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Exploring Blockchain Adoption Supply Chains: Opportunities and Challenges

March 31, 2022

Dr. Adrian V. Gheorghe
Dr. Omer F. Keskin
Dr. Farinaz Sabz Ali Pour
Department of Engineering Management and Systems Engineering
Old Dominion University

Dr. Unal Tatar
University at Albany, State University of New York

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Abstract

In modern supply chains, acquisition often occurs with the involvement of a network of organizations. The resilience, efficiency, and effectiveness of supply networks are crucial for the viability of acquisition. Disruptions in the supply chain require adequate communication infrastructure to ensure resilience. However, supply networks do not have a shared information technology infrastructure that ensures effective communication. Therefore decision-makers seek new methodologies for supply chain management resilience. Blockchain technology offers new decentralization and service delegation methods that can transform supply chains and result in a more flexible, efficient, and effective supply chain.

This report presents a framework for the application of Blockchain technology in supply chain management to improve resilience. In the first part of this study, we discuss the limitations and challenges of the supply chain system that can be addressed by integrating Blockchain technology. In the second part, the report provides a comprehensive Blockchain-based supply chain network management framework. The application of the proposed framework is demonstrated using modeling and simulation. The differences in the simulation scenarios can provide guidance for decision-makers who consider using the developed framework during the acquisition process.

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About the Authors

Adrian V. Gheorghe, Ph.D., is a system engineering professor with 40+ years of research, academic, and practical experience in the areas of systems engineering, decision-making in engineered systems, and analysis of extreme and rare events – including acquisition. Dr. Gheorghe has published five books on Systems Engineering, Critical Infrastructure, and derived Supply Chain/ Blockchain monography, and several articles on Blockchain Governance and Cybersecurity.

Omer F. Keskin, Ph.D., is a researcher in the cybersecurity risk management field. He holds a BS in Systems Engineering, MS in Engineering Management, and Ph.D. in Engineering Management and Systems Engineering. He is a graduate research assistant and has worked on several projects, including the grant proposal writing phase. His main fields of research include cybersecurity, enterprise cyber risk management and risk quantification, modeling, and simulation.

Farinaz Sabz Ali Pour, Ph.D., is a Simulation Specialist in Health care with more than ten years of research experience in industry and academia. She holds a BS in Industrial Engineering, an MS in Risk Management, and a Ph.D. in Systems Engineering and Engineering Management. She has published several articles on Blockchain technology and supply chain management. Her main topics of interest are resilient system design, Blockchain-based models, and risk management using modeling and simulation techniques.

Unal Tatar, Ph.D., is an Assistant Professor of Cybersecurity at the College of Emergency Preparedness, Homeland Security, and Cybersecurity, University at Albany. He has almost two decades of cybersecurity experience in government, industry, and academia. He is the former coordinator of the National Computer Emergency Response Team of Turkey. Dr. Tatar's research is funded by NSF, NSA, DOD, NATO, AFRL, and the Society of Actuaries. He holds a BS degree in Computer Engineering, an MS degree in Cryptography, and Ph.D. in Engineering Management and Systems Engineering. His main topics of interest are information/cybersecurity risk management, cyber resilience, cyber insurance, and Blockchain.

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Table of Contents

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List of Figures

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List of Tables

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List of Acronyms and Abbreviations

ABM	Agent-Based Modeling
ABMS	Agent-Based Modeling and Simulation
DES	Discrete Event Simulation
DoD	Department of Defense
IoT	Internet of Things
PoW	Proof of Work
PoS	Proof of Stake

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Introduction

Projection of Department of Defense (DoD) operations' capabilities is supported by complex supply chains (Alberts et al., 2017). The complexities arising from various factors, such as changes in customer expectations, multiple market channels, and international markets, create significant challenges throughout the supply networks. New models are required to support supply chain management in the future (Ivanov et al., 2019). There is a rise in the interest level in Blockchain technology reflected by Google trends that returned 21.6 million Google searches for Blockchain released on January 10, 2017 (Fosso Wamba et al., 2018). Blockchain provides a faster transaction by reducing the required time of obtaining confirmation from multiple participants, providing reliable and verified information, and automating some of the transaction logic through smart contracts (Babich & Hilary, 2021). Hence, this study intends to adopt Blockchain solutions to enhance the efficiency and resilience of supply chain networks.

Aim of the Research

This study aims to explore the application of Blockchain technology to enhance supply network resilience. As the first objective to define the scope of this research, supply chain challenges and limitations are mapped with the Blockchain features. The second objective is to provide a comprehensive Blockchain-based supply network management framework. The proposed framework is demonstrated via simulation to provide visualization and computation. By simulating various scenarios, differences between the current and proposed systems can be evaluated to provide guidance for acquisition decision-making processes, and the developed framework will be validated.

Research Questions

In this research, to obtain a robust model-based acquisition, a Blockchain-based supply chain framework is developed to facilitate collaboration and communication among suppliers. The distributed system can nullify adversaries and establish trust among stakeholders. Projecting the proposed framework on an agent-based model and simulating multiple scenarios assist management with visual analytics and decision-making. The following research questions are proposed for the research.

Research Question 1: What limitations and challenges of the supply network system can be addressed by applying Blockchain technology?

Research Question 2: What kind of Blockchain-based supply network management framework can be developed to enhance supply chain management?

Contribution and Novelty of the Study

The shortage of medicines and facilities during the COVID-19 pandemic crisis illustrates the importance and necessity of the supply chain more than before for the United States and the entire world. Hence, more long-term holistic changes in the supply chain structure are required to be prepared for future crises (Dyatkin, 2020). Sternberg et al. (2021) argue that there are very few implementations of Blockchain technology solutions in supply chains within the literature. There is not much empirical knowledge on the Blockchain adoption obstacles in the supply chain (Alla et al., 2018). This study is one of the few research projects that model the Blockchain application into supply network resilience using agent-based modeling and simulation (ABMS) and smart contract tools. This study contributes to the body of knowledge on the Blockchain in supply chain management, provides future research directions and managerial insights for supply chain resilience.

The rest of the report is structured as follows: Section 2 presents the results of a systematic literature review on supply chain challenges, identified gaps, and Blockchain adoption solutions, Section 3 offers the research methodology and the conceptual model, Section 4 presents the model development, Section 5 contains the analysis and evaluation of the simulation results on the Blockchain adaptation on supply network challenges, and finally, Section 6 concludes the report.

Literature Review

This study applied a systematic literature review using VOSviewer software to identify challenges, methodologies, and research avenues on the current supply chain network. A systematic literature review is an official tool to assess the consistency of previous studies (Queiroz et al., 2019). For this purpose, this study used the Web of Science database. The protocols applied for paper selection are shown in Table 1. Figure 1 depicts the supply chain and Blockchain bibliography using VOSviewer software adapted from (Sabz Ali Pour et al., 2021).

Table 1. Literature Review Protocols

Supply Networks and Blockchain Technology Systematic Literature Review	
Keywords:	Blockchain technology AND supply chain AND supply network challenges
Databases:	Web of Science (3555 results) & Google Scholar (156 results)
Final Selection:	156 journal articles and conference papers
Main technologies:	Blockchain technology, smart contracts, modeling & simulation
Main theories:	Conceptual, reviews, frameworks, and case studies

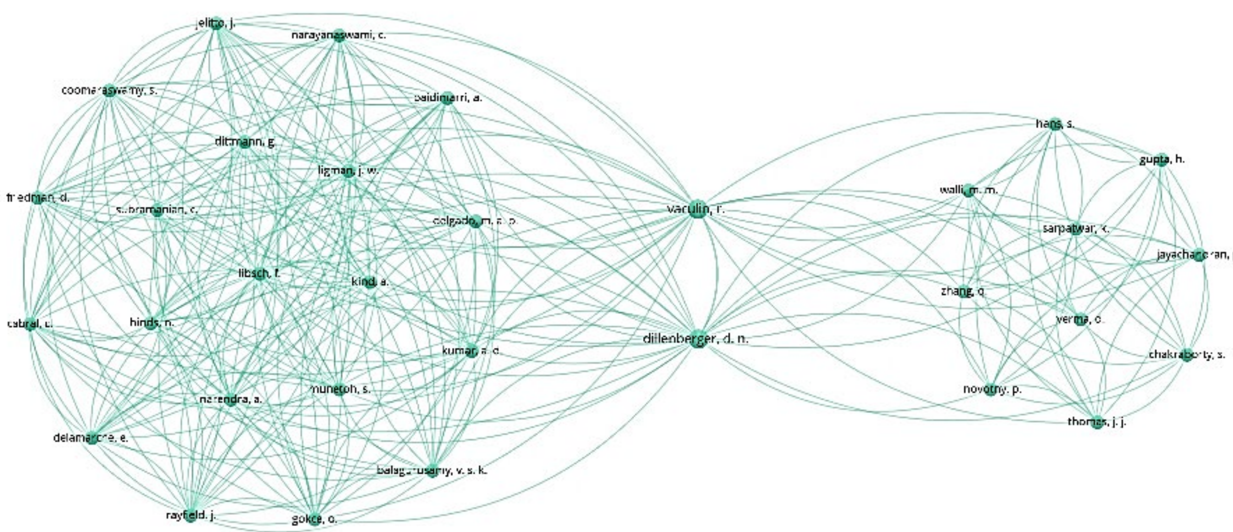

Figure 1. Supply Chain – Blockchain Bibliography retrieved from (Sabz Ali Pour et al., 2021)

The results of the literature review provide a background on the foundation of Blockchain technology, the main challenges of supply chain management, and the solutions applied to improve efficiency and resilience in supply networks.

