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Analysis of resilience strategies and ripple effect in blockchain-coordinated supply chains: An agent-based simulation study

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ABSTRACT

Resilience enables supply chains to reduce their proneness to disruptions and recover faster. Many existing strategies to strengthen the resilience of supply chains are facilitated by the use of digital technology. Blockchain, as one of the promising innovative technologies, enables a transparent, secure, and timely data exchange and automation via smart contracts. In this paper, we discuss the impact of blockchain technology on supply chain risk management and, in particular, on supply chain resilience. We identify potential risk-related blockchain application scenarios and examine their impact on the existing resilience strategies. We explore the impact of the most promising applications with respect to resilience by using an agent-based simulation model of a complex supply network affected by disruptions. The theoretical analysis reveals a promotion of supply chain resilience strategies, especially if smart contracts are used for risk-related collaboration. The simulation study indicates an increase in resilience if the underlying collaboration is based on time-efficient processes: The propagation of disruptions, the network recovery time, and total costs can be substantially reduced. However, depending on the duration of the disruption, negative effects can occur if process efficiency is insufficient. From our investigations, we derive insights for managers who are interested in practical implementation.

1. Introduction

In recent years, supply chains (SCs) have experienced various incidents that have fundamentally endangered their operational performance and the existence of individual members. One example is the COVID-19 pandemic, which has recently threatened global and intertwined supply networks (Ivanov, 2020; Ivanov and Dolgui, 2020a). The vulnerability of SCs to disruptions has grown over the last decades due to intensified collaboration and a stronger focus on SC efficiency (Kamalahmadi and Parast, 2016; Papadopoulos et al., 2017; Stecke and Kumar, 2009) and the effects of disruptions no longer only affect individual members but tend to spread across the entire network, a phenomenon known as the ripple effect (Dolgui et al., 2018, Dolgui et al., 2020b; Ivanov, 2018a; Pavlov et al., 2019). In response, SCs are investing in increasing SC resilience by developing capabilities such as redundancy, multi-sourcing, collaboration, and inventory or capacity flexibility, which promise to better protect SCs against unforeseen disruptions (Ivanov, 2018a; Tukamuhabwa et al., 2015). By increasing their resilience, SCs reduce the likelihood of negative disruption impacts on SC operations and performance. SCs are then able to rapidly detect the occurrence of a disruption, and swiftly recover and even improve their prior performance level through appropriate mitigation and recovery strategies (Hosseini et al., 2019).

Collaboration can increase dependencies on other participants due to stronger interactions, therefore increasing risk exposure and the ripple effect, but may also have a positive effect as a resilience strategy when used appropriately. Collaboration encompasses information sharing, decision synchronization, resource sharing, collaborative communication, and goal alignment (Cao and Zhang, 2010; Park et al., 2004). Information technology is primarily used as a catalyst for fast, secure, and frictionless collaboration (Fawcett et al., 2011; Li, 2006). Scholars have recently highlighted the value of digital information technologies and SC digital twins to manage disruption risks (Ivanov and Dolgui, 2020b). A new promising digital technology that proves to be particularly helpful in the field of transparent, secure, and efficient collaboration is blockchain technology (BCT) (Leible et al., 2019). According to a study by KPMG in 2019, 48% of the 740 global technology leaders surveyed believe that BCT is likely or very likely to change their business in three years (KPMG, 2019). In a Deloitte survey, 53% of respondents already view BCT as a critical priority in their organizations (Deloitte, 2019). In

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the research area of supply chain risk management (SCRM), BCT has only been marginally investigated.

Therefore, our research goals (RGs) and novel contributions to the research field of SCRM consist of developing potential application scenarios for this new technology (RG1) and the theoretical investigation of the impact on resilience strategies (RG2). Furthermore, instead of the abstract consideration of the mechanism of resilience strategies in previous literature, we conduct a detailed quantitative analysis of the benefits and influencing factors of the most promising BCT potential application (RG3) and also derive managerial insights to support the implementation of BCT for practitioners (RG4).

The remainder of our study is organized as follows. In Section 2, we first give an overview of the research field of SCRM and SC resilience, highlighting the research deficits in terms of how exactly resilience strategies affect SC resilience. We then examine BCT in more detail, emphasizing the limited consideration in SCRM so far. In Section 3, we develop potential application scenarios of BCT in connection with SCRM and supply chain disruptions. We then examine the influence on resilience strategies to identify the theoretical advantages of the application scenarios on SC resilience and to select the most promising approach. Section 4 critically examines the most promising application scenario in a simulation study to determine the exact impact on the resilience of the SC. Results, a sensitivity analysis of structural parameters, and managerial insights for the implementation of this technology are provided in Section 5. With Section 6, we conclude the contribution and provide meaningful future research directions.

2. Supply chain resilience and blockchain technology in the context of SCRM

2.1. Supply chain resilience

Resilience refers to a multi-dimensional and multi-disciplinary concept that originates from psychology and ecology and has been applied to SC management (Pettit et al., 2010; Ponomarov and Holcomb, 2009). It can be described as the capability of the system to anticipate, detect, and defend itself against risks before negative consequences occur (Hollnagel et al., 2017). SC resilience capacity is made up of two parts (Dolgui et al., 2018): resistance and recovery. Resistance describes the ability of the network to minimize disruption impacts by avoiding the disruption or beginning to recover promptly. Recovery is concerned with the network's ability to return to a steady or improved system state once a disruption has been encountered (Melnyk et al., 2014).

Specific SC resilience strategies (also called enablers, elements, or principles) on how to increase SC capabilities are proposed in the literature (Li et al., 2017). The strategies are either proactive, reactive, or both and usually target specific risks that need to be prevented or addressed efficiently (Kamalahmadi and Parast, 2016). Frequently mentioned more general attributes include flexibility, redundancy, collaboration, visibility, and agility (Hohenstein et al., 2015; Johnson et al., 2013). More specific resilience strategies recognized in the literature include backup capacity and inventory, increased security, economical supply incentives, postponement, supplier relationship building, demand forecasting, as well as the development of IT infrastructure and information sharing (Chopra and Sodhi, 2004; Ivanov and Rozhkov, 2017; Melnyk et al., 2014; Tang, 2006a; Tomlin, 2006; Yilmaz et al., 2017).

The effectiveness of certain resilience strategies has been examined in several empirical studies. Jüttner and Maklan (2011) observed that SC risk effect management and SC risk knowledge management increase SC resilience. Pettit et al. (2010) proposed that SC resilience should be balanced with SC vulnerability in order to achieve better performance. Empirical studies showed that SC resilience increases as resilience capabilities increase and SC vulnerabilities decrease. Wieland and Wallenburg (2013) revealed a positive connection between communication, cooperation, integration, and SC resilience. Mandal et al. (2016) surveyed 339 SC professionals and found a positive impact of collaboration, flexibility, visibility, and velocity on SC resilience. The authors also found a positive impact of integrated logistics capabilities on SC collaboration and visibility. Yu et al. (2019) revealed a significant positive effect of dynamism (pace of changing products and processes) on SC resilience.

The quantification of SC resilience is essential to gain feedback on past resilience-related decisions and be able to make future decisions in a targeted manner. The so-called transient response, the reaction of performance measures in a time-plot after a disruption has occurred (Melnyk et al., 2014), can be used to measure the resilience of the system quantitatively (Fiksel, 2003; Melnyk et al., 2014). Bruneau et al. (2003) developed the so-called resilience triangle to measure resilience and considered the aspects of robustness and speed in the calculation of the integral over the performance losses up to the stabilization of the system. Falasca et al. (2008) applied the resilience triangle to evaluate the three SC design attributes complexity, density, and node criticality. Several authors then evaluated the resilience of various industry-specific supply chain models using simulation (Carvalho et al., 2012; Munoz and Dunbar, 2015; Spiegler et al., 2012) or analytical models (Cardoso et al., 2015; Dixit et al., 2016; Garcia-Herreros et al., 2014; Zobel and Khansa, 2014). In recent contributions, Ivanov, 2018b examined the spread of disruptions in the SC, taking sustainability factors into account. Sabouhi et al. (2018) evaluated the resilience strategies of multi-sourcing, reinforcement of suppliers, and pre-positioning of emergency stocks. The implementation of all these strategies led to the lowest costs. Ledwoch et al. (2018) discovered a moderating effect of SC network topology on the effectiveness of risk management strategies (inventory mitigation, contingent rerouting) and ultimately on SC resilience using agent-based modeling.

This first part of our literature review reveals that previous empirical and quantitative studies have not yet considered the impact of BCT on supply chain resilience. This is one of the motivating factors behind our in-depth analysis. Other reasons are statements of authors such as Babich and Hilary (2020), Ivanov et al. (2019), and Min (2019), who assume a positive influence of BCT on SC resilience. BCT would establish itself as another promising tool of SCRM and possibly motivate further research and practical applications if these statements were to be assessed by research.

2.2. Blockchain technology

Blockchain essentially represents a distributed ledger, a special distributed database that is managed decentrally. A copy or version of the ledger is stored on every node in the network. The ledger is a list of transactions that records events as well as information and value flow between participants in a peer-to-peer network (Crosby et al., 2016). Transactions are aggregated in blocks and distributed across the network with reference to preceding blocks, building the figurative "chain" of blocks. The ledger is protected by strong means of cryptography, including private keys to sign transactions, hash functions to link blocks, and consensus mechanisms (Swan, 2015). Disintermediation is a crucial feature of BCT as decentralized nodes instead of intermediaries verify transactions. To coordinate the nodes and decide which block should be added to the ledger next, consensus mechanisms like Proof-of-Work, Proof-of-Stake, or Proof-of-Authority are used (Makhdoom et al., 2019). The most important influencing factors and features of blockchain are immutability, transparency (single source of truth), disintermediation, irreversibility, and the automation potential through smart contracts (Babich and Hilary, 2020; Pournader et al., 2020).

The various configurations of blockchains in use today differ in their access control (public vs. private and permissioned vs. permissionless) and the employed consensus mechanism. Public and permissionless usually refer to cryptocurrencies like Bitcoin or Ethereum, while most proofs-of-concept in business have been deployed on private and permissioned networks (Wang et al., 2019a). As a disruptive technology, blockchain could lead to a comprehensive change in the design and operation of SCs. This is strongly related to features such as reliability, traceability, and smart contracts for trustworthy relationships across the network (Saberi et al., 2019; Wang et al., 2019b). Smart contracts are key features of BCT to enhance SC operations. They represent agreements that are digitalized and stored on the blockchain with a unique address. Smart contracts can self-execute when certain conditions specified in the protocol are met and can be linked to natural language contracts or run independently to automate actions (Weber et al., 2016). Entities in the blockchain system can also trigger the transaction's execution. By automating transactions, value exchange, and information sharing, smart contracts promise increased process accuracy, security, speed, and traceability, while at the same time reducing costs (Dolgui et al., 2020a).

Several specific applications of BCT for SC management have been developed by scholars and industry recently, which can be assigned to certain primary categories including product provenance (traceability), enhanced SC operations (related to security, transparency, visibility), trade finance, disintermediation, data security, and smart contracts (Cole et al., 2019; Pournader et al., 2020; Wang et al., 2019a). Popular industrial initiatives with proofs-of-concept are indicated in the following: Provenance and Everledger reveal the provenance of diamonds or food products and enable tracking and tracing, enhancing trust through technology. Information about individual steps in the SC can be shared, e.g. when, where, and by whom a production step was carried out and to which transport partner the product was handed over when and where (Everledger, 2019; Provenance, 2020). Maersk works with IBM on the digitalization of maritime trade and creating an end-to-end transparent SC in their TradeLens project, with a secure audit trail of transactions consisting of logistics milestones, movement information, and trade documents (TradeLens, 2020). Secure information sharing between SC partners in near real-time is facilitated and thus also influences risk management in the SC. For SC financing, Daimler and LBBW examined the use of BCT to speed up and simplify financial transactions (LBBW, 2017). Using BCT reduces the risk of non-payment and minimizes dependency on intermediaries. Combined with tracking and tracing, the use of smart contracts can further simplify and automate financial settlements between SC partners. FedEx uses BCT to store data in a streamlined and secure way (Rajamanickam, 2018), which prevents risks like fraud or loss of expertise.

The applications presented are primarily aimed at general SC management, but blockchain also has particular merits for SCRM. An integration of IT systems with SC processes to build collaborative platforms which share data like demand forecasts, inventory levels, or production capacities to enhance risk management processes has been highlighted by several studies (Duhamel et al., 2016; Li, 2006). The key drivers for SC resilience are integration and flexibility capabilities to enable trustworthy collaboration (Brusset and Teller, 2017), secure communication channels and built trust (Kamalahmadi and Parast, 2016), information sharing (Duhamel et al., 2016), and a decentralized structure of the SC (Datta et al., 2007). However, vertical and horizontal collaboration with information sharing and other means such as joint decision-making (Barratt, 2004), has not been easy to achieve with traditional methods. The security features, the decentralized structure, and the detailed transaction history of blockchain are some of the advantages that also support the consideration and application of BCT for SCRM.

However, existing blockchain research in the area of SCRM is limited. Kshetri (2018) highlighted the ability to verify product provenance as well as a possible reduction of cybersecurity-related risks. Min (2019) argued that BCT might transform SCRM into a proactive, multi-layer protected risk management based on the sharing of both risk and information. Choi et al. (2019) conclude that BCT can limit opportunism, enables faster forecasting and scheduling, increases visibility, and simplifies contract design using smart contracts. Choi et al. (2020) argue that BCT helps reduce information audit costs, increases information awareness on the customer's side, and thus reduces demand volatility. Babich and Hilary (2020) indicated SCRM as an essential research area for BCT, with links to visibility, product provenance, and transparency. BCT also enables the identification of all customers affected by a disruption. Recently, Ivanov et al. (2019) analyzed the impact of several digital technologies on the ripple effect and SCRM. The authors highlighted the improved SC visibility and real-time event identification using blockchain and argued that the implementation of BCT could have a positive impact on the ripple effect.

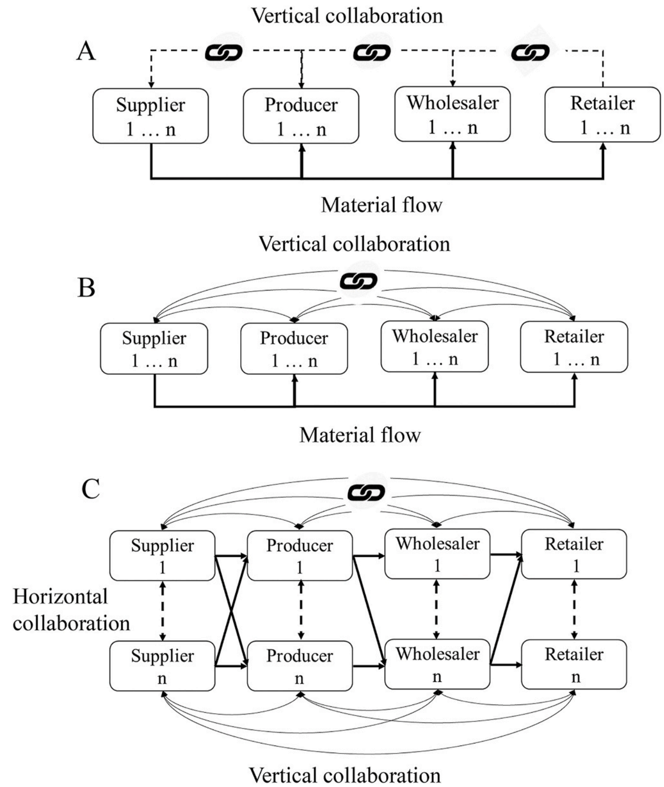

Fig. 1. Potential application scenarios for blockchain implementation in SCs to increase collaboration and SC resilience.

So, blockchain may increase SC visibility and enable real-time sharing of data in the network, which could reduce the number of partners affected by a disruption and support SC resilience strategies. As an in-depth analysis of the impact of blockchain on risk management has not been conducted yet, we start with a systematic investigation of BCT for SCRM and known strategies that may increase SC resilience, as the above approaches demonstrate. We develop several potential application scenarios of BCT in SCRM and analyze their impact on resilience to select the most promising scenario that is then used for the quantitative simulative analysis. Thus, the theoretical investigation can be supplemented by a detailed quantitative investigation and further influencing factors, such as the specific design of the blockchain solution, and causal relationships can be investigated. In the quantitative analysis, we do not rely on only one or two performance indicators at a company level to discuss resilience, like many of the above approaches, but instead use the total costs, recovery time, and the number of affected partners of the entire network.

3. Theoretical analysis of the impact of blockchain technology on SC resilience

3.1. Illustration of feasible potential application scenarios of blockchain technology in SCs to support SC resilience and SCRM

When BCT is considered with SCRM and the context of enhancing the resilience of the whole network, there are several conceivable potential

Table 1
Assessment of different SC resilience strategies and influence of blockchain technology on the resilience approach.

Resilience strategies		*Approach*	*Risk prevention/Performance improvement*	*Influence by application scenario*			*Supporting source in literature*
				A	*B*	*C*	
Collaboration	Information sharing	Enhance connectivity IT to share information	Signaling potential disruptions, initiate countermeasures	o	++	++	Min (2019); Saberi et al. (2019); Swan (2015)
	Social capital and relational competences	Communication, cooperation, integration of SC partners	Increase risk awareness, build trust (formal & informal)	o	+	+	Hull (2017); Scott et al. (2017); Wang et al., 2019a
	Coopetition	Sharing of demand or resources	Build security and resilience, working for mutual benefit	o	+	++	Li et al. (2018); Lohmer (2019); Wang et al., 2019a
	Contractual agreements	Contracts (long/short term) to enable flexibility, sharing of risks and revenues	Minimize disruption impacts (e.g., supply shortages)	+	+	++	Saberi et al. (2019); Wang et al., 2019a
SC Reengineering	Supply chain network structure/design	Constructing SC networks tailored for resilience	Balancing redundancy, efficiency, vulnerability	+	+	+	Cole et al. (2019); Hull (2017); Ivanov et al. (2019); Saberi et al. (2019)
	Contingency planning	Reactive measures and protocols	Prepare contingency plans	o	++	++	Cole et al. (2019); Ivanov et al. (2019); Saberi et al. (2019)
	Creating redundancy	Use of spare capacity and inventory (e.g., redundant supplier)	Avoid capacity or inventory scarcity due to disruptions	o	o	+	Babich and Hilary (2020); Ivanov et al. (2019); Makhdoom et al., 2019
Agility	Increasing flexibility	Postponement, flexible supply base	Adapt to changing requirements	+	+	++	Ivanov et al. (2019); Kshetri (2018); Li et al. (2018); Wang et al., 2019a
	Increasing visibility	Transparency across the entire SC	Identify threats, react quickly to disruptions of all kinds	o	++	++	Blossey et al. (2019); Ivanov et al. (2019); Petersen et al. (2018); Wang et al., 2019a
	Increasing velocity	Enable rapid adaptation to new conditions	Mitigate the impact of unpredictable disruption	+	+	++	Cole et al. (2019); Ivanov et al. (2019); Kshetri (2018); Saberi et al. (2019); Wang et al., 2019a
Miscellaneous	Risk management culture	Implement and develop SCRM culture	Top management support for efficient SCRM strategies	+	+	+	Ivanov et al. (2019); Kshetri (2018); Saberi et al. (2019)
	Increasing innovativeness	Invent and seek new business models	Diversification, reduce vulnerability	o	+	+	Blossey et al. (2019); Oh and Shong (2017)
	Building logistic capabilities	Increasing delivery speed, reliability, and cost-efficiency	Logistical vulnerabilities in the SC (e.g., delays in transport)	o	+	++	Choi et al. (2019); Cole et al. (2019); Treiblmaier (2018)
	Building security	Protection of the SC (e.g., cyber-security)	Reduction of theft or infiltration	o	+	+	Hull (2017); Li et al. (2018); Makhdoom et al., 2019; Wang et al., 2019a

Scale: –, -, o, +, ++ corresponding to a Likert scale (–: strong negative influence of the blockchain on the efficient application of the resilience strategy, -: negative influence, o: no perceived influence on strategy execution, +: positive influence, and ++: strong positive influence).

application scenarios for BCT application. Based on the applications for SC management in Section 2.2, we now present three specific scenarios of BCT for SCRM in Fig. 1 and describe them in detail below. The degree of integration and collaboration between the SC partners gradually increases (from scenario A to C).

The first scenario (A) involves unidirectional sharing of demand data in vertical collaboration. The downstream partners regularly (e.g., daily) pass on demand data to the upstream partners. Unlike in conventional, centralized systems, this is executed as a transaction on a blockchain, which is configured exclusively for the exchange of information between two partners. Immutability is thus guaranteed and each transaction is provided with a timestamp. Following this structure, entities in the SC are thus only connected to neighboring entities and visibility of the entire value chain is missing. Several blockchains are needed to serve the network. Trade finance is another scenario, where blockchain facilitates the processing of financial flows, ensuring direct and transparent payment for services, which can improve trust and collaboration in the network. Individual IT systems of the partners can automatically check transactions and reactively make adjustments to operations. This application scenario has the same theoretical foundation as well-known concepts of information sharing in the literature that aim to reduce, e.g., the bullwhip effect (Ouyang and Li, 2010) since timely information transfer in the SC increases the ability to react. Methodically, this approach is easy to implement. The partners only need to increase their collaborative efforts to a small extent. The technical implementation is subject to change as simple private blockchains can be used for the respective relationships between entities. However, BCT's only advantage over a conventional solution using other IT methods in this scenario is its immutability.

The second application scenario (B) represents an increased state of collaboration in the SC as information is shared bidirectionally between all entities. This information exchange is much more comprehensive and could include, e.g., orders, production capacities, stock levels, forecasts, or disruptions. This scenario is related to the focus categories of tracking and tracing, product provenance, data security, and disintermediation (see Section 2.2). The SC partners can share regular (e.g., hourly) updates of their information as transactions with the partners using one blockchain for the whole SC. A consortium blockchain would be feasible in this scenario. This method naturally requires an increased level of trust and collaboration (Barratt, 2004). In addition to cooperation in sharing information, this scenario also involves the coordination of activities. The partners can adapt their processes more efficiently and retain visibility along the entire value chain. This data can also be used as an additional sales argument if it is disclosed to end customers as it relates to product provenance (e.g., social and ecological commitments). Similar to scenario A, partners can evaluate transactions and trigger actions based on the transaction content. In order to efficiently organize governance in the network, a consortium blockchain is recommended for this application scenario.

The third scenario (C) is the most integrative one. Besides the vertical information sharing and collaboration, this scenario includes horizontal collaboration between entities on the same SC tier (Barratt, 2004). The collaborative efforts may include suppliers or producers sharing demand data, capacities, or stock levels via blockchain and thus goes beyond the BCT applications presented for SCM in Section 2.2. Smart contracts are a central feature here, as collaboration can be considerably simplified and facilitated using the automatic setup and execution of smart contracts. If resources are shared among the same SC tier, collaborating partners would then be able to take over manufacturing services for others, e.g. disrupted partners, if their capacities are sufficient. The coordination can be carried out through a permissioned blockchain with a Proof-of-Authority (PoA) consensus. PoA is particularly suitable for networks in which all entities are known and trusted and where reputation is an important parameter. The system is permissioned, so only actors who are part of the SC have access. PoA follows the idea that opportunistic behavior is limited by the fact that the validators responsible for creating and validating the blocks stake their reputation to ensure that the system runs error-free. Compared with Proof-of-Work, PoA is less energy-intensive and can validate blocks in a shorter time.

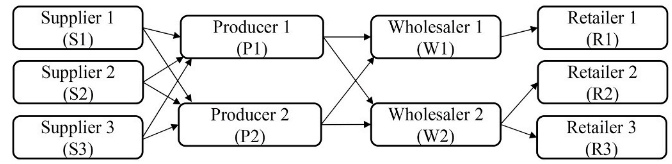

Fig. 2. Supply network structure.

Several concepts in the literature (Gourisetti et al., 2019; Lohmer, 2019) and industry projects (Parity, 2019; POA Network, 2019) use permissioned blockchains with PoA consensus. Transactions can contain daily free capacities, the prices of production services of respective participants for all collaborating companies, and the current as well as finished production orders. A specific scenario to increase SC resilience in this potential application is resource sharing. Existing literature on resource sharing has indicated improved performance through collaboration, although SC resilience has not been addressed so far. Scholars proposed distributed coordination mechanisms to allocate demands and share capacity but focused on examining performance measures for individual companies only (Moghaddam and Nof, 2016; Seok and Nof, 2014; Tan, 2006; Yilmaz et al., 2017). Industrial applications of capacity sharing, on the other hand, used centralized platforms or databases vulnerable to failures, hacking attacks, and opportunism (i.Revitalise, 2020; Van Arnum, 2012). If BCT is utilized for this application scenario, free capacities and the respective prices for the use of the capacities are recorded in smart contracts, which are then triggered by the other partners if required. Each entity assures cost-efficiency by using its production capacities first since the use of other members' capacities requires higher unit costs. If the production capacities are not sufficient for the current production lot (e.g., because one factory experiences a disruption), the capacities are utilized to the maximum, and the remaining production capacity is determined. Analyzing the blockchain transactions, the entities with sufficient capacities to carry out the entire production are identified. The one entity with the lowest costs is selected and the agent initiates the production through autonomous decision-making using the smart contracts.

3.2. *Analyzing the impact of BCT on SC resilience strategies*

Managers (and scholars) will be particularly interested to learn which traditional SC resilience strategies are affected by BCT and how. We therefore consider the presented potential application scenarios and investigate the influence of these collaborative scenarios on the SC resilience strategies of the literature. The analysis is presented in Table 1, in which we map identified SC resilience strategies (Hosseini et al., 2019; Kamalahmadi and Parast, 2016; Tukamuhabwa et al., 2015) to scenarios A to C and examine the influence of using BCT in the SC on each resilience strategy referring to existing literature.

The analysis indicates that with increasing integration between SC partners from application scenario A to C, the positive impact of BCT on resilience strategies also increases. The following strategies are positively affected in scenario A: SC collaboration (contractual agreements), risk management culture, SC structure, and increased SC agility, including flexibility and velocity. For scenario B, there are additional strategies with a strong positive influence involved, including information sharing, increased visibility, coopetition, and contingency planning. The implementation of BCT in scenario C affects most of the resilience strategies, of which the following main strategies are particularly significant and will now be examined in more detail: supply chain collaboration (including information sharing with information technology and contractual agreements) as well as supply chain agility.

Table 2
Model parameters.

	S1	S2	S3	P1	P2	W1	W2	R1	R2	R3
Mean production time [days]	8	8	8	5	5	–	–	–	–	–
Production time standard deviation [days]	2	2	2	1	1	–	–	–	–	–
Production capacity [pieces]	10,000	10,000	10,000	6000	6000	–	–	–	–	–
Production setup costs [$]	40.00	50.00	60.00	50.00	50.00	–	–	–	–	–
Variable production cost [$/piece]	2.75	2.50	2.20	5.00	5.00	–	–	–	–	–
Order-up-to level [pieces]	11,000	11,000	12,000	3000	4000	2000	4000	1500	1500	1500
Fixed order cost [$]	90.00	90.00	90.00	180.00	180.00	120.00	120.00	90.00	90.00	90.00
Sales price [$]	12.48	14.26	14.98	48.95	49.02	50.62	50.14	51.11	50.63	50.63
Mean delivery time [days]	6	6	6	4	4	2	2	–	–	–
Delivery time standard deviation [days]	2	2	2	1	1	1	1	–	–	–

3.2.1. SC collaboration

SCs should be perceived as collaborative structures to increase their resilience (Christopher and Peck, 2004; Kamalahmadi and Parast, 2016). Collaborative environments are usually based on trust and information sharing, two important inter-relational attributes that are directly related to information technology, and thus BCT. BCT might act as a suitable intermediary for relationships between firms that have not yet been established due to a lack of trust or have been operated at high expenses (Crosby et al., 2016; Swan, 2015). Several properties of BCT are advantageous here, including the decentralized nature of data storage, data validation, immutability, and transparency (Hull, 2017; Li et al., 2018; Wang et al., 2019a). The process of information and data sharing is more resilient using BCT, as no single point of failure exists. This will lead to increased trust in transactions and mitigate certain persistent cybersecurity risks (Min, 2019; Stecke and Kumar, 2009; Wang et al., 2019b). As the transactions are logged in a matter of seconds (depending on the protocol used), SC entities can receive information about risks and disruptions faster than before. Advanced information can be used to mitigate risks and prepare appropriate contingency plans (Min, 2019; Papadopoulos et al., 2017). Connecting BCT with other Industry 4.0 technologies and big data analytics is also promising. These digital technologies are increasingly applied in SCRM research as they influence the optimization of processes to avoid disruptions and risks (Bugert and Lasch, 2018; Hosseini et al., 2019; Ivanov et al., 2017).

Contingency and recovery plans are supported by the smart contract functionality that allows for automated contract execution if the contracted event occurs (Weber et al., 2016). This enables swift implementation without manual intervention. Resilient SC design is further supported by enhanced collaboration due to transparency, trust, and reliability (Saberi et al., 2019). This collaboration is also dependent on the efficiency of contractual agreements. Portfolio diversification with flexible contracts and contracts to share revenue and risks are successful, robust strategies to build resilient SCs (Tang, 2006a, 2006b). BCT is useful in this context as full transparency is inherently provided and disintermediation enabled, which could mitigate risks related to contractual agreements and facilitate efficient processes (Saberi et al., 2019; Wang et al., 2019a). Through the use of built-in smart contract functionalities (scenario C), the blockchain simplifies the creation and execution of contracts leading to time savings and risk reduction in SC operations (Ivanov et al., 2019). The transparency and distributed nature of systems could facilitate a transition to operational rather than strategic cooperation in the future, as confirmed by Saberi et al. (2019). This implies that management decisions have to be made differently and the design of governance systems will become a key issue in resilient SC design using BCT.

3.2.2. SC agility

Agility is a resilience strategy to face change with corresponding organizational actions quickly (Christopher and Peck, 2004; Ponomarov and Holcomb, 2009). Visibility and velocity are two essential factors that determine agility (Wieland and Wallenburg, 2013). In a blockchain system, agility can be promoted by the easy and fast addition of new business partners. Sharing information about capacities and sharing resources (scenario C) enables early reactions and risk mitigation in the event of a disruption (Cole et al., 2019; Li et al., 2018; Saberi et al., 2019). Visibility is increased along the whole SC; goods can be tracked and traced through the system, which enhances SC resilience as information is available in real-time (Datta et al., 2007). This characteristic also influences the issue of the velocity of information, which can be significantly increased by using BCT. Velocity is related to flexibility and adaptability, as the speed of adapting to disruptions is an important issue (Christopher and Peck, 2004; Wieland and Wallenburg, 2013). BCT can notably influence the speed of discovering disruptions. Digital and streamlined processes using smart contracts have an impact here (Ivanov et al., 2019). Agility is also influenced by communication, cooperation, and integration (Wieland and Wallenburg, 2013), which can be facilitated by BCT.

Table 3
Parameters of the simulation experiments.

Model runtime	0–1000 days, with a warm-up phase of 500 days
Disruption	Loss of production capacity of producer P1 on day 500; Capacity available again after initial disruption time
Varying input parameters	Initial duration of disruption (P1) of 15–30 days Degree of integration efficiency of BCT by variation of process time between 3–23 days for total completion of BCT-coordinated production service
Output parameters	Transient response (network disruption costs, network recovery time, number of disrupted entities)
Number of runs	67,200 with 336 iterations, each iteration with 200 replications

The analysis has shown several positive influences of BCT on SC performance in general and on SC resilience in particular. We presented three potential application scenarios for BCT (RG1) and investigated the impact on SC resilience enhancers subsequently (RG2). Depending on the implementation of BCT in the SC, the impact on SC resilience differs. The conclusion can be drawn that increased collaboration, as in scenario C, has the most positive influence on SC resilience through intensified information sharing and automation potential using smart contracts to share resources. In order to investigate the expected positive effect on SC resilience in application scenario C also quantitatively and to point out potential risks or pitfalls, we carry out a simulation study in the next section based on horizontal collaboration between SC partners that share capacities.

4. Simulative analysis of the resilience of a network applying BCT

This section critically examines the impact of BCT on SC resilience using two simulation models (both confronted with the same disruptive scenarios): (1) a basic model with a conventional structure and (2) a collaborative SC based on BCT with resource sharing. For a multi-faceted investigation, we vary the duration of the initial disruption and consider the degree of integration efficiency of the blockchain

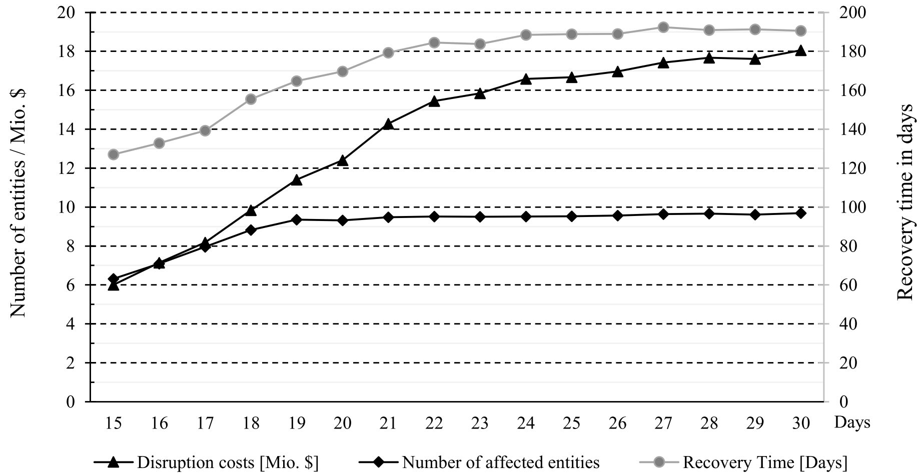

Fig. 3. Performance of the baseline model with respect to different disruption lengths.

solution by varying input parameters. Thus, our simulation experiment allows us to make statements about the influence of the efficiency of BCT-based collaboration on SC resilience and the extent to which the duration of the disruption influences this potency.

4.1. Baseline model description without collaboration

The network presented consists of producing and non-producing entities in a supply network with several tiers and more than one entity per tier. The network structure and material flows are presented in Fig. 2. The suppliers (S1, S2, S3) provide the producers (P1, P2) with raw material for the production of the desired products. These two producers supply the two wholesalers (W1, W2) with the same final goods, which they pass on to the three retailers (R1, R2, R3). The daily number of potential customers of each retailer is modeled with a truncated normal distribution to prevent negative demand. It is assumed that each customer buys an individual item if the product is in stock, and the customer's waiting time limit, which is modeled by a Gaussian distribution, has not been exceeded. Since the end customer's order quantity is one, orders can be executed either in full or not at all, based on the retailer's stock levels. Unsatisfied retail demand is considered as lost sales and valued at opportunity cost. Upstream entities receive orders with an order quantity of more than one. If stock levels are not sufficient to meet the order in full, partial deliveries are permitted. Upstream entities will be penalized with backlog costs for each piece they cannot ship directly.

Each entity is capable of sending shipments and receiving orders from downstream partners or end customers. The shipments reach the downstream partner after a normally distributed delivery time, which depends on the total quantity already in transit. The inventories of the producing entities, that is, the suppliers and the producers, are divided into raw materials, unfinished goods, and finished goods. The value per item of raw material is given by the purchase price, while the finished products are priced by the retail value. The value of a mid-manufactured

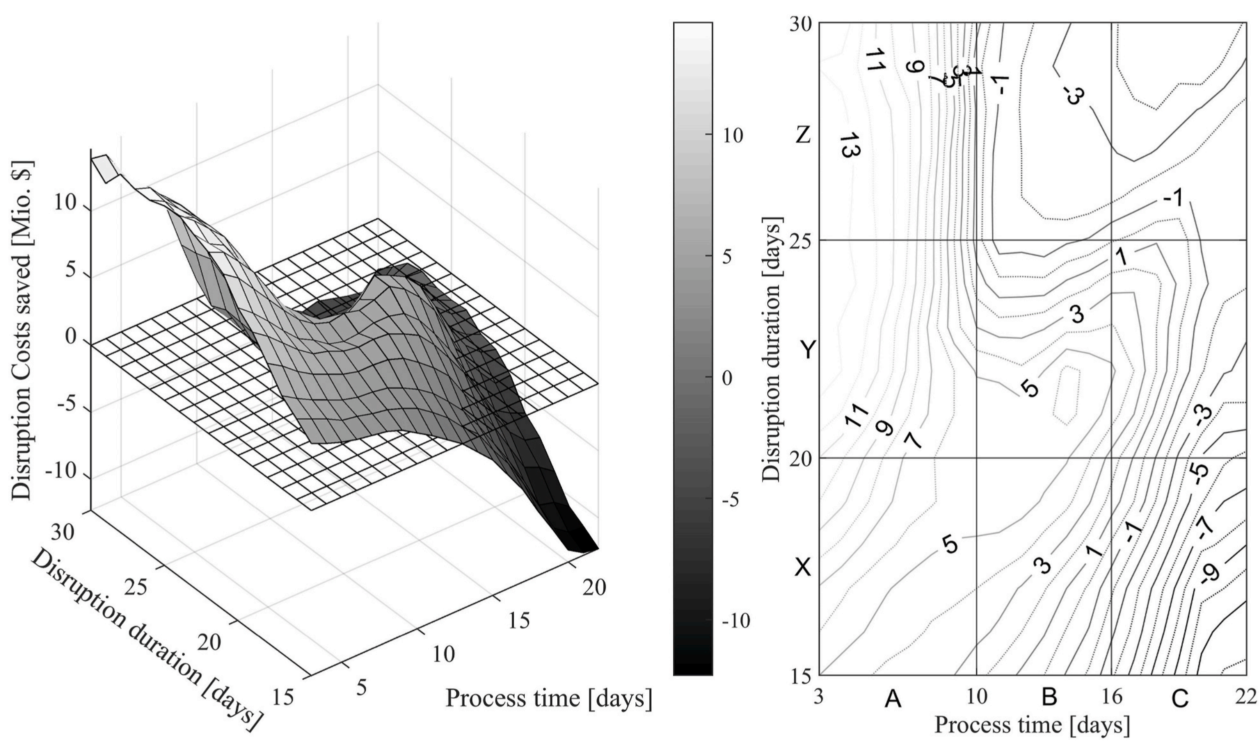

Fig. 4. Surface plot (left) and contour diagram (right) of the disruption costs saved.

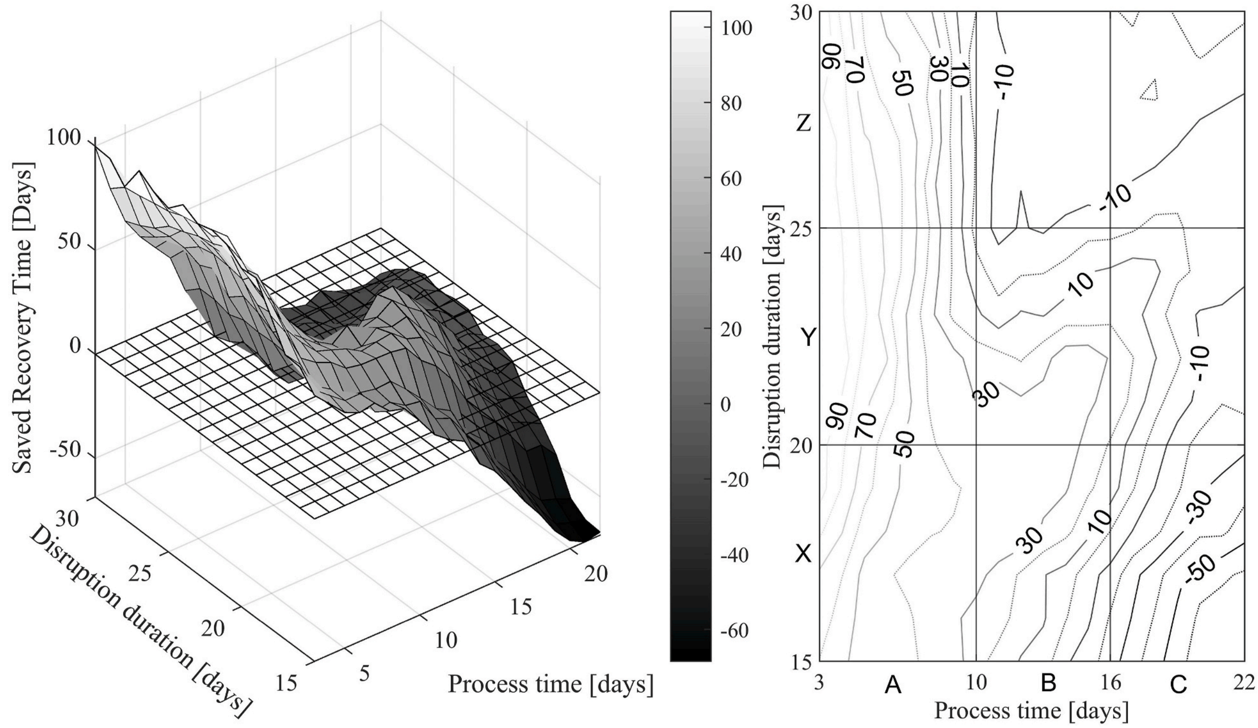

Fig. 5. Surface plot (left) and contour diagram (right) of the saved recovery time.

item in production is considered to be exactly halfway between the purchase and sales price. Non-producing units determine the value of their stored goods as the average between the purchase and the sales price. Due to the capital lock-up and warehousing costs, holding costs are incurred per unit and day. Stocks are replenished using an order-up-to policy. Stock levels are checked daily to ensure steady flow through the network, and order points are defined so that each unit orders once a day when the system is in balance. Fixed and variable order costs are tracked, and orders are forwarded immediately.

The production process associated with suppliers and producers requires a normally distributed production time. The production capacity and thus the quantity of goods produced is limited. Once goods are available in the receiving warehouse, production is initiated. Production is associated with fixed and variable production costs. Every day, each unit tracks important data such as stock levels, the amount of goods sold, and the amount of backorders. After all executable orders are shipped, the current stock level and expected quantity from upstream partners is compared with the predefined target stock level to calculate the order quantity and the associated revenues. Orders are shipped immediately, and the expected volume from the upstream unit is increased by the order quantity and decreased as soon as the delivery arrives. The associated fixed and variable order costs, production costs, and transportation costs are tracked. The final daily process step of each unit is the calculation of profit.

4.2. Blockchain-coordinated model with resource sharing

To examine the behavior of a SC network that takes advantage of BCT, we apply the structure as shown in scenario C above (Section 3.1). We assume that producing entities on the same SC tier have substitutable production processes and infrastructure. The blockchain was modeled using Hyperledger Fabric (Hyperledger, 2020), and the simulations for both models were conducted with AnyLogic 8.5.0. As an input for the simulation model, we examined the times needed for block verification and passing transactions in the Hyperledger network as well as prospective transaction costs. These times and costs were used to determine the parameters. A detailed description of the technical integration of the systems is beyond the scope of this article. We focus on the differences of the simulation models, the necessary parameters, and the results of the simulation runs below.

The costs for using a blockchain solution mainly depend on the implementation efforts needed and, in operative use, on annual transaction volume, transaction sizes, and type of consensus mechanism. On top of that, running costs for monitoring and maintaining the system must be taken into account. Cost advantages can arise from the autonomous transaction initiation through smart contracts, which are referred to as chaincode in Hyperledger (2020). We assume that fixed costs per transaction must be considered but are lower than the fixed ordering costs of the baseline model (see section 4.3).

The monetary incentive to collaborate comes from a fixed and fair profit margin on the total cost of production. This prevents the service provider from exploiting a possible monopoly position while still having an incentive to collaborate. The entity initiating the transaction pays the full cost of transport to and from the service provider as well as the total cost of production of the lot plus the profit margin premium. The process time, which is normally distributed, consists of the times for decision making, packaging, unitizing, transport, quality control, and production provision. The service provider is responsible for dispatching production. Since transport times can cause changes in the free capacities of the service provider, waiting times can occur. In the case of free capacities, order processing of the transactions triggered by the blockchain takes place with higher priority in order to account for the spirit of collaboration. The time risk is thus borne by the entity that triggers the transaction. In order to retain the incentive to collaborate, there are no penalties for late returns.

4.3. Model parameters

The number of customers wishing to buy a single product each day is modeled by a normal distribution with a mean of 250 units per day and a standard deviation of 35 units per day. Customers are willing to wait a day for their product if the corresponding retailer (R1, R2, or R3) is out of stock. Holding costs, which include physical storage costs and capital commitment costs, are set at 18% of the product value per year, which is

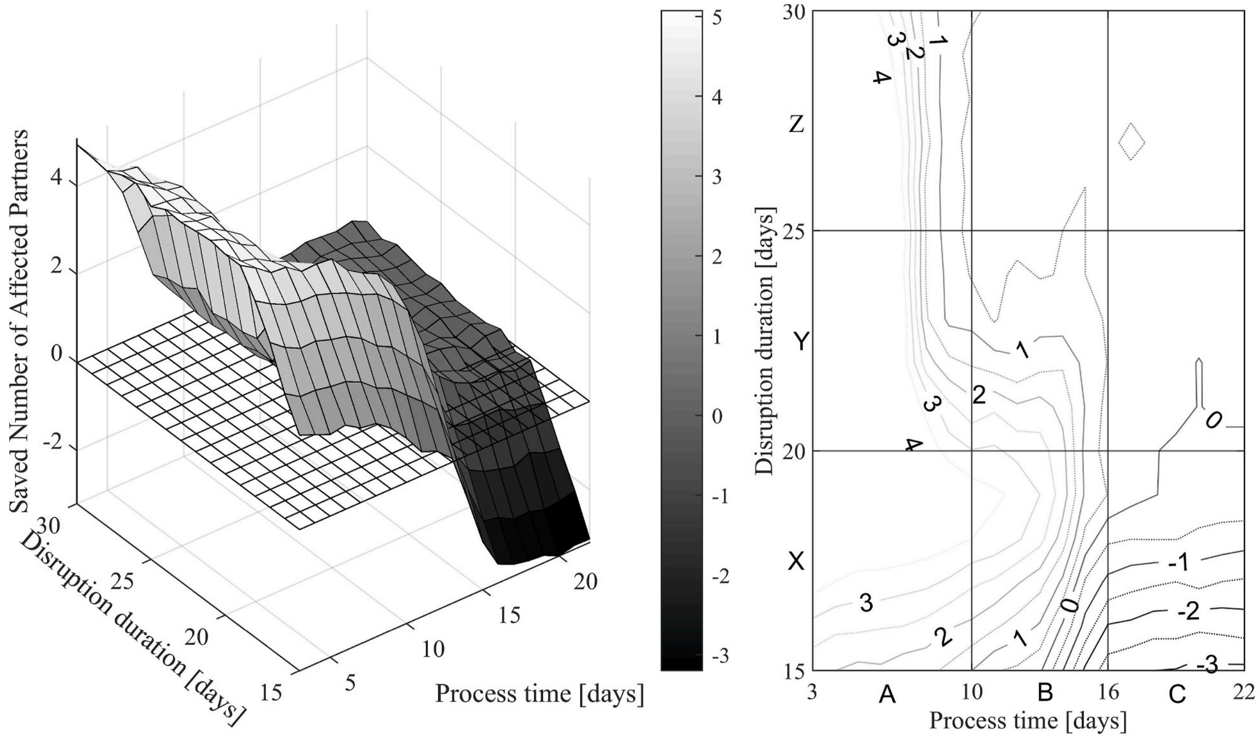

Fig. 6. Surface plot (left) and contour diagram (right) of the saved number of affected partners.

