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Blockchain-Based Digitalization of Logistics Processes

Innovation, Applications, Best Practices

Edited by
Herwig Winkler

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Editor

Herwig Winkler

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About the Editor

Herwig Winkler

Prof. Dr. Herwig Winkler is currently the chair of production and operations management and is a director of the industrial engineering and management study program at the Brandenburg University of Technology in Cottbus, Germany. Formerly, he was an associate professor of applied business administration at the University of Klagenfurt, Austria. Prof. Winkler is conducting research in different fields, such as industrial digitalization, supply chain management, flexibility enhancement, and blockchain technology. His recent projects have dealt with the decarbonization of value creation networks, use of machine learning in the order management process, as well as blockchain technology in industrial environments.

Preface to "Blockchain-Based Digitalization of Logistics Processes—Innovation, Applications, Best Practices"

Blockchain technology is becoming one of the most powerful future technologies in supporting logistics processes and applications. It has the potential to destroy and reorganize traditional logistics structures. Both researchers and practitioners all over the world continuously report on novel blockchain-based projects, possibilities, