps and Social Media

- Enhanced Connectivity (e.g. 5G)
- Radio Frequency Identification/Advanced Tracking and Tracing Systems
- Machine-to-Machine Communication
- Robotics and autonomous vehicles (e.g. drones)

The stated DTs can be categorized into (1) connectivity, data and computational power (i.e. sensors, IoT, cloud technology or blockchain), (2) analytics and intelligence (i.e. big data, advanced analytics, machine learning, AI), (3) human-machine interaction (i.e. virtual and augmented reality, robotics, automation, further types of robots like collaborative robots or autonomous guided vehicles) and (4) advanced engineering (i.e. additive manufacturing/3D printing, nano- engineering) [64, 65]. Overall, SCD is expected to be a major lever for performance improvement with estimations suggesting up to 30% lower operational costs, a decrease of 75% in lost sales and inventory reduction by up to 75%, realized, e.g. by better SC orchestration, automation, network optimization, enhanced interaction with suppliers and customers, adequate inventory profiles, more accurate demand forecasting or more precise and frequent planning cycles [66]. In addition, these strategic outcomes are achieved along several SC stages and processes through digitally-enabled benefits like transparency, efficiency, agility, integration, leanness, interoperability, flexibility, collaboration, data-sharing, communication, connectivity, visibility, responsiveness, accelerated decision-making and better performance measurement [58, 60, 62, 67, 68, 69, 70]. However, some scholars further note necessary drivers for successful SCD, e.g. leadership support, infrastructure, cyber security, strategic vision or organizational skills [58].

IV. Interrelationship of Supply Chain Resilience and Digitalization

Interestingly, there exists substantial common ground between proposed business benefits of DT adoption in SCM and formative capabilities of SCRES. Consequently, academia recently highlighted the opportunity of DTs for transforming traditional approaches aiming at strengthening SCRES during disruptive events like the COVID-19 pandemic [18, 61, 63, 71, 72, 73, 74, 75, 76, 77]. Given the immense potential and topicality of the interrelationship of SCD and SCRES, first conceptual studies attempt to consolidate existing academic work and establish a holistic link between both concepts, i.e. adoption of individual DTs and specific SCRES elements during SC disruptions [54, 56, 61]. As such, utilizing advanced DTs can support the development of SCRES capabilities like visibility, collaboration, data analytics-driven decision-making, flexibility or agility. Further, SCD is set to enhance traditional SC risk management tools and practices towards more data-driven approaches, e.g. by creating end-to-end disruption monitoring or early detection systems and timely providing necessary information to take effective countermeasures [78, 79]. However, the individual impact of particular DTs on SCRES may vary depending on the specific organizational setting and adoption scenario. While it is not the aim of this paper to examine all links between specific DTs and SCRES capabilities, some examples are provided in the following.

For instance, digital twins of SCs can improve strategic decision-making by enabling advanced simulations and what-if planning, visualizing dynamics and supporting companies in developing and evaluating appropriate SCRES measures. During pandemics like COVID-19, digital twins provide insights into pressing issues like e.g. what are the short-term and long-term impacts of disruptions on the SC performance, how long does the recovery take after a disruption process, how long can a SC maintain normal operations or what role can related dynamic features play (e.g. virus spread rate, disruption propagation, political interventions, etc.) [18, 73, 80]. Further, big data platforms enable the collection and processing of massive amounts of data from various sources, e.g. to improve demand forecasts, automate replenishment or perform SC network optimization simulation [81]. Big data combined with advanced analytics, computing capabilities and AI enable real-time data collection and support the rapid processing, analysis and interpretation of SC risk data. As such, big data analytics can enhance a range of SCM processes by predicting disruptions, improving contingency planning or creating real-time visibility [56, 74, 75, 82]. Moreover, cloud-based SC technologies can serve multiple different purposes, e.g. SC planning integrating massive amounts of internal and external data to train AI and ML algorithms, in order to improve demand forecasting (e.g. SAP Integrated Business Planning, BlueYonder Luminate or Kinaxis RapidResponse) or enable real-time replanning and rescheduling. Additionally, big data and AI can be used to enhance sensing and disruption capabilities (e.g. Everstream, RiskMethods or Resilinc) [83]. Distributed ledger technologies like blockchain can improve traceability, visibility and information-sharing while ensuring data privacy and security [84, 85].

In addition to these information and knowledge-focused approaches, technologies like the IoT, automation, robotics, additive manufacturing and augmented reality transform SCs and manufacturing sites into cyber-physical systems, enhancing manufacturing flexibility and reducing SC disruption risk, e.g. during pandemics by replacing labor capacity [60]. IoT technologies represent a network of numerous interconnected and interacting physical objects gathering data by e.g. monitoring systems, RFID, GPS, sensors, cameras, lasers, barcodes, data matrix codes, QR codes or near field communication. As such, IoT expands the opportunities to generate data, create visibility and helps to mitigate disruptions, e.g. by monitoring transportation conditions like temperature or physical shocks [56, 86, 87]. Cyber-physical systems in manufacturing integrate physical infrastructure and information systems to create autonomous, self-managing processes based on information exchange, monitoring, controlling and sensing risks (e.g. automated system for detecting and transporting samples to quality management) [88, 89]. Additive manufacturing may support disruption mitigation by producing lower volumes of complex (spare) parts flexibly and independent of the geographic location, eliminating the need for transportation [54, 61, 71]. Digital platforms enhance different SC processes like procurement (e.g. SupplyOn), manufacturing (e.g. Siemens MindSphere) or sales (SalesForce) through more efficient information flows and embedded analytics, extending traditional SCs to digital ecosystems [90]. Other applications include e.g. augmented reality to improve picking operations or to conduct remote support in manufacturing and maintenance, machine-vision technologies to improve quality management, sensor data in manufacturing to enable predictive maintenance or reporting efficiency through business intelligence, control towers and better data visualization [18, 64].

V. State of Literature and Research Gap

Despite the progress in SCRES research, there have only been initial efforts to examine the impact of SCD on SCRES. Even though the phenomenon has recently experienced a dynamic increase in interest due to rapid technological progress and a series of crisis during the past few years, there are still deficits concerning an integral view. Traditionally, both literature streams have worked to a great extent in isolation, leading to both topics being discussed independently in academia. As such, SCRES research has not sufficiently taken into consideration the potential impact of DTs, whereas studies on SCD have in most cases not explicitly focused on the potential benefits regarding SCRES and reducing vulnerability. Current research is limited to few theoretical conceptualizations [54, 56, 61] and first empirical studies indicating some positive causal relationships [68, 74, 75, 76, 81, 82, 91, 92]. However, they often consider IT factors, SCD and SCRES as general capabilities or constructs and have not particularly examined in-depth how specific DTs are effectively implemented to build distinct formative elements of SCRES. Most other existing research on the intersection of SCD and SCRES remains, unfortunately, to a substantial part rather anecdotal. However, there exists a broad spectrum of opportunities at the intersection of SCD and SCRES, constituting an interesting and future-oriented research field which is subject to ongoing rapid technological development. For example, most recent impressive technological advancements in different types of AI (e.g. ChatGPT) and its potential for SCRES are yet to be explored. The context of the amalgamation of SCD and SCRES is determined by the following four perspectives:

- Adoption of distinct DTs
- Enhancement of specific SCM processes
- Building formative capabilities of SCRES
- Disruption type (internal vs. external) and phase (proactive vs. reactive approaches)

Based on the work of [56], Fig. 1 provides a hierarchical relationship between these mentioned constructs. In fact, many scholars have called for research extending knowledge on the intersection of SCRES and SCD [18, 40, 52, 53, 54, 56, 61, 65, 72, 80, 82, 83, 84, 90, 91, 93, 94, 95, 96, 97]. Research on the intersection of SCD and SCRES also contributes to the critical call for research for advancing the understanding and exploring innovative ways of building SCRES [17, 18, 48, 94, 95, 98, 99] and the need for further research regarding the application of Industry 4.0 in SCM [57, 58, 60, 62, 63]. Given the infant stage of research, especially qualitative empirical studies (e.g. field research, case study research about practical implementation scenarios) is deemed a valuable and established research method, especially for novel areas that require substantial exploration [100, 101, 102, 103, 104, 105]. This is reflected in a comprehensive call for qualitative empirical studies from the SCRES research community [17, 43, 45, 60, 78, 79, 72, 80, 81, 91, 95, 96, 97, 106, 107].

VI. THEORETICAL LENSES

Recently, scholars have noted the limited use of existing theoretical lenses to expand the understanding of SCRES [17, 93]. Given the multidimensionality and interdisciplinarity of the resilience concept, there is no unified or integrated theory for SCRES and its link to SCD [42, 79]. Therefore, this chapter presents some helpful theoretical lenses to foster the adoption of existing theories. It aims to serve as basis and guidance for urgent future research on the phenomenon of digitally-driven SCRES. Established theoretical lenses support research in examining a phenomenon, identifying relevant variables and relationships among them [17]. In this way, research will achieve more holistic models and conceptualizations of the phenomenon and benefit from increased prescriptive rigor for management practice. Some of the presented theories have been traditionally established as rigorous lenses in the fields of SCRES and SCD, whereas others are relatively novel to the field and may inspire future research on their intersection.

A. *Resource-Based View*

The resource-based view (RBV) contends that companies achieve sustainable competitive advantage through irreplaceable, valuable, rare, and inimitable resources. Firm resources are tangible or intangible assets which support the implementation of strategies to increase efficiency or effectiveness, e.g. technology, knowledge, efficient procedures, firm attributes, information, organizational structures, capabilities or skilled personnel [108, 109, 110]. From this perspective, SCD-driven capabilities related to SCRES can be viewed as potential competitive resource, especially against the backdrop of an increasingly disruptive business environment.

In fact, DTs can potentially epitomize a critical physical capital resource by themselves (e.g. IoT, cyber-physical systems, additive manufacturing) or at least support their general development (e.g. smart factory concepts which achieve superior operations and competitive advantage) [64, 87, 88]. In addition, digitally-driven SCRES also requires and impacts human resource capital (e.g. learning, judgement, intelligence, relationships) and organizational capital (e.g. reporting, planning, controlling, coordination) [56, 61, 74, 75, 92, 108]. This stems from different adoption scenarios, e.g. big data analytics and AI to increase the efficiency and effectiveness how companies sense and cope with disruptions through better decision-making and coordination or the implementation of blockchains, digital platforms or cloud applications to improve connectivity and integration with other SC members, fostering efficient information-sharing, data security and accuracy, lasting relationships and a robust reputation among customers [54, 56, 61, 68, 82, 85, 90].

However, despite unprecedented technological progress and the promising potential of DTs for SCRES, the adequate and widespread implementation is still limited, depending on the specific technology. This fact allows for early adopter advantages which can be critical during crisis situations [13]. Further, many DTs and their adoption process are characterized by a high technological and organizational complexity related to their truly beneficial integration in existing systems, structures and processes, requiring novel skill sets in organizations (e.g. data scientists). From this perspective, building SCRES through SCD fits the requirements of being a valuable,

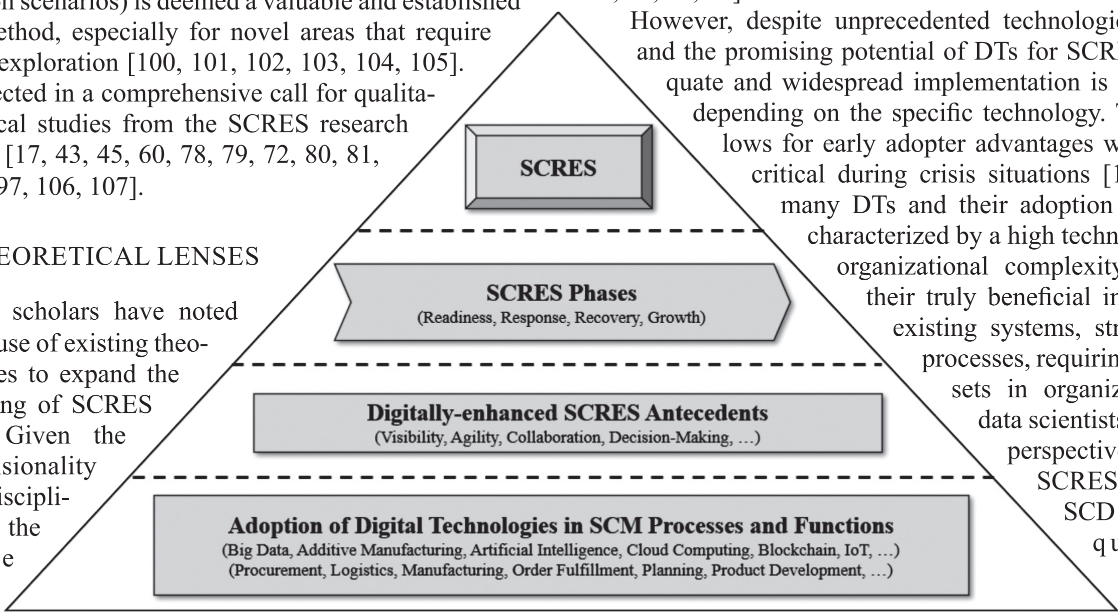

Figure 1: Digital SCRES Framework (based on [56])

rare and hardly imitable or substitutable resource, especially when exposed to volatile environments. In fact, the RBV has been extensively used in traditional SCRES and SCD research, e.g. to examine antecedent resources and capabilities of SCRES [16, 48] or the relationship between firm size and DT adoption in SCM [111].

B. *Dynamic Capabilities Theory*

Despite its prevalence and value, some scholars have noted limits and shortcomings of RBV. A main point of criticism refers to its inherent static perspective, primarily due to the stickiness of resources and endowments [91, 112, 113, 114]. Furthermore, in dynamic and fast-changing environments competitive forces and rules may quickly shift towards innovation and adaption, rendering static resources futile to maintain sustained competitive advantage, therefore limiting the applicability of RBV in such markets [91, 112, 113, 114, 115]. Subsequently, the dynamic capability theory (DCT) was developed as advancement ensuing from the RBV, focusing on exploiting capabilities in dynamic environments and combining them with resources to form competitive advantage [112, 114, 116, 117, 118]. The DCT assumes that companies cannot achieve competitive advantages by simply accumulating a significant base of assets without having appropriate capabilities to orchestrate and synergize with them like e.g. responsiveness, agility, innovation or the management capability to coordinate and redeploy competences [112]. As such, dynamic capabilities are defined as "higher-level competences that determine the firm's ability to integrate, build, and reconfigure internal and external resources/ competences to address, and possibly shape, rapidly changing business environments" [117, p. 1395]. They are considered as antecedent organizational routines (e.g. strategic decision-making, product development, transfer processes, learning, knowledge generation or alliancing) and drivers of competitive advantage through creating, evolving and recombining resources [114]. Dynamic capabilities focus on adaption to sustain competitiveness in dynamic environments [115], determine the rate and level of change of ordinary capabilities (e.g. manufacturing, accounting, HR capabilities) [116] and are generally more difficult to replicate [118].

Notably, the nature of DCT exhibits strong links to SCRES. Different literature reviews on organizational resilience conclude that it is a dynamic capability of companies to respond to change and embrace it as opportunity [41, 42]. Dynamic capabilities can be described in a threefold differentiation, i.e. sensing opportunities and threats, seizing opportunities, and maintaining competitiveness by enhancing, combining, protecting or reconfiguring tangible and intangible assets [116]. SCRES is consistent with this definition [91], because it can be considered a dynamic capability which enables companies to early recognize, prepare or even absorb SC risks and disruptions (sensing) as well as swiftly responding to dynamics by adapting and reconfiguring structures, resources and capabilities in order to restore or even enhance performance (seizing) [16, 42, 43, 119]. The strategic value of SCRES lies in the fact that companies which better resist, cope with and quickly recover from disruptions can strengthen and sustain competitiveness, e.g. by maintaining operations and delivery reliability during crisis or achieving higher pace in capturing market shares after a disruption (maintaining competitiveness) [24, 39, 42, 74, 91]. Further research on DCT has identified adaptive capability, absorptive capability, innovation capability, timely perception capability, learning capability, and resource reconfiguration capability as dimensions of dynamic capabilities [120] which is to a great extent equally congruent with approaches in SCRES [17, 40, 42, 43, 45]. Several recent disruptions like the COVID-19 pandemic, have tremendously increased uncertainty and environmental dynamics, requiring companies to implement certain practices and reconfigure internal and external resources and capabilities [17, 22, 24, 40, 119, 121].

The emergence of DTs in recent years has also contributed to increasing dynamics of environments and competition [61]. On the one hand, dynamic capabilities may be necessary to effectively integrate DTs, i.e. effectively adjusting the resource base of a company. On the other hand, DT adoption has the potential to affect both ordinary operational capabilities as well as dynamic capabilities like SCRES. The strategic value of DT adoption is enrooted in the specific integration with existing SC processes, structures, skills and resources to support the development of dynamic capabilities like SCRES and its formative capabilities [91, 115]. For instance, technologies like IoT or blockchain may help to collect, process, analyze and share data to increase SC visibility and sense abnormalities early in SCs, allowing reconfiguration and response development as an adjustment of resources, capacities or practices [56, 84, 85]. Digital SC twins and big data analytics improve strategic decision-making and resource (re)configuration problems [73, 74], e.g. the allocation of excess capacities and stocks at the most vulnerable points of a SC. Another set of DTs may enhance agility and flexibility (e.g. additive manufacturing, robotics) as well as collaboration and information-sharing (e.g. digital platforms), required to achieve SCRES [54, 56]. Consequently, many scholars consider SCRES and SCD as dynamic capabilities [91, 96, 122, 123, 124]. Recently, DCT has been adopted to investigate e.g. the relationships of data-driven digital transformation, big data capabilities, predictive analytics and SCRES [79]. In addition, there has also been developed a combination of RBV and DCT, i.e. dynamic resource-based theory and capability lifecycle concept, assuming capabilities go through stages of evolution and transformation [63, 125]. This approach integrates the strategic perspectives of resources (assets or production inputs) and organizational capabilities (performing a coordinated set of tasks to achieve desired results). Applied to SCD and SCRES, the adoption of DTs can be considered resources which needs to build and transform into capabilities [63, 126]. Accordingly, digital SC capabilities refer to DT resources which are exploited by companies to achieve a range of benefits, e.g. network visibility, flexible production, stronger collaboration across SC stages or increased efficiency [86].