0.05% per day when considering a 360-day financial year. The variable transport costs are set at $0.50 per piece. Sales prices have been calculated in such a way that the profit of each partner is $0 in a balanced system in order to facilitate the quantification of the disruption costs of each entity. Table 2 presents the remaining parameters. The normal distributions we have used are truncated to ensure that no negative values can emerge.

In the blockchain-coordinated model, further parameters are needed. The fixed costs for each transaction are considered to be $20. The variable costs for all processes to share capacities are assumed to be $1 per piece. The profit margin for offering production services to other entities is assumed to be 20%. The capacity sharing process is detailed in the next subsection.

4.4. Design of the simulation study

In a simulation study, the following aspects must be specified: input parameters to be varied, output parameters, length of the warm-up phase and model runtime, and the number of replications (Carson, 2004). The detailed parameters of our simulation study are shown in Table 3.

The degree of integration efficiency initiated and coordinated by BCT depends on the reliability and speed of the entire collaborative process. This includes not only the availability and flawless functioning of the blockchain solution, but also the speed of the underlying processes, such as transport, goods receipt, or production. For this purpose, this input parameter is taken into account for a total average period of 3 days in the most efficient case and 23 days in the worst case. The standard deviation is assumed to be 2 days due to the probabilistic process times, and the distribution is truncated so that at least one day is required.

A distinction must be made between a balanced and a disrupted state of each entity to determine the recovery time within the simulation automatically. Therefore, once each entity has reached a stable state after 130 days, it measures the average and standard deviation of its inventories, the backlog costs, and the capacity utilization for the next 360 days. If one of the three values is outside three times the standard deviation, the condition is considered disrupted. After the recovery phase, the model returns to a state of equilibrium so that the total cost of disruption, the total recovery time, and the total number of entities affected can be determined.

5. Simulation results, sensitivity analysis, and managerial insights

5.1. Discussion of simulation results

We first present the simulation results of the baseline model in order to have a point of comparison for our further statements. Fig. 3 presents the resilience parameters of our baseline model. The total disruption costs of the network and the number of affected partners are displayed on the left ordinate and the recovery time on the right ordinate.

Findings of the conventional baseline model: (1) Disruption costs depend significantly on the initial disruption period: Increase in disruption costs from $6 million at 15 days to $18.1 million at 30 days

Table 4
Results of the sensitivity analysis: percentage changes in disruption costs [%].

	Variation of the input parameters [%]							
	-20	*-15*	*-10*	*-5*	*5*	*10*	*15*	*20*
Delivery time	-0.13	0.13	0.12	-0.4	0.46	-0.64	-0.19	0.23
Production time	-48.20	-42.04	-32.80	-20.22	37.49	169.22	668.20	3471.12
Stock levels	929.82	954.76	852.78	113.00	-29.94	-21.07	-57.96	-65.58

Table 5
Findings of this study, compared with theory and derived managerial insights.

Finding	*Comparison with theory*	*Managerial insights*
A positive influence on resilience strategies is evident in all BCT application scenarios. However, the more integrated the SC is, the greater the positive influence.	This finding is consistent with previous findings that identified integration and flexibility for trustworthy collaboration and information sharing as key drivers of SC resilience (Brusset and Teller, 2017; Datta et al., 2007). BCT can contribute significantly increasing SC resilience.	Regardless of the scale of the existing integration and collaboration in the SC, managers should take a closer look at BCT and not shy away from taking small steps, as there is already potential for optimization here. The more effort is made, the greater the expected positive effects of BCT.
Blockchain enables an intensified collaboration through smart contracts and shared resources, which increases SC resilience.	Our simulation results quantitively support and extend the findings of Kshetri (2018), Min (2019), Choi et al. (2019), and Ivanov et al. (2019) that argue that blockchain increases resilience especially by providing transparency, increased visibility and agility.	Blockchain is particularly valuable if features like smart contracts are utilized to share data and resources, which increases SC resilience notably. Managers should perceive blockchain not only as a technology for operational activities, but also consider the strategic relevance of the technology.
The advantage of sharing data using a blockchain solution depends on the disruption duration and the collaboration efficiency (process times).	Ivanov et al. (2019) and Babich and Hilary (2020) suspected a generally positive impact of using blockchain due to improved visibility and real-time event identification. Our results reveal a more complex picture – the impact strongly depends on the underlying processes established for collaboration. The disruption duration is also a major influence.	Efficient and fast processes are crucial to realizing the full potential of collaboration. The SC network needs to have specific regulations concerning the execution and priorities of collaboration operations. Managers should ensure that short process times prevail throughout the SC.
Blockchain solutions are only reasonable if a joint SCRM process has already been established in the supply chain.	Some industry consortia market their blockchain products as "plug-and-play" solutions that are easy to set up and take advantage of the low-hanging fruits of data sharing (Hyperledger, 2020). Our results show that sharing data and capacities can even have adverse effects on poorly coordinated supply chains.	Managers should utilize blockchain as one method within a framework of defined joint risk management systems in the SC, including a joint risk strategy and organizational frameworks. The underlying risk management processes must be strengthened and aligned in advance of implementing blockchain solutions.
The number of entities affected by the disruption can be limited when material flows are highly efficient and process times are short using BCT.	This result is in line with theory that indicates that increased visibility allows the swift identification of and reactions to threats and disruptions (Blossey et al., 2019; Ivanov et al., 2019; Petersen et al., 2018; Wang et al., 2019a). Using simulation, we validate that the number of partners affected by a disruption can be significantly reduced using blockchain to share data.	SC partners should not only invest in the technical infrastructure but also in the processing capabilities to minimize the number of affected partners. Regular audits and tests should be carried out to be prepared for emergencies.
Stock levels and production time have a strong influence on the performance of disruption mitigation.	Literature frequently refers to risk mitigation through sufficient inventory as an efficient resilience mechanism (e. g., Hosseini et al., 2019; Ivanov and Rozhkov, 2017). Production time is a new aspect that is especially significant in collaboration as the capacity bottlenecks are more difficult to resolve and the disruptions affect the network for a longer time when production times are long.	Managers should invest efforts in finding a reasonable safety stock, including the consideration of disruptions. Production times in the collaborative setting are to be minimized to ensure smooth network operation in a disrupted scenario.

(an increase of 200%, slightly steeper at first, then increasing more slowly after 22 days), (2) strong disruption propagation in the entire network (at 15 days already an average of 6.2 entities disrupted, more than 9 of 10 entities at 19 days initial disruption), and (3) recovery time is long, but is not as sensitive to the length of the disruption as the other two resilience indicators (127.1 days recovery time with 15 days of initial disruption, increases by about 50% to 192.4 days with 30 days of disruption).

Comments on the further evaluation of results: In the following we will compare the simulation results of the BCT-based collaborative model with the baseline model. We present the results concerning the resilience metrics in the following order: network disruption costs, recovery time, and disruption propagation. Relative values for the resilience indicators are used to facilitate the interpretation of the results and to make straightforward statements about the advantages and disadvantages. Positive values indicate an advantage of the BCT-based collaboration model. We use a surface diagram with a grid plane (indicating the equal performance of both models) on the left side of the following three figures to illustrate the results. On the right side of each figure there is also a comprehensive contour diagram, which we divided into nine quadrants to improve clarity, with three areas for each of the two coordinate axes. The x-axis consists of high process efficiency [A] 3–10 days, medium process efficiency [B] 10–16 days, and low process efficiency [C] 16–22 days. The y-axis contains short disruption duration [X] 15–20 days, medium disruption duration [Y] 20–25 days, and long disruption duration [Z] 25–30 days. A combination of these areas can refer to quadrants such as [BX] and [CY], but also whole areas such as [A], which consists of the three quadrants [AX], [AY], and [AZ].

Analysis of the total network costs (Fig. 4)

[A]: The BCT-based model performs significantly better than the base model and has between $3 million and over $13 million fewer disruption costs. The longer and therefore the more profound the initial disruption of P1, the more disruption costs can be avoided by applying BCT. A strong decrease of the saved disruption costs is observed with decreasing process efficiency.