Background

Foundations of Blockchain Technology

Blockchain technology, created by Nakamoto (2008), is an emerging information technology for designing more transparent decentralized systems that enable consumers to participate in decision-making (Sabz Ali Pour et al., 2021). Blockchain is formally defined as a "fully distributed system for cryptographically capturing and storing consistent, immutable, linear event log for transactions between network participants (Risius and Spohrer, 2017, p. 386)"; transparency is enforced within the network with system-wide consensus on the validity of the entire history of transactions (Queiroz et al., 2019). The cryptographically linked blocks of transactions form a Blockchain (Kshetri, 2017) that occurs through hash functions (Casado-Vara et al., 2018). Hash is a unique code to identify each block (Moosavi et al., 2021), and hashing is critical for the immutability of the Blockchain.

Nodes in the Blockchain communicate through the network by common communication protocols. Every Blockchain network needs a distributed consensus mechanism. The consensus function provides immutability by verifying the network transactions (Wang et al., 2019). New transactions are added to the Blockchain by miners using a consensus algorithm that should be confirmed by most of the nodes of the network through a voting operation. As the transaction is approved by the network, it will be a valid and permanent part of the database. The system rewards miners for adding valid blocks to constantly validate and maintain consistent data by spending their computing power (Tian, 2017). A valid block is generated using a consensus algorithm, which is a challenging puzzle to be solved, requires a massive amount of computational cost, but is easy to verify. The completed blocks are broadcasted by the mining node. The most notable consensus algorithms are proof of work, proof of stake, practical Byzantine fault tolerance, Ripple, and Tendermin (Gausdal et al., 2018).

As the blocks are collected in a chain, they are verified and managed through governance protocols. Every party can verify the records without a distributed consensus mechanism or an intermediary. The modern encryption methods and verification process secure the data on the ledgers against manipulation. Users have access to the audit trail of activity. The decentralized storage of data decreases the risk of failure of any single point (Wang et al., 2019). Figure 2 demonstrates the Blockchain operation.

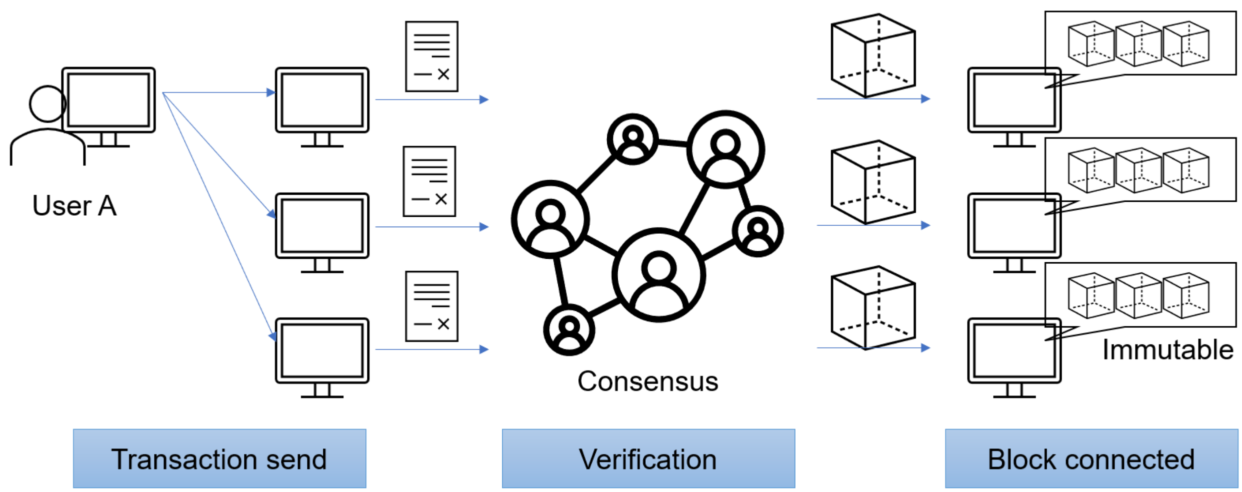

Figure 2. Blockchain Operation adapted from Yoo and Won (2018)

The main characteristics of a Blockchain identified through literature are decentralization, immutability, disintermediation, transaction sharing, and creation and movement of digital assets (Queiroz et al., 2019; Tian, 2017). With the Blockchain implementation, trustless networks, which do not need trust for transferring to other users, are developed. The disintermediation feature makes transactions faster between users. Also, information is secure in the Blockchain with cryptography.

The data integrity and distributed nature of Blockchain enable participants to transact with a high level of confidence (Ivanov et al., 2019). Making any changes in a backdated transaction would be very complicated since it requires modifying all of the following blocks (Guan et al., 2018). The modulation of the block needs more time than the verification, which makes forging and falsifying the data difficult (Yoo & Won, 2018). The scalability of Blockchain technology can be realized by five planes of network, consensus, storage, view, and side planes, which are dependent in an order from bottom to top (Tian, 2017).

A smart contract is a software program that stores policies and rules for negotiating terms and actions between parties (Casado-Vara et al., 2018). The smart contract concept was introduced by Nick Szabo in 1994 as a "computerized transaction protocol that executes the terms of a contract" (Casado-Vara et al., 2018). Yoo and Won (2018) define a smart contract as "a protocol that automates and replaces the necessity of a contract, such as negotiation, expediting performance, confirmation, and contract clauses on execution." Wang et al. (2019) define a smart contract as "a computerized transaction protocol that automatically executes the term of a contract upon a Blockchain." Smart contract applications can reduce the costs and delays of traditional contracts and satisfy common contractual conditions. Smart contracts can represent business logic, mechanisms, or decision-making and also provide communication for the participants. Smart contracts can hence create a web of tiny services that enable the creation and autonomous activity of very complex systems (Glaser, 2017). Smart contracts offer significant support to the critical activities across industry sectors, including supply chain, finance, and medical services (Tolmach et al., 2021). The network participants can reach a consensus on the outcome of the contract execution. The transaction in the smart contract is executed independently and automatically in a prescribed way on every node of the network based on the data included in the triggered transaction (Casado-Vara et al., 2018).

Kshetri (2018) claims that Blockchain has the potential to support supply chain critical objectives achievement. Based on the Blockchain decentralization feature, the intermediaries can be eliminated by applying a smart contract, which is an automated means for asset transfer in case the determined conditions are fulfilled. Thus, the decentralization and disintermediation features of Blockchain can support supply network management innovation and reconfiguration (Queiroz et al., 2019). Blockchain can be applied to register time, location, price, involved parties, and related information while the ownership of an item is changing (Kshetri, 2017). Trust enhancement, accurate information sharing, and verifiability are crucial for contracts because of current challenges, such as inefficient transactions, fraud, pilferage, and poor performance in supply networks (Saberi et al., 2019). The technological developments and applications of Blockchain technology can make improvements in supply chain transparency, security, durability, and process integrity in organizational, technological, and economic feasibility (Saberi et al., 2019). As the supply networks contain large numbers of stakeholders, tracking processes becomes more difficult. Smart contracts can automate the processes. The agreed contracts can be delivered to the specified parties for digital execution, programs can be updated based on agreed verifications, and copyright documents can be released to the relevant parties. The adoption of smart contracts can fundamentally change the supply chain structures and governance (Wang et al., 2019). Smart contracts can facilitate supply chain monitoring and control. The logistics planning, commercial contracts, and requirements of customers automatically and efficiently can be transmitted from retailers to manufacturers and suppliers (Chen et al., 2017). Smart contracts impact data sharing among supply network participants and provide continuous process improvement (Saberi et al., 2019).

Foundations of Supply Chain Management

A supply chain is a set of three or more entities directly involved in the upstream and downstream flows of products, services, finances, or information from a source to a customer (Mentzer et al., 2001). A supply chain is a network of multiple businesses and relationships considered a complex system due to having multiple levels, numerous facilities at each level, and being dispersed over a large geographical location (Beamon, 1999; Lambert & Cooper, 2000). The critical objectives of the supply chain are determined by Kshetri (2018) as cost, quality, speed, dependability, risk reduction, sustainability, and flexibility. Coordination among the supply chain organizations on tactical, operational, and strategic levels is essential for an effective supply chain (Ludema, 2002).

Supply chain management represents a novel way of business management and relationships for the chain members' total business process excellence (Lambert & Cooper, 2000). In order to consider the collaboration, integration, and coordination necessary for the entire supply chain, as well as the importance and roles of network relationships, this study considers supply chain management as "the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, to improve the long-term performance of the individual companies and the supply chain as a whole (Mentzer et al., 2001, p. 18)". Supply chain management can be grouped into operation, design, and strategy categories (Huan et al., 2004). The supply chain management framework is depicted in Figure 3, and the supply chain management flow is presented in Figure 4.