C. *Practice-Based View*

From another perspective, the strategic role of physical technologies and complex information management systems as source of competitive advantage and performance enabler has been discussed controversially in literature. The original work on RBV stated, on the one hand, that these technologies cannot fit all four RBV criteria, because once they are built or developed, every company could purchase them. On the other hand, the exploitation of such technologies depends on complex social firm resources and the specific implementation, leading to different levels of competitive advantages among companies using the same technologies [108]. This discussion highlights the critical point of considering the implementation process and building specific practices when adopting DTs to achieve competitive advantage.

Ensuing from this perspective, the practice-based view (PBV) represents a relatively new and alternative strategic approach which explains performance variations of companies based on adopting certain imitable practices or even day-today activities that are transferrable across firms [75, 127, 128]. As theoretical justification, the authors of PBV [127] refer to a number of empirical studies from different research fields that find variations across companies in the adoption of publicly known standard practices which might at least partially explain variations in firm performance while more recent studies indicate similar observations [69]. Within this context, a practice is defined as an activity or a set of activities which can be developed and executed by various companies to achieve a desired performance level, contrasting the RBV emphasis on inimitable resources and isolation mechanisms [127, 129]. The PBV criticizes that many studies in strategic management focus on macro-level firm behaviors or characteristics and their impact on firm performance, neglecting thereby feasible, specific and real-world techniques that companies develop or adopt to achieve higher performance [127]. This perception of PBV relates to risk management, operations and SCM research as theoretical lens in the way that the focus of investigation is set on explaining which firms adopt which feasible practices and understanding the impact on firm performance [89, 129].

Within the context of the intersection of SCD and SCRES, PBV-driven research can explicitly focus in-depth on feasible and practically imitable practices how to exploit DTs for building SCRES. This further includes applicable practices like e.g. how do companies identify SCRES needs and appropriate DTs, how are different DTs and adoption scenarios evaluated or how is the implementation process effectively executed (barriers and success factors). Moreover, while acknowledging a great range of opportunities and variations regarding the specific adoption of different DTs in certain SCM processes to foster distinct SCRES capabilities, PBV also scrutinizes the transferability of such practices (e.g. technology acquisition or adoption of DT-driven practices to enhance SCRES).

Further, the authors of PBV [127] note a link to other theories, i.e. behavioral theory of the firm which considers a firm as complex system of routines and decision-making processes [130], evolutionary economics [131] or firm capabilities [132]. From these points of view, practices form the base for routines, decision-making processes, continuous improvement (e.g. quality management practices) or building capabilities [127]. Recently, the PBV has gained interest in related research [69, 128] and has been increasingly applied, e.g. to investigate relationships between Industry 4.0 implementation, resilience and performance stability of manufacturing companies during the COVID-19 pandemic [89], the impact of intra- and inter-organizational SC practices to respond to natural disasters [133] or the role of artificial intelligence-driven big data analytics capability for fostering agility, resilience and performance in humanitarian SCs [75].

D. *Organizational Information Processing Theory*

Organizational information processing theory (OIPT) may also provide a beneficial lens to the proposed research stream. From an OIPT perspective, organizations are considered information processing systems which have to deal with uncertainty, whereby information processing refers to the collection, interpretation, distribution and synthesis of information for the purpose of organizational decision-making [134]. The fundamental assumption of OIPT is that the greater the uncertainty originating from a complex task, its environment or its interdependence with other tasks, the greater the information processing requirements are to achieve a desired performance level. As such, information processing capabilities provide the foundation of organizational decision-making, leading to strategic and operational adjustments in resource allocations, schedules, priorities, relationships with partner, organizational design or sales and operations [134, 135, 136].

Interestingly, OIPT additionally relates to SCRES by stating that variations in the organizational abilities of preplanning (related to the notions of robustness or preparedness) and adapting to the inability to preplan (related to unexpected disruptions) explain variations of organizational forms and performance along with intended performance reduction to survive [135]. Further, it highlights the creation of slack resources as means to reduce the information processing requirements within organizations as exceptions and complexity start overload organizations [135]. Furthermore, the OIPT states that information processing requirements and information processing capabilities must be balanced to achieve high performance levels [134]. Given the number of participants, processes, transactions, interactions, products, services and interdependencies, SC networks naturally generate huge amounts of data far beyond the human information processing capacities [83]. Moreover, the ongoing adoption of DTs like IoT in SCM will further increase the amount of generated data significantly [91].