[B]: Positive values can be seen for almost the entire quadrant [BY]. The maximum savings in this quadrant are $5 million. Process efficiency is less important here than the duration of the disruption - the higher it is, the less advantageous it becomes. For quadrant [BX], except for the lower right corner, there is a benefit that increases to over $5 million as the disruption length and process efficiency increase. BCT is almost exclusively of no benefit in quadrant [BZ]. Here, the disruption costs depend more on the process efficiency and the disadvantages increase with lower process efficiency.

[C]: In all three quadrants, BCT-based collaboration is almost consistently disadvantageous. Only the upper left corner of quadrant [CX] and the left edge of quadrant [CY] have a slight advantage. Interestingly, the strongest disadvantages are found in the case of short disruptions and very low process efficiency. The disruption is too short to take advantage of collaboration, which is also inefficiently executed. The entities would have been better off relying on higher safety stocks rather than sharing capacity in this extreme scenario.

Findings: (1) At a high process efficiency, the cost advantageousness of the BCT-based model increases even with longer disruption duration. (2) Inefficient processes lead to high cost disadvantages, especially with short disruptions. (3) For a medium process efficiency, the cost advantageousness is unsteady and depends on the disruption duration.

Analysis of the recovery time (Fig. 5)

[A]: The recovery time of the network is significantly shortened when using BCT. The results in all three quadrants are positive (decrease of 10–90 days) without exception and hardly depend on the length of the disruption and strongly on the process efficiency.

[B]: [BX] and [BY] show a predominantly shortened recovery time. In [BX] the recovery time is more advantageous with higher process efficiency and longer disruption period. In [BY] the recovery time decreases again with longer disruption duration and lower process efficiency. [BZ] demonstrates a complete disadvantage of the BCT-based solution, with a deterioration of the recovery time by about 10 days being fairly independent of the disruption duration and efficiency.

[C]: Only the upper left corner of [CX] and the left half of [CY] show a minimal advantage of the BCT-based solution. Strong negative effects can be seen with short disruptions and poor process efficiency [CX] (up to more than 50 days longer recovery), which decreases with longer disruptions and improved process efficiency. In [CY], the benefits are more dependent on process efficiency because the duration of the disruption has little influence on the recovery time. In [CZ], a negative plateau is formed, meaning changes in the duration of the disruption and process efficiency have little effect.

Findings: (1) The advantage in recovery time is significant at high process efficiency and increases even with longer failure duration. (2) Strong deterioration of the recovery time can be observed at poor process efficiency, especially at low disruptions. (3) At medium process efficiency, the results are more inconsistent.

Analysis of the disruption propagation (Fig. 6)

[A]: All three quadrants exhibit a definite advantage in terms of disruption propagation. Independent of the duration of the disruption, up to four entities are less affected. Large parts of [AX] show that more than three entities are less affected.

[B]: Quadrant [BX] shows negative values in the lower right margin, while the advantage of the BCT-based solution increases the longer the initial disruption is and the better the process efficiency is. Quadrant [BY] shows improvements in disruption propagation, which increases at lower disruption duration and higher efficiency. For longer durations [BZ], the results are mostly comparable to the baseline model, except for the left margin.

[C]: Quadrant [CX] reveals that up to three more partners are affected by a disruption in the network, so that the propagation of the disruption may even be enhanced by BCT. The longer the disruption lasts, the better the degradation becomes, so that in quadrant [CY] and [CZ], there is little difference from the baseline model.

Conclusions on SC resilience: (1) For high process efficiency, significant improvements in SC resilience can be seen, since not only the cost of disruption but also the recovery time and the number of affected partners have changed significantly in a favorable manner when using BCT. (2) The application of BCT is not exclusively positive. Interestingly, in the case of poor implementation, short disruptions have a strong negative effect on SC resilience. Lengthy disruptions reduce these disadvantages, but an advantageousness of the BCT model does not emerge. (3) With a medium process efficiency, the results are variable and depend strongly on the length of the disruption and the specific process efficiency. Significant improvements are not visible, so an investment in BCT would hardly be financially worthwhile.

5.2. Sensitivity analysis of structural parameters

A sensitivity analysis is now conducted to consider the influence of the structural parameters on the model output. A sensitivity analysis calculates the effect of a change in input values on the response of the model and depends on the purpose of the model (Borgonovo and Plischke, 2016; Saltelli and Scott, 1997). There are different types of sensitivity analyses, depending on the target of the analysis (Borgonovo and Plischke, 2016). We chose factor prioritization to investigate the influence of different model parameters. The identification of key factors plays a vital role in this process, as data collection on important parameters should be carried out more carefully. In order to keep the computational effort manageable, we focused on the three structural parameters *delivery time*, *production time,* and *stock levels.* We varied these three parameters between -20% and +20% and considered the resulting network costs. For the sensitivity analysis, we selected 16 data points in the solution space (disruption lengths of 15, 20, 25, 30 days and process times of 5, 10, 15, 20 days each) and calculated the change in average disruption costs. The percentage changes in the disruption costs of the overall network are shown in Table 4.

The results of the sensitivity analysis show that the delivery time has hardly any influence on the total disruption costs of the system. On the other hand, stock levels have a significant influence. This is not surprising since safety stock increases resistance to disruptions but also leads to higher operating costs during periods of no disruption. Inadequate stock leads to a sharp increase in the cost of disruptions. Production time also plays an important role. Longer production times lead to a significant increase in total costs. A disruption has a longer impact on the network with higher production times and capacity bottlenecks are present much longer in the event of an interruption. It is thus essential to ensure that, in particular, stocks and production times are accurately measured when building a model.

5.3. Managerial insights

SC resilience is a multi-dimensional construct that can only be investigated in the presence of a disruption. This precondition makes it hard for managers to justify investments in higher SC resilience. Quantitative models, especially simulation models, can help evaluate the usefulness of resilience strategies and provide valid arguments for improved SCRM. Table 5 summarizes the findings of the theoretical and quantitative analysis of BCT and SC resilience, compares the findings with existing theory, and presents meaningful managerial insights.

Our findings show that using blockchain to share data in the SC can significantly reduce the number of partners affected by a disruption, the disruption costs, and the recovery time in the network. Implementing a blockchain can be a rewarding solution to increase SC resilience. However, the costs and efforts for implementation and operation must be estimated individually. Suitable expertise must also be available at each SC partner. The network partners should only then implement the technology if the SC is based on a joint, established risk management framework and a high degree of collaboration efficiency is ensured. The advantages of the solution depend strongly on the lengths of disruptions and collaboration efficiency. Carrying out detailed process analysis and modeling before implementation, paying particular attention to accurate process times, is vital. This data should be incorporated into quantitative decision-making. Process quality is also of particular importance and should be ensured using recurring audits and process improvements to maintain process quality, which has significant influence on the process time at a high level.

6. Conclusion

This article develops different potential application scenarios of BCT in SCRM and conducts an in-depth analysis of the influence of this new technology on SC resilience. Therefore, the effects of different risk-related application scenarios of BCT on known resilience enhancing strategies are theoretically investigated. The most promising application scenario is examined in more detail in a quantitative simulation experiment in order to not only provide general statements but also to investigate indications of the exact functioning mechanisms of the resilience alterations. For this purpose, the efficiency of BCT-based collaboration and the disruption lengths as influencing factors are investigated. The results indicate a significant improvement in SC resilience in efficient BCT-based collaboration. In contrast to previous theoretical statements and discussions in the literature, this study also reveals detrimental effects on SC resilience. In the case of poor BCT-based collaboration efficiency, even deteriorations may result. Further theoretical, empirical, and quantitative studies are needed to assess the role BCT can play in SCRM. Besides, we call for research on meaningful indicators for the quantification of resilience, empirical investigations of disruptive events in real networks, quantitative models for the investigation of resilience strategies, and conceptual theories on possible influencing factors of resilience. The use of BCT in supply chains and production networks in general should also be examined conceptually and empirically, e.g. to uncover potentials and barriers.

CRediT authorship contribution statement

Jacob Lohmer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Niels Bugert:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Rainer Lasch:** Supervision, Writing - review & editing, Validation, Project administration, Resources.

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