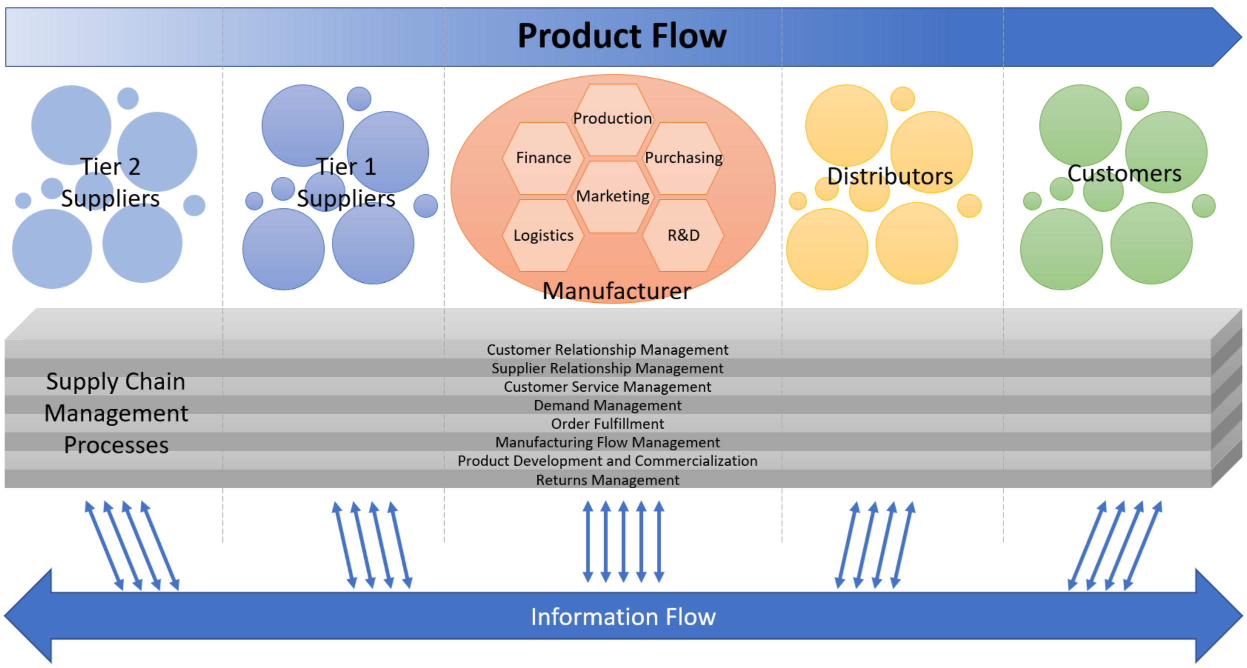

Figure 3. Supply Chain Management Framework adapted from (Yoo and Won, 2018)

Interaction of different groups of a system with each other and information sharing play a critical role in the success of the business. A standard representation for information sharing can be obtained through a supply chain framework that facilitates communication among different parties (Sharawi et al., 2006). A supply chain is ultimately a human activity and a multidisciplinary approach where systems engineering would be an appropriate foundation to tackle the challenges in cross-organizational supply chains (Haskins, 2006).

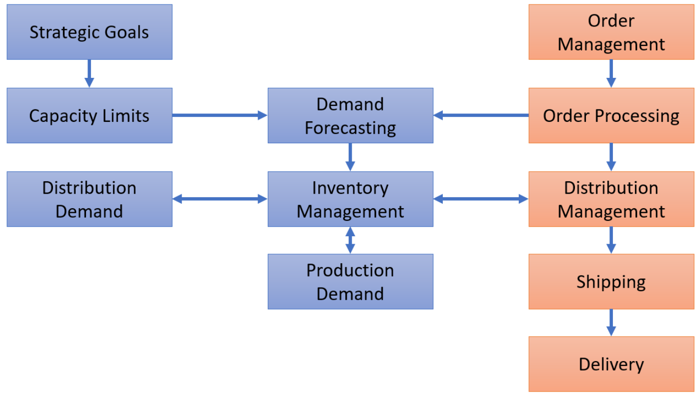

Figure 4. Supply Chain Management Flow adapted from (Yoo and Won, 2018)

The evolution of supply chain management is rooted in the 1960s when the focus was on minimizing production costs. In the 1970s, the focus shifted to material requirement planning. In the 1980s, the concept of Just-In-Time was developed that offers low-cost, high-quality, and reliable products. In the 1990s, the focus was more on integrations among different involved parties in a supply network. The focus shifted more to collaborations and performance management of a supply network for the success of a firm. With the advent of new technologies and the use of the World Wide Web (Web 2.0), the concentration extends more on creativity, improving collaboration, and communication among the stakeholders (Fawcett and Magnan, 2002).

The supply chain management framework relies on the distinction between two directions: function-oriented and organization-oriented. The focus of function-oriented is on purchase and supply, logistics, transport, marketing, and business management. The focus of organizational-oriented is on industrial organization, supply chain configuration, transaction costs, and system dynamics. The latter emphasizes the networked nature of supply chains and the processes that shape them (Park et al., 2013). Hence, supply chain management success is related to synchronizing various activities within the network (Flint et al., 2012). Performance measurement is an essential strategic tool to achieve the acquired objectives and fulfilling the company's mission (Fawcett & Magnan, 2002). There are different aspects in the supply chain performance measurement systems, including resources, output, and flexibility (Beamon, 1999). Several dimensions for performance measurement have been identified in the literature, as shown in Table 2.

Table 2. Supply Chain Performance Dimensions

Dimensions	(Kshetri, 2018)	(Neely et al., 1995)	(Fawcett & Magnan, 2002)	(Kamble & Gunasekaran, 2020)
Cost	×	×	×	×
Speed	×	×	×	
Dependability	×			
Risk Reduction	×			
Sustainability	×			
Time				×
Quality				×
Flexibility	×	×	×	×

The extended enterprise view has recognized that the companies compete on coordinated supply chains or a network of companies (Haskins, 2006). The critical elements for the success of supply chain integration are the development and integration of people and technological resources along with the coordinated management of materials, information, and financial flows (Haskins, 2006). The roles of different actors involved and the management of the supply chain are dependent on the company and the industry. Fawcett and Magnan (2002) provided a systematic literature review that helps understand the main activities and a complete picture of the supply chain. Based on their findings, advanced techniques such as simulation, artificial neural network, and fuzzy logic has been applied for decision-making in the supply chain (Fawcett & Magnan, 2002). Park et al. (2013) argue that the literature has developed a hierarchy of relationships on the degree to which a lead firm controls the entire supply chain, which is dependent on information requirements, the capacity for product differentiation, the inherent complexity of the product, the degree of durability needed in a relationship, and the market power.

The categories of issues and challenges of supply chain management identified in a systematic literature review by Fawcett and Magnan (2002) are, first, the new cultural development based on ongoing and shared learning and continuous improvement, and second, the emergence of the network organization, which has a complex web of linkages that needs coordination and management. The emergence of the network organization can add more difficulties, including a lack of common purpose, multiple and hidden goals, power imbalances, culture and procedures, conflict over autonomy and accountability, over-dependence, and lack of openness and opportunistic behavior (Fawcett & Magnan, 2002).

This study focuses on the network aspect of a supply chain and the challenges that arise from the collaboration and communication among the networks. The term “supply network” has been used since the 1990s to describe the dynamic, interconnected, complex, interdependent network of suppliers, manufacturing facilities, and other relevant organizations (Bales et al., 2004). A supply network comprises the member companies and the links between them. Three primary aspects of a network structure suggested by Lambert and Cooper (2000) are the members, the structural dimensions of the network, and the different types of process links across the supply chain.

The classification criteria for the characteristics of a supply network adopted through literature are listed in Table 3. The integration and operation of the supply network require continuous information flow to create the best flow for the product. The critical point for having effective supply network management is controlling uncertainty in customer demand, manufacturing processes, and supplier performance (Lambert & Cooper, 2000).

Table 3. Supply Network Characteristics

	(Craighead et al., 2007)	(Basole et al., 2016)	(Terzi & Cavalieri, 2004)	(Saberi et al., 2019)	(Wang et al., 2019)
Density & Network Size	×	×			
Complexity	×			×	×
Risk level		×			
Mutual Trust			×		×
Information Sharing			×		×
Collaboration			×		×

The decentralized network architecture of Blockchain creates a robust structure against failures and attacks. The trust provided through the decentralized data management, and peer-to-peer network makes it suitable for stakeholders to collaborate in a trustworthy fashion with one another without needing a central intermediary. Hence, a Blockchain-based supply network can eliminate some of the current challenges and provide a more efficient and resilient supply chain management.

Knowledge Gap

Resilience is a measure of the persistence of systems and their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables (Gheorghe & Katina, 2014; Holling, 1973). Resilience is recognized as a key construct to represent the network's ability to withstand disruptive events that stop or reduce the exchange of materials, information, and knowledge. Supply chain network resilience is an emergent structural property of a supply network, suggesting that different network structures will have varying degrees of resilience (Y. Kim et al., 2015). The common resilience metrics for supply network systems are availability, connectivity, and accessibility. The decentralized, distributed, and fault-tolerant features of Blockchain technology can be applied to improve the resilience metrics. The highly resilient architecture and distributed nature of Blockchain technology make it a promising platform to defend against attacks and preserve the integrity of the identity network (Shrier et al., 2016). The effects of applying Blockchain on each supply chain actor were described by (Litke et al., 2019), as shown in Table 4.