The OIPT fits with the two underlying concepts of this paper. Firstly, SCRES from the perspective of the VUCA notion, i.e. an increasingly volatile, uncertain, complex and ambiguous environment which represents a major current challenge for many businesses. SC risks and disruptions vary in their nature and represent a major source of uncertainty characterized by complex interdependencies along multiple functions and processes in intertwined SCs. This clearly implies that in cases of SC disruptions, the information processing requirements increase significantly. Consequently, companies are required to build capabilities and formal mechanisms related to collecting, processing and analyzing large amounts of data which is considered indispensable to build SCRES [137] and can foster higher performance and competitiveness [96]. Secondly, a range of innovative DTs like AI, blockchain, IoT, cloud computing or big data analytics have the potential to automatically collect and store massive amounts of data and tremendously enhance information processing and analytics capabilities to achieve better and accelerated decision-making [138]. In terms of SCRES, this implies that risk data lead to a more effective disruption discovery and response planning [79, 86].

Some recent studies have applied the OIPT lens [68, 96], e.g. to examine the positive impact of big data analytics capabilities on organizational information processing capacity to establish more accurate and integrated SC planning processes [136], to reveal how DTs influence economic and environmental performance [139] or along with RBV to study the association between I4.0 and SC performance through SCRES [140].

E. *Contingency Theory*

Another fruitful theoretical extension lies in the combination of traditional approaches like RBV or DCT with contingency theory (CT) to more holistically explain the adoption of SCM practices with higher explanatory and prescriptive rigor [98, 141, 142, 143. 144]. Scholars have argued that with a growing maturity of operations management practice research the focus has shifted from investigating the value of specific practices towards understanding the contextual factors determining their effectiveness [143]. The core of CT proposes that companies should align their structures and practices to the specific context in which they operate. This also implies the requirement to adjust structures and routines in response to changing environments to ensure a desired performance level [145]. Therefore, the main contribution of CT is the examination under what conditions or in which situations specific practices or capabilities achieve higher effectiveness or performance [146]. It deals with the identification and integration of contextual variables in research models and the measurement of their impact on potential causal relationships, deepening the understanding of investigated phenomena and strengthening the generation of prescriptive knowledge about feasible practices [143]. Examples of contextual variables include firm size, geographic location, industry, level of country development, strategic orientation, level of international competition, level of internationalization, product value, product complexity, product volume or type of production process and strategy [143]. Interestingly, CT also provides an important extension to PBV, as there have been controversial results in literature about the benefits and performance impacts of different SCM practices, supporting the argument that the effectiveness of practices is depend on certain conditions.

CT provides the important implication for research on the intersection of SCD and SCRES to factor in moderating variables or specifically examine under which conditions different DT adoption scenarios are particularly (in)effective to build SCRES (e.g. SC complexity, firm size, culture, digital management capabilities, etc.). Past research adopts CT e.g. to examine the performance impact of SC agility and SC adaptability under consideration of the moderating effect of product complexity [146]. In combination with RBV it has been adopted to examine the resource bundling effect of SC connectivity and information sharing to build SC visibility capability which in turn enhances SCRES [98] or to investigate the relationships between intrinsic and extrinsic barriers to digitalization, I4.0 adoption and the impact on operational performance and SC competence [147].

F. *Systems Theory and Complex Adaptive Systems*

Systems theory (ST) is considered another promising theoretical lens for SCRES and SCD research as it overcomes some shortcomings of other theories like RBV, DCT or CT which e.g. focus on internal resources and individual companies as unit of analysis [17, 148]. According to ST, organizations are open systems interacting with their environment to maintain functionality [48, 148, 149]. Therefore, ST proposes systems as unit of analysis instead of singular firms which fits the general argument that SCs constitute open systems composed of several nodes that are linked by material, information and financial flows which continuously interact with their environments. It further matches the notion of SCRES as systemic feature and network or system level phenomenon [17, 150, 151]. As such, vulnerability to disruptions and the impact on the system functionality depends on the system-level resilience [48]. Historically, the concept of resilience has been discussed in different system settings like ecological systems (persistence of relationships) [152], engineering systems (anticipation, recognition and proactive protection against disruption) [153, 155] and social-ecological systems (magnitude of shock absorption, degree of self-organization, learning and adaption [154, 156]. In SCRES research, ST has been applied to examine extended enterprise resilience based on IT-enabled capabilities like agility, flexibility, adaptability and connectivity [150] or in conjunction with RBV to identify antecedents of SCRES [48].

Recently, the adoption of ST in SCRES research was extended by cybernetics, i.e. the science of information control and communication supporting dynamic decision-making [148, 157, 158, 159] which lends itself as theoretical lens for SCD. Cybernetics extends traditional ST with a focus on cyclical, feedback-driven, causal processes to cope with disruptions and recovery control actions [148] which can be facilitated by DTs enhancing connectivity, data analytics and automation.