Table 4. Blockchain Impact on Current Supply Chain Actor Limitations Adapted from (Litke et al., 2019)

Actor	Current Limitations	Blockchain Impact
Raw material	Lack of transparency in origin and product quality metrics	Increase trust to keep track of the value chain from raw material to end consumer
Manufacturer	Lack of monitoring products to the final destination	Provide shared information system in the distribution networks
Distributor	Poor collaboration capabilities in the custom tracking system	Provide proof-of-location certification registered in the ledger
Wholesaler / Retailer	Lack of trust and certification of the product's path	Provide a tracking system for each product. Effectively return malfunctioning products
End-user	Lack of trust regarding the compliance of the product	Provide a complete and transparent view of the supply chain

The study by Sabz Ali Pour et al. (2021) explored the main challenges of supply networks identified in the literature as well as the provided solutions. The results indicate that the adoption of Blockchain technology to supply networks can facilitate communication and collaboration among the network actors and lead to a more efficient and resilient network. The study divided the taxonomy of challenges into four categories: network communication and information flow, transparency, data and information management, and performance.

Network Communication and Information Flow

In this category, the visibility of Blockchain can address the issues related to miscommunication, lack of effective collaboration, and conflict of interests (Fawcett & Magnan, 2002; Ludema, 2002; Saberi et al., 2019; Tatar et al., 2020; Terzi & Cavalieri, 2004; Wang et al., 2019). The parties in a supply network may be skeptical of the improper use of power and opportunistic behavior (Dani et al., 2003). The decentralized feature of Blockchain incentivized collaboration behaviors among participants (Wang et al., 2019). The supplier relationships can be automated, and data can securely be stored through smart contracts (Yoo & Won, 2018). The features of Blockchain that provide tracking and visibility through the whole supply chain can enhance the flow of information and reduce the generated costs in the supply network (Queiroz et al., 2019).

Transparency

The immutable ledger, decentralized platform, smart contracts, private and public keys, authenticity, and trust are some of the features of Blockchain technology that can provide solutions for the transparency category of challenges (Sabz Ali Pour et al., 2021). In a supply network, each entity needs to have a significant level of trust in other organizations to store their valuable and sensitive information. The single point of failure of centralized information systems can lead an entire network to be vulnerable to errors, hacking, corruption, or attacks (Saberi et al., 2019). Blockchain-powered trust enables point-to-point trading, payment, and communication that significantly reduces the structural complexity of supply network systems (Yuan & Wang, 2016). The diffusion of

Blockchain protocols can vastly improve product transparency (H. M. Kim & Laskowski, 2018).

Blockchain technology can offer advantages to complex supply networks, such as capturing the environmental characteristics of the product as well as the location and timestamps throughout the supply chain network. Moreover, the shared database using Blockchain technology can provide highly secure and immutable access to supply network data (H. M. Kim & Laskowski, 2018). In addition, Blockchain technology is suitable for supply chain traceability. In a Blockchain-based network, a digital token is associated with physical items when they are created. The final recipient can authenticate the token through the history of the item to the origin (Ivanov et al., 2019).

Blockchain can create a permanent, shareable, and actionable record of every step of a product in a supply chain, which provides efficiency throughout the global economy. The visibility feature also provides product traceability, authenticity, and legitimacy (Wang et al., 2019).

Data and Information Management

The data and information management category can be improved by disintermediation, traceability, and authentication provided by Blockchain (Sabz Ali Pour et al., 2021). One of the complexities in the supply network is due to geographically dispersed facilities and trade partners where acquiring and maintaining reliable data is critical (Wang et al., 2019). Evaluating information and managing risks in the supply network is complex and challenging due to globalization, various regulatory policies, diverse cultures, and human behavior (Saberi et al., 2019). Blockchain can provide seamless network visibility and symmetric information to all actors (Wang et al., 2019). Blockchain technology adopts the human society governance model in information technology systems and develops a decentralized system that enables multiple stakeholders to share power in the same information technology system (Chen et al., 2017). Decentralization is one of the critical features of Blockchain technology that can enhance information validity. The lack of need for assessing the trustworthiness of intermediary or other participants of the network makes trust a major characteristic of decentralization (Saberi et al., 2019). Blockchain technology and IoT offer provenance in complex supply chains (H. M. Kim & Laskowski, 2018). The real-time visibility of shipment to customers improves the available information for risk analysis and control of safety and security (Wang et al., 2019).

Information completeness is enhanced through Blockchain timestamping. Timestamping is a process that provides temporal orders among sets of events. Data can have ownership, location, product information such as attributes, performance, environmental impacts, cost, and quality (Wang et al., 2019). The material and information flow through the supply network can be more effectively facilitated by the Blockchain reliability and transparency features, which are automated with governance requirements. Thus, production will not be dependent on the characteristics of the materials but on knowledge, communication, and information (Saberi et al., 2019).

Performance

The last category of challenges can benefit from the less regulation compliance costs, tracking, digitalization, audit trail, and IoT integration of Blockchain technology (Sabz Ali Pour et al., 2021). One of the critical advantages of the Blockchain in the supply chain performance is the financial intermediary's disintermediation, including payment networks, stock exchanges, and money transfer services, which provide more efficiency among partners. The other advantage is the high secure audit trails with details to monitor the activities of users (Saberi et al., 2019).

Paper-based processes can cause delays and hinder the efficient flow of goods. Blockchain provides digitalized documentation and establishes immutable and shared records of transactions among network nodes in real-time (Wang et al., 2019). Blockchain facilitates effective performance and outcome measurement of key supply chain management processes. The immutable ledger can be used as a real-time input basis for tracking data, enhancing suppliers' trust, and ensuring consumers with legitimate and high-quality products (Kshetri, 2018).

Blockchain technology provides the creation of a record of activities and data required for recovery in terms of synchronized contingency plans, which can reduce the inefficiencies in anticipation of disruptions risks. The decentralized feature can decrease the supply chain redundancy requirement with the help of manufacturing flexibility. The root causes of disruption can be traced to observing disruption propagation and selecting short-term stabilization actions due to accurate data on the availability of capacities and inventories. Third, develop a mid-term recovery policy. Fourth, analyze the long-term performance impact of the ripple effect (Ivanov et al., 2019).

In conclusion, Blockchain-based systems introduce new ways of decentralization and delegation of services, which can be embedded into autonomous interacting pieces of code, such as smart contracts and support supply networks for more efficient and resilient acquisitions.

Summary of Blockchain Applications in Supply Chain

A case study is an in-depth description and analysis of a bounded system that captures the key requisites in the context of research for a diverse range of issues and is empirical (Harrison, H., Birks, M., Franklin, R., & Mills, J., 2017). One of the gaps in Blockchain technology application in supply chain literature is the lack of case studies that could provide a better understanding.

In the study by Sabz Ali Pour et al. (2021), three case studies were analyzed to explore the feasibility of Blockchain application in supply network resilience. Walmart was the first case study that used Blockchain to enhance transparency. The two pilot studies of Walmart are in China and United States for improving the safety of food, building trust for their customers, and reducing their costs. The results indicate that the adoption of Blockchain is achievable for the processes. Walmart faced some challenges through this transition in this adaptation, including the lack of technological infrastructure and training in all the enterprises and the high cost of implementation.

The second company analyzed by (Sabz Ali Pour et al., 2021) is Maersk, the largest integrated shipping company in the world. Maersk developed a Blockchain-based platform with the support of IBM to improve the collaboration and trust across the diverse set of stakeholders of the global supply chain. The developed platform provides more visibility, traceability, and immutability. The immutability, auditability, and transparency features of the platform were demonstrated in the pilot project, which resulted in a significant decrease in administrative costs.

DHL, an international courier and package delivery company, was the third case study for Sabz Ali Pour et al. (2021). A Blockchain-based serialization prototype with supply chain partners in different locations was developed to manage risks regarding counterfeit drugs. The simulation results demonstrate a significant improvement in genuine medicine transactions while being immutable and traceable.

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Research Methodology

The methodology for achieving the research objectives includes several steps. In the literature review stage, the identified challenges and limitation of the supply network through the systematic literature review is mapped with Blockchain features to evaluate the feasibility of Blockchain adoption for a more resilient supply network. Second, a conceptual framework is developed to explore the Blockchain application in supply chain resilience. In the next stage, an ABM is developed to analyze the benefits of a Blockchain-based supply network platform. Various scenarios are simulated for validation.

Agent-Based Modeling and Simulation

Agents are computer systems that are situated in a defined environment where the designed objectives would be obtained through a set of interactions and actions (Sabz Ali Pour et al., 2018). Agents are components that can learn from their environment and change their behavior in response. The capability to make independent decisions is a core feature of agents. Agents have specific characteristics, including being self-contained, identifiable, interactive, goal-directed, autonomous, and flexible (Macal & North, 2005).

ABM is a powerful approach to capturing complex structures, interdependencies, and dynamics. ABMS can impact how businesses use computers in decision support systems (Macal & North, 2005). The need for ABM application increases as the computational power is advancing rapidly and systems are becoming more complex in terms of interdependencies. The other reason is the more refined granularity level of data (Macal & North, 2005).

The agent-based approach can help better understand the interacting factors within a supply chain and analyze the dynamic and strategic behaviors of a supply network. Very few studies have focused on the ABMS advantages over the other simulation tools for production and operations management (Jalilian et al., 2021). One of the main advantages of ABM in the supply chain is to capture the dynamic nature of transactions and explore the effects on the evolving behavior of the entire system

(Abdollahzade et al., 2018). Julka et al. (2002) used ABM to develop a framework to support the modeling, monitoring, and management of the supply chain. Belhadi et al. (2021) used multi-criteria decision-making techniques and AI-based algorithms to identify patterns for developing supply chain strategies. The results indicate that the agent-based system is one of the most promising techniques to promote supply chain resilience strategies. Jalilian et al. (2021) used ABMS to configure the supply chain challenges within a bank process; Azar et al. (2021) used ABM to simulate the steel supply chain. Resilience is the factor that enables supply chains to eliminate potential risks and recover faster from any disruption. Colon et al. (2021) generated an ABM to explore supply chain disruption in case of a disaster and to analyze the indirect losses. (Massari & Giannoccaro (2021) developed an ABMS to analyze the supply chain resilience performance in different environmental conditions and levels of complexity. Rahman et al. (2021) developed an ABM for the supply chain recovery due to the COVID-19 pandemic.

Blockchain technology can strengthen supply chain resilience through the use of digital technologies. Lohmer et al. (2020) explored the Blockchain application on supply chain resilience by employing ABMS to simulate different disruption scenarios. Longo et al. (2019) conceptualized the supply chain operations and then conducted an ABMS to analyze the impact of Blockchain technology on the data accuracy and authenticity of supply chain inventory management. Betti et al. (2019) simulated a private Blockchain network using ABMS, and the results indicated that Blockchain with support of IoT fits well for hyperconnected logistics.

Based on the literature review findings, this study aims to emphasize more the advantages of Blockchain application on supply network resilience.

Steps of the Methodology

To conduct the methodology, firstly, the system of interest is thoroughly analyzed systematically. The main components, the relevant data sources, and agent behaviors are identified. The next step would be identifying the agents' relationships and interactions. Then, the most practical simulation platform and model development strategies are determined. Through the literature review, the main roles in a basic supply chain consist of the following actors, which are defined as agents for this model. In the traditional system, point to point communication method was more in practice, which has several limitations, including the need to contact various other companies to fulfill the requirements of the order, which can create delays and backlogs in the system. Based on the literature review, the importance and significant role of communication and information exchange in supply chain networks are mainly targeted in this study.

Discrete event simulation (DES) models permit representing real-life circumstances to identify bottlenecks and enhance systems performance (Ballali & Tan, 2021; Fischer et al., 2021). This study integrates DES and ABM to conduct the model for the traditional supply chain and the newly proposed concepts.

To capture the Blockchain features in the simulation, Aurachain, an intuitive low-code platform, is used for the smart contract execution and decentralized communication of the supply network participants.

For this study, the primary agents defined for the supply chain include customer, retailer, distributor, manufacturer, and supplier (Macal & North, 2005). The process for ordering a new product defined for this study includes several steps. The agents execute behaviors as the customer places an order with the retailer. The retailer checks the inventory to fulfill the order. The distributor sends the items in response to previous orders. The distributor receives items from the manufacturers and forecasts the future demands of retailers.

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Model Development

This section provides guidance on how to implement the developed framework, including the phases of the methodology and example implementation on a supply chain network using scenario simulation.

Phases to Implement the Methodology

In order to implement the methodology, the first requirement is having a substantial level of understanding of the supply chain under focus since the supply chain can have significant differences based on various factors, including the type of the product, transportation means, and international characteristics. This is followed by determining what supply chain challenges are to be addressed by the implementation of Blockchain technology. Only then the use cases and requirements for the Blockchain technology can be decided to be implemented into the supply chain. At this stage of the methodology, the decision-makers ought to utilize modeling and simulation techniques to test the intended Blockchain technology for their supply chain network. Actual data from the existing supply chain network can be employed in the simulations to test and tune the proposed Blockchain implementation. Following these phases can help managers have informed decision-making for the investment.

Simulation Model and Scenarios

The developed methodology is explained in this section by implementing it on a sample network with three different supply chain scenarios. Each scenario is provided with two cases where the differences between a supply chain with and without Blockchain technology can be analyzed.

The sample supply chain network is presented in Figure 5. There are four main categories in the supply chain: suppliers, manufacturers, distributors, and retailers. The products usually flow in this direction from the upstream suppliers to customers. Trucks deliver the goods among the nodes of this supply chain. Customers can analyze their supply chain network using various means that will be further explained later in this section. As shown in the figure, there are five suppliers, four manufacturers, three distributors, and nine retailers. Each entity is a different company; therefore, in the traditional communication structure, there is no established trust among the companies in terms of sharing an information technology infrastructure.

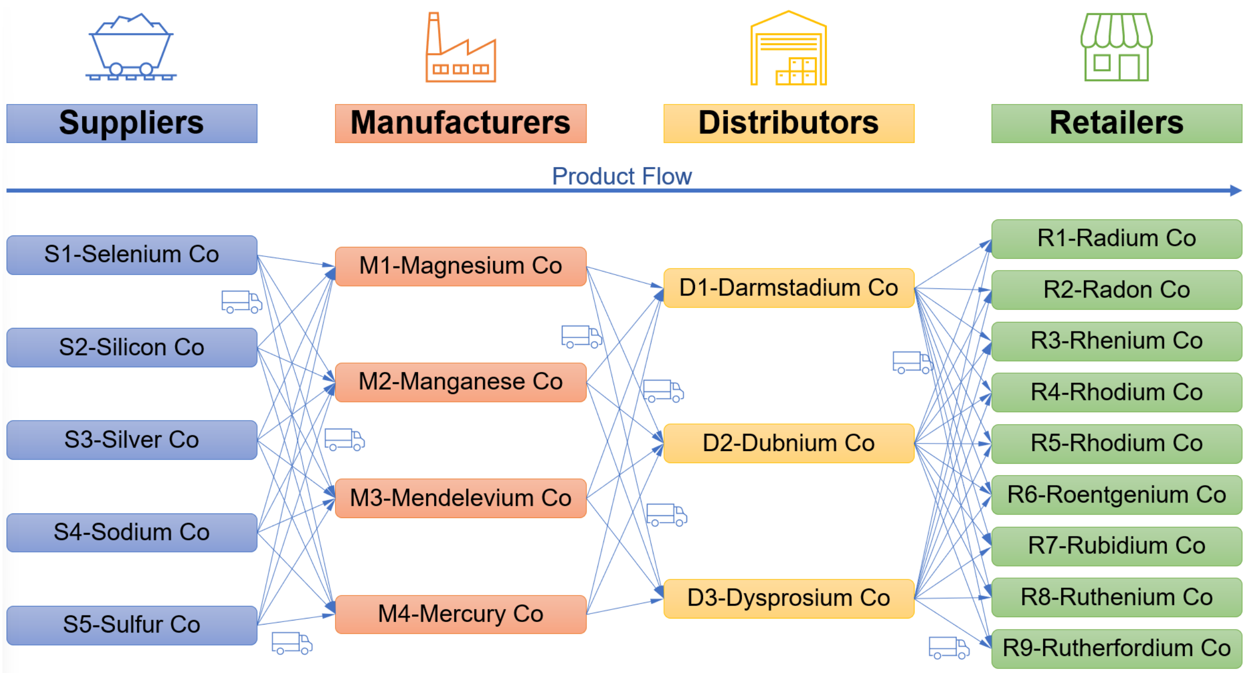

Figure 5. Simulation Model

Communication among the parties of a supply chain is crucial for maintaining the working state of the supply chain and addressing any possible disruptions that can occur during the operations. Customers can analyze their supply chain network using various means: horizontal collaboration and vertical collaboration. Vertical collaboration occurs among the entities in the same category, either in suppliers, manufacturers, distributors, or retailers. On the other hand, horizontal collaboration exists among the entities from an upstream or downstream party. Figure 6 represents the horizontal and vertical collaboration among the supply chain entities. Both vertical and horizontal collaboration is crucial for the supply chain management. Especially when there are problems to address, the timeliness of communication becomes critical. When the entities in the supply chain do not belong to one company, longer lags in communication are expected because the lack of trust among third party organizations might lead to having independent information technology infrastructure. This leads to a slower turnaround for any information needed from an upstream or downstream entity for horizontal collaboration or another party from vertical collaboration.