Associated with the ST perspective is the notion of complexity and constant change. As such, SCs can be described as “complex networks of enterprises that experience continual turbulence, creating a potential for unpredictable disruptions“ [160, p. 1]. In fact, complexity has been a central notion and driver in SCM research with many scholars stating that global SCs are increasingly more difficult and complex to manage [3, 35, 91, 161]. Against the background of SCD, information complexity (i.e. poor data integration, quality and delayed access to valuable information) is highlighted as critical success factor for SCRES [75]. Therefore, some authors have called for considering SCs as complex adaptive systems (CAS), synthesizing theory of both fields [17, 106, 162, 163]. A CAS refers to a system “that emerges over time into a coherent form, and adapts and organizes itself without any singular entity deliberately managing or controlling it” [163, p. 352]. As thoroughly elaborated by [17], CAS theory provides important network and system-related features and dynamics which fit contemporary SCs and the concept of SCRES. This comprises heterogenous agents (suppliers, customers, service providers, etc.), multi scale (SCRES as collective outcome of interacting agents), schema (SCRES strategies and plans), adaption and co-evolution (responding to disruptions), environmental dynamism (internal and external changes and risks), ability to learn (organizational learning, social capital), nonlinearity (ripple effect, small disturbances can lead to large-scale disruption in interdependent SCs), network connectivity (information and material flows), dimensionality (individual agent´s freedom of intentional decision-making to influence the course of actions), self-organization and emergence (SCRES decisions by individual SC agents lead to collective self-organization of the system, resulting in new structures and patterns) and scalability (SCRES as collaborative system property, sharing of common strategies and practices).

The common ground of CAS theory and SCRES represents a starting point to establish links to SCD. For instance, when visibility for individual nodes in SCs is limited (e.g. to T1 supplier), what lies beyond this horizon will simply emerge and requires a certain degree of self-organization of the SC network [106]. However, several DTs can significantly increase SC visibility, network connectivity and collaboration among heterogeneous SC agents with subsequently higher levels of interactions and feedback loops through an effective web of information flows [56, 61]. Furthermore, enhanced data processing and analytics capabilities as well as simulations improve the ability of organizations and individual nodes to better understand or cope with complexity, nonlinearity or volatile environments which also impact their dimensionality (decentralized decision-making) regarding the development of proactive or reactive disruption responses [163]. Moreover, big data analytics and AI may be used to improve forecasts, enhance the ability to learn, or recognize changing patterns and disruption risks in complex and dynamic environments through huge amounts of different data sources [106]. Therefore, DTs may directly impact SCRES strategies and specific practices (schema) involving other SC agents while representing technologically and organizationally scalable approaches. Thus, DTs can arguably shape the degree of self-organization and increase the interdependency of decision-making of individual SC members, leading to a more coordinated and structured SC system behavior regarding SC disruptions [162]. Overall, DTs provide the opportunity to better manage the characteristics of CAS and extend the limits of static and deterministic plans, controls and operations. Further, the adoption of DTs in SCM links to a certain extent to the evolution feature of CAS, viewing SC systems as undergoing constant evolutionary change through SCD in the quest of optimizing SCM performance [88].

G. *Normal Accident Theory*

Ultimately, normal accident theory (NAT) is presented as seminal lens for future research on SCRES and SCD. The core of NAT elaborates conditions under which accidents or disruptions are more likely to occur with impact propagation across multiple system elements [165, 166, 167]. In contrast to CT, NAT proposes distinct conditions which favor the occurrence of accidents, i.e. interactive complexity, the degree of tight coupling and the link of both variables [166, 167]. Interactive complexity refers to unfamiliar, unplanned, unexpected, invisible or not immediately comprehensible sequence of actions [165] which strongly links to the nonlinear interactions and behaviors in CAS [160]. Interactive complexity causes accidents to take place in unanticipated ways while a system´s proneness to be affected by rapidly spreading disruption impact depends on whether elements are tightly or loosely coupled [168]. Given the presence of the two factors of interactive complexity and tight coupling, NAT considers accidents to be normal and inevitable [166] which greatly overlaps with the perception of many SCRES scholars that risks and disruptions are inherent to contemporary SCs due to their complexity [19, 21, 35, 36, 91].

Accordingly, NAT proposes the development of capabilities which address the complexity of interactions and level of interconnectedness in systems [169]. In SCRES research, NAT has been complemented with systemic risk theory to provide a theoretical basis of why and how SC disruptions emerge and what drives their systemic propagation in SC networks [78]. In fact, scholars highlight the interconnectedness of contemporary SC networks, leading to disruption propagation risks (ripple effect), i.e. a failure in one company may lead to disruptions in other SC nodes or even to a dysfunctionality of the entire SC [39, 48, 61, 168]. Scholars have adopted NAT, e.g. to examine the relationship between supply network complexity and the traceability of adverse events in food SCs [170], SC disruption mitigation in the steel industry [168], mitigation of product safety and security risks [171] and antecedents and measurement dimensions of SCRES [169].

Overall, NAT highlights critical system features related to SCRES which are worthwhile to be examined in-depth, taking into consideration the impact of SCD. Regarding interaction complexity, DTs like digital business networks, ecosystems or platforms enable higher levels of integration and fundamentally transform how companies in a SC interact internally across functions and externally across organizational boundaries with suppliers or customers [62, 64, 86, 90]. Furthermore, some SC interactions are automated and digitalized (e.g. smart contracts based on blockchain), partially reducing human interaction [64] while machine-to-machine communication and interaction is increased by e.g. IoT, cloud computing, mobile applications or AI [86, 172]. Huge amounts of data and advanced analytic capabilities provide useful insights and are considered a major lever to handle complex SC risk interactions [83]. The issue of tight coupling can be mitigated by incorporating slack resources like inventories in the SC [168]. DTs can render this process more effective by supporting SC understanding (disruption impact and propagation) and SC re-engineering through big data analytics, digital twins and SC visibility to determine suitable spots in the SC where to integrate precise levels of slack resources like inventories or where are weak spots requiring more flexibility [1, 61, 73]. In addition, DTs enhance the capacity to proactively reduce the probability of some risks or increase velocity when collaborating to respond to disruptions in tightly linked system [56].

VII. SUMMARY AND CONCLUSION

This conceptual paper presents an innovative and critical research field at the intersection of SCRES and SCD to inspire future research, following recent calls from academia. Given the limited use of theory in SCRES research and many literature reviews in this field neglecting the adoption of theories, this work attempts to provide some relevant theoretical lenses and indicates their applicability. It aims at informing and enriching future research by highlighting the potential for integrating knowledge of SCRES, SCD and their interrelationship with an established and structured body of knowledge to provide deeper insights and more holistic frameworks. According to the best of the author´s knowledge, this is the first attempt to provide a set of fruitful theoretical lenses to the intersection of SCD and SCRES. While frequently used theories in SCRES research like RBV or DCT need to integrate SCD, relatively novel or rarely adopted theoretical lenses like IPT, CAS, PBV or NAT can serve scholars to conduct more rigorous and insightful research, in order to guide SC managers to build future-proof SCs that are not only lean and cost-efficient, but are also more data-driven and resilient to build competitive advantage. However, the list of potential theories that might enrich the presented research area is non-exhaustive and goes far beyond the contents elaborated in this work (e.g. high reliability theory [173, 174]), representing a subject of future research.

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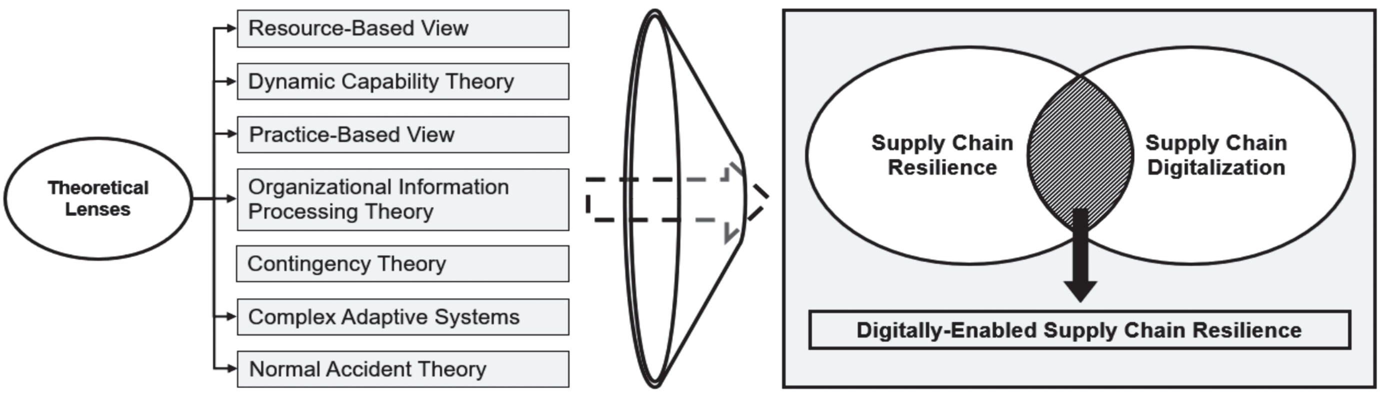

Figure 1: Digital SCRES Framework (based on [56])

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