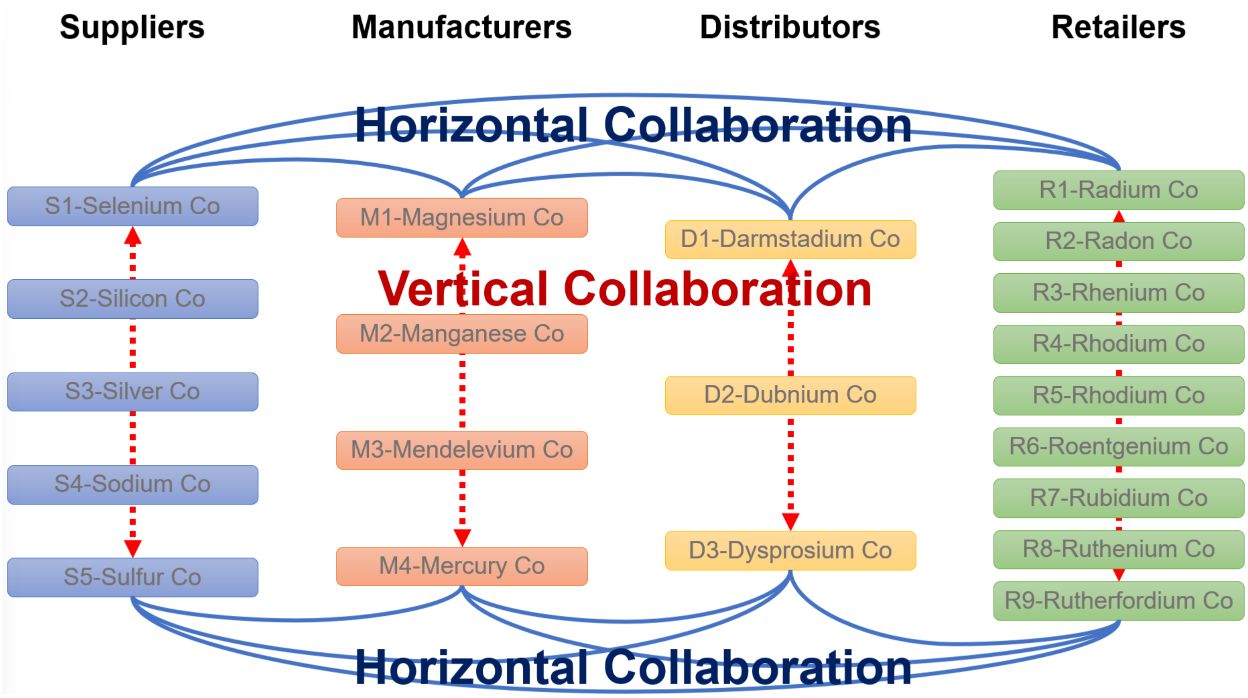

Figure 6. The Characteristics of Horizontal and Vertical Collaboration

The simulation model is used to analyze the impact of the utilization of Blockchain technology using three scenarios. Table 5 presents the scenarios along with the supply chain challenges they address and which features of Blockchain technology are utilized. Each scenario is analyzed by simulation with two cases where the differences between a supply chain with and without Blockchain technology can be observed.

Table 5. Comparison of Simulation Scenarios

Scenario #	Case and Story	Supply Chain Challenge	Blockchain Features	Resiliency	Efficiency	Time	Accountability	Traceability	Expected Results
1	**Computer Chips** Issue emerges at a supplier. There is a need to reroute supply.	Lack of effective communication	Network visibility, reduce lead time	*	*	*		*	Trace issue and find the source: supplier node 4. Check supply capacity of suppliers and reroute from suppliers 3 and 5.
2	**Pharmaceutical** Companies are audited to find out record fraud.	Product quality and lack of visibility	Network visibility	*	*	*	*	*	Record fraud is identified. The company is profiled as disqualified. Products are recalled.
3	**Lubricant (Liquid)** Damaged Package. Find the cause, reroute to meet demand.	Lack of monitoring	Reduce lead time, monitoring cost	*		*	*	*	Trace the source of the damage to the distribution center. Redundant products rerouted to demand.

The first scenario focuses on supply reroute needs for the computer chips supply chain. Based on the case, the supply chain manager needs to identify the issue, determine the supplier of computer chips that are subject to disruption and reroute the supply from the suppliers with sufficient stock. In this scenario, it is expected to trace the issue to one of the suppliers. Then the suppliers with sufficient capacity are needed to be determined, and rerouting of the supply is performed. The supply chain challenge that is addressed in this scenario is the lack of effective communication. Blockchain technology proposes providing network visibility to address this issue and reduce the lead time. The benefits of Blockchain technology that can be demonstrated with this scenario are traceability, time, efficiency, and resilience.

In the second scenario, a recall for a pharmaceutical product is simulated from a regulator's perspective. Based on the case, the manufacturers are audited, and one of the products is found fraudulent/counterfeit. This scenario is about the product quality and lack of visibility challenges regarding the supply chain. Such discovery leads to the disqualification of the manufacturer and a product recall for all relevant goods. Blockchain technology proposes to provide network visibility to address this issue. The benefits of Blockchain technology that can be demonstrated with this scenario are accountability, traceability, time, efficiency, and resilience.

The third scenario focuses on the product replacement need for the liquid lubricant supply chain. Based on the case, the supply chain manager of the customer needs to trace the source of the damage, determine which company is responsible for the damage and where the replacement product exists, and reroute the undamaged products. The supply chain challenge that is addressed in this scenario is the lack of monitoring. Blockchain technology proposes to reduce lead time and provide monitoring. The benefits of Blockchain technology that can be demonstrated with this scenario are resilience, traceability, accountability, and time.

Each scenario is simulated with two cases, one with Blockchain and one traditional supply chain, to analyze the impact of Blockchain technology.

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Analysis and Results

In this section, details for each scenario and the total time for the completion of the problem resolving process, including the communication activities, are provided.

Steps of Scenario 1 with Blockchain are presented in Figure 7. Three main steps of the scenario are (1) Initiate Supply Reroute Order, (2) Trace the Source of Issue, and (3) Reroute Supply. Since this scenario presents a supply chain with Blockchain technology implemented, it provides high visibility, and tracing the source of the issue becomes relatively easy as looking up the ledger and analyzing the current capacities of each node of the supply chain to identify the one that has no current capacity. It is followed by rerouting supply by again looking up the ledger for current supply capacities and preparing and sending the order request to the suppliers that have sufficient supply.

Figure 7. Scenario 1 with Blockchain

Steps of Scenario 1 without Blockchain are presented in Figure 8. Three main steps of the scenario are (1) Initiate Supply Reroute Order, (2) Trace the Source of Issue, and (3) Reroute Supply. Since this scenario presents a traditional supply chain without Blockchain technology, it does not provide easy access to the historical data from third parties; therefore, tracing the source of the issue and analyzing the current capacities of others in the supply chain becomes relatively difficult since these tasks are conducted by contacting third parties individually and waiting for the response from them. The third step is rerouting supply by again contacting the third-party suppliers for their current capacities and preparing and sending the order request to the suppliers that have sufficient supply.

Figure 8. Scenario 1 without Blockchain

Steps of Scenario 2 with Blockchain are presented in Figure 9. Three main steps of the scenario are (1) Initiate Recall, (2) Identify Product Inventories, and (3) Notify Customers. This scenario also presents a supply chain with Blockchain technology implemented; therefore, it provides high visibility, and locating existing inventories of the recalled product becomes relatively easy as looking up the ledger and analyzing the transactions. It is followed by notifying customers by again looking up the ledger to identify the customers who bought the product and preparing and sending the notifications to the customers.

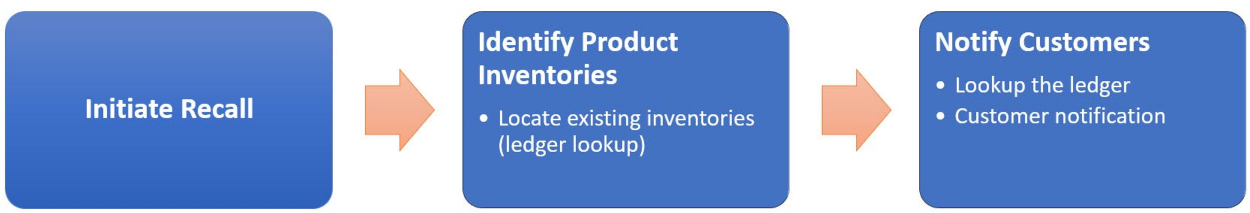


Figure 9. Scenario 2 with Blockchain

Steps of Scenario 2 without Blockchain are presented in Figure 10. Three main steps of the scenario are (1) Initiate Recall, (2) Identify Product Inventories, and (3) Notify Customers. This scenario presents a traditional supply chain without Blockchain technology; thus, it does not provide easy access to the historical data from third parties. Third parties can only contact relevant parties to learn about their inventories. Moreover, in this scenario, the regulators cannot directly identify the end customers who possess the recalled product. They can only order retailers to notify their customers.

Figure 10. Scenario 2 without Blockchain

Steps of Scenario 3 with Blockchain are presented in Figure 11. Three main steps of the scenario are (1) Initiate Replacement Request, (2) Reroute Products, and (3) Trace the Source of Damage. This scenario also presents a supply chain with Blockchain technology. The high visibility feature makes it easy to locate products by looking up the ledger and identifying which the third party has inventory. It is followed by tracing the source of the damage by looking up the ledger for monitoring notes that indicates where the damage originated.

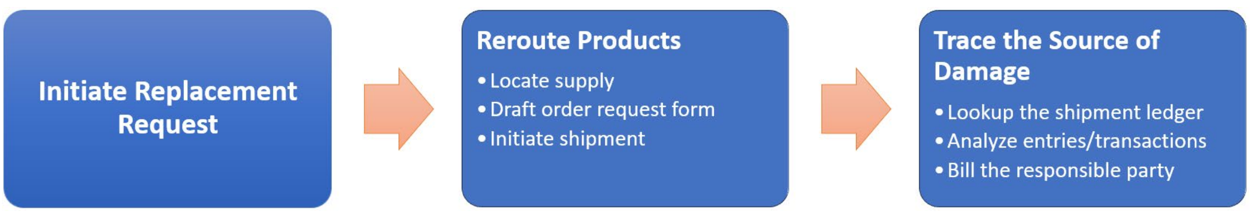


Figure 11. Scenario 3 with Blockchain

Steps of Scenario 3 without Blockchain are presented in Figure 12. Three main steps of the scenario are (1) Initiate Replacement Request, (2) Reroute Products, and (3) Trace the Source of Damage. This scenario also presents a traditional supply chain without Blockchain technology; therefore, it does not provide easy access to the inventory information of third parties. The customer depends on contacting third parties individually to check their stock and initiate replacement shipments. In order to trace the damage source, it is again needed to be manually investigated by contacting upstream third parties to understand when and where the damage originated.

Figure 12. Scenario 3 without Blockchain

In order to run the simulations, durations for each step of each scenario were randomly generated based on realistic distributions. The total duration for each scenario has been computed for four thousand trials, and the results were visualized using histograms.

Figure 13 presents the histogram for Scenario 1 with Blockchain. The total duration for this scenario has a mean of 130.0 and a standard deviation of 8.3, with a minimum and maximum value of 100.0 and 160.2, respectively.

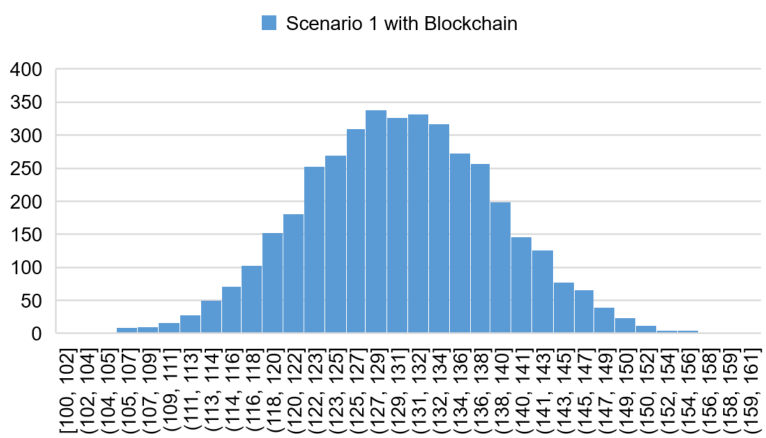


Figure 13. Histogram for the Results of Scenario 1 with Blockchain

Figure 14 presents the histogram for Scenario 1 without Blockchain. The total duration for this scenario has a mean of 1604.3 and a standard deviation of 8.65, with a minimum and maximum value of 1343.9 and 1912.1, respectively.

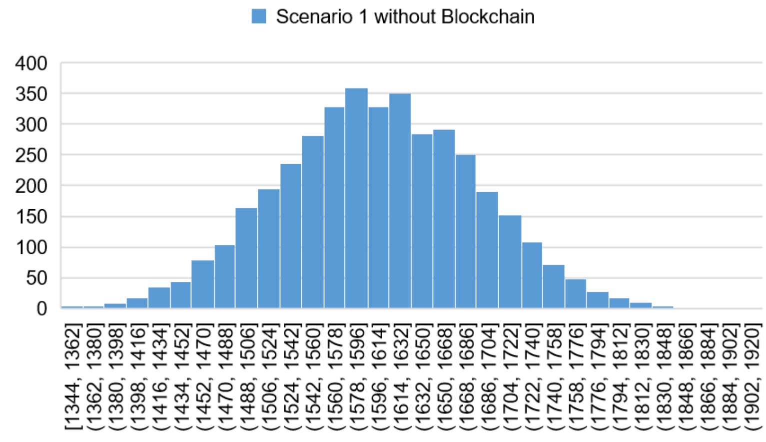


Figure 14. Histogram for the Results of Scenario 1 without Blockchain

Figure 15 presents the histogram for Scenario 2 with Blockchain. The total duration for this scenario has a mean of 79.9 and a standard deviation of 10.55, with a minimum and maximum value of 42.2 and 119.5, respectively.

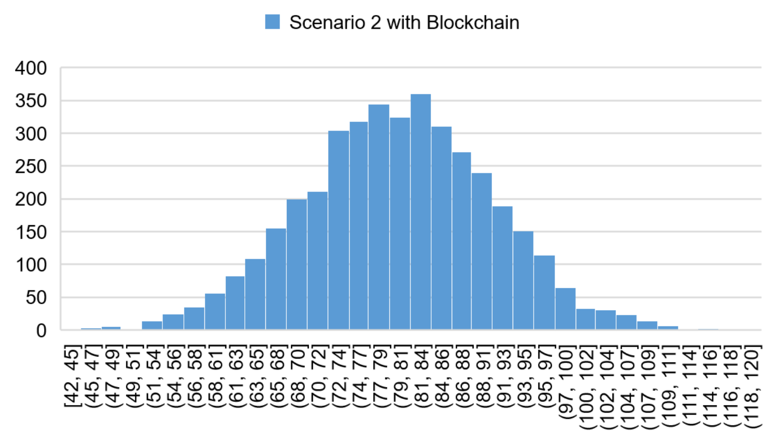


Figure 15. Histogram for the Results of Scenario 2 with Blockchain

Figure 16 presents the histogram for Scenario 2 without Blockchain. The total duration for this scenario has a mean of 257.0 and a standard deviation of 18.58, with a minimum and maximum value of 191.3 and 325.4, respectively.

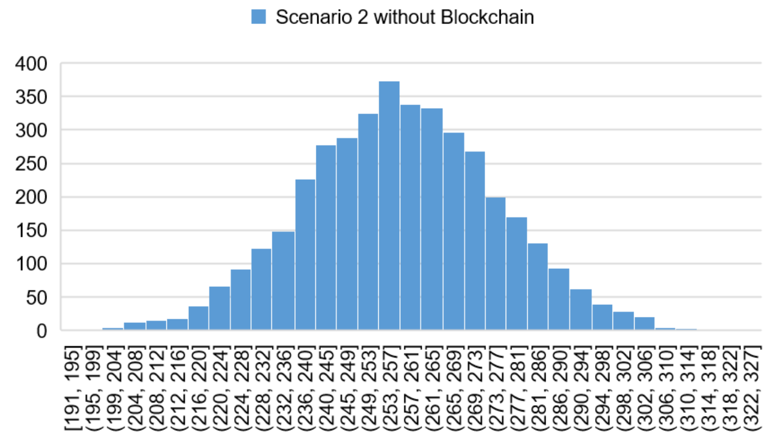


Figure 16. Histogram for the Results of Scenario 2 without Blockchain

Figure 17 presents the histogram for Scenario 3 with Blockchain. The total duration for this scenario has a mean of 130.2 and a standard deviation of 7.30, with a minimum and maximum value of 107.9 and 158.3, respectively.

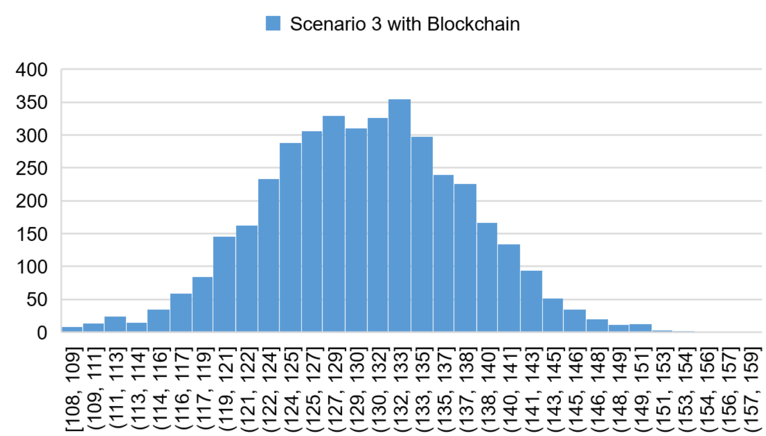


Figure 17. Histogram for the Results of Scenario 3 with Blockchain

Figure 18 presents the histogram for Scenario 3 without Blockchain. The total duration for this scenario has a mean of 569.7 and a standard deviation of 232.31, with a minimum and maximum value of 375.7 and 1948.5, respectively. As different for this scenario, the results do not converge to a normal distribution, rather three clusters that only one has a shape of the typical normal distribution. The reason for this result is originated in the characteristics of this specific scenario where the investigations to trace the source of the damage are conducted starting from the retailers and going back to distributors and manufacturers only if the previous category of the upstream third parties is not the party that the damage is originated from. In the cases that the damage originates at the manufacturers or distributors, the total time to complete the replacement request increases significantly.

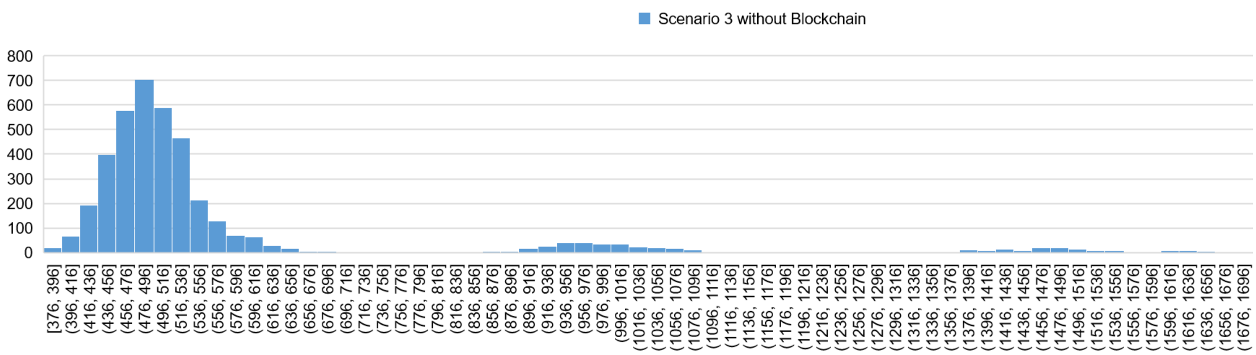
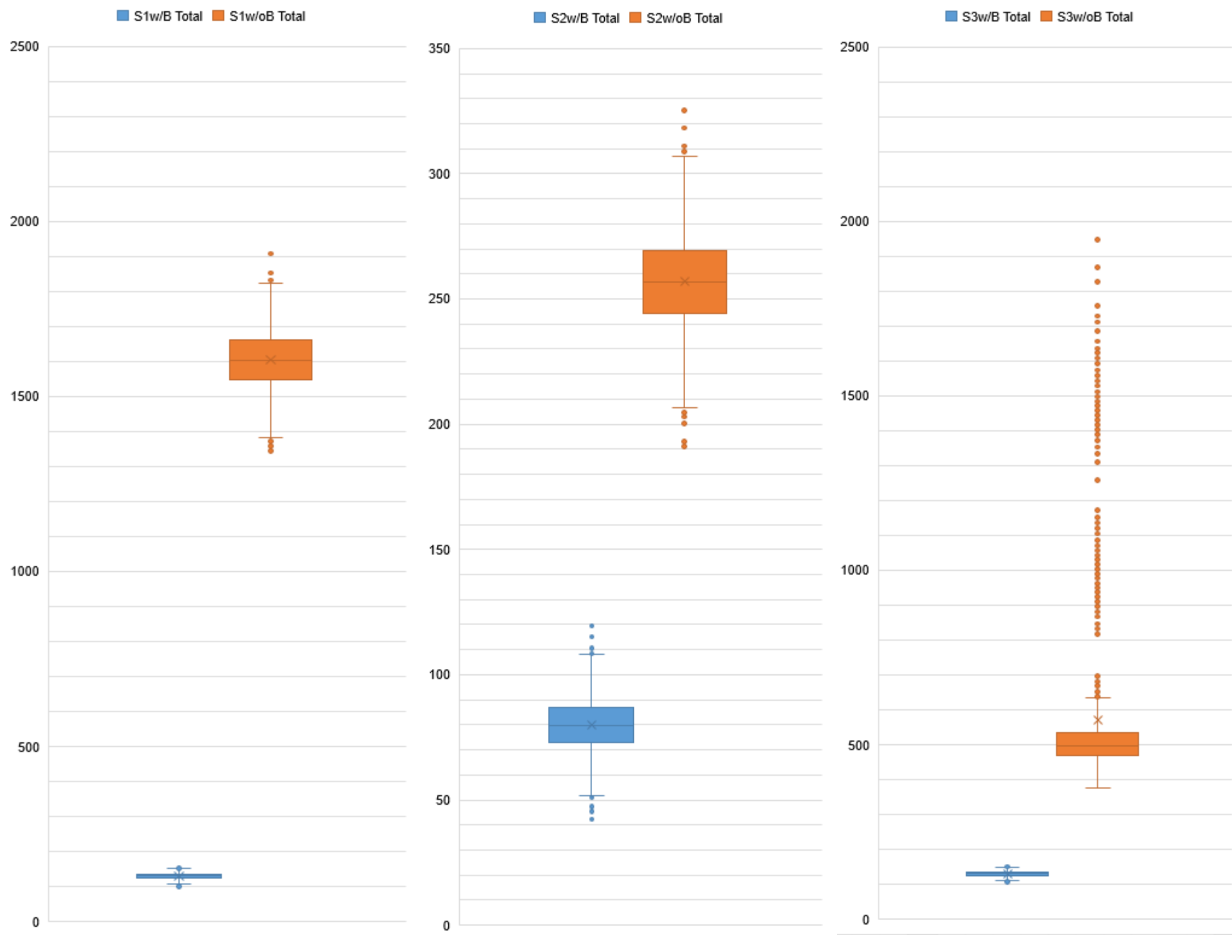


Figure 18. Histogram for the Results of Scenario 3 without Blockchain

Figure 19 presents box plots for all scenarios in a way that makes comparisons easier. (a), (b), and (c) stands for Scenarios 1, 2, and 3, respectively, while blue box plots are for the scenarios with Blockchain, and orange box plots stand for the scenarios without Blockchain. It should be noted that the ranges of the y-axes are different for (a), (b), and (c). It can easily be seen that for each scenario, implementation of the Blockchain technology significantly reduces the total time to address the disruption the supply chain is subject to. The results indicate how beneficial Blockchain technology can be for the resilience of the supply chain.



(a) (b) (c)

Figure 19. Box Plot Comparison for the Total Time for the Supply Chain with (Blue Plots) and without Blockchain (Orange Plots) for Scenario 1 (a), Scenario 2 (b), and Scenario 3 (c)

Conclusion & Discussion

Whether an organization needs to adopt Blockchain is a business decision that requires proper consideration because not all problems are resolved with Blockchain technology. Blockchain technology is useful only when it is implemented for an appropriate use case, not solely for the sake of using it. As described in this study, there are several features of Blockchain technology that make it more effective or efficient than existing methods, including being immutable, traceable, and decentralized. Figure 20 presents a decision-making process that can be employed by business leaders to make an informed decision regarding investing in Blockchain technology adoption (Yaga et al., 2018).

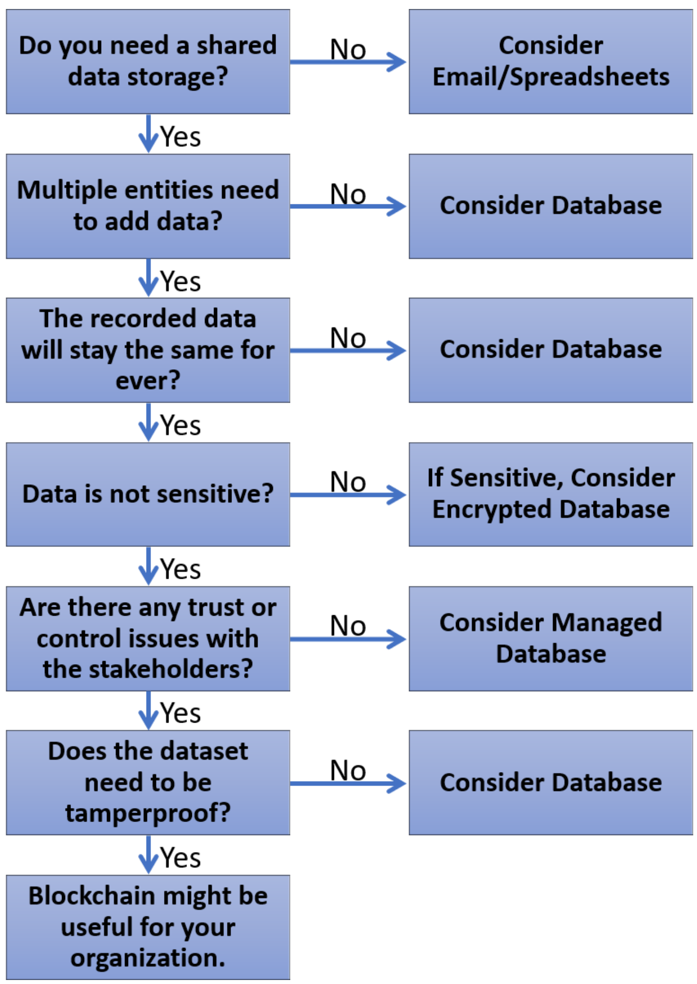


Figure 20. Decision mechanism to adopt Blockchain adapted from (Yaga et al., 2018)

This report presents a framework for the application of Blockchain technology in supply chain management to improve resilience. In this report, firstly, supply chain challenges and limitations are mapped with the Blockchain features. The report also provided a comprehensive Blockchain-based supply chain network management framework. The developed framework is useful when it is implemented for relevant supply chain use cases, such as increasing product traceability, avoiding counterfeits, and increasing flexibility (Queiroz & Fosso Wamba, 2019). The application of the proposed framework is demonstrated using modeling and simulation. Various types of scenarios are simulated to show how Blockchain technology can improve the resilience of the supply chain network. The scenarios investigated how Blockchain technology can benefit against counterfeits, improve the flexibility of the supply network, and improve resiliency by reducing the time to recover from disruptions. The simulation outcomes highlighted the improvements the Blockchain technology can provide. The differences in the simulation scenarios can provide guidance for decision-makers who consider using the developed framework during the acquisition process.

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Acquisition Research Program
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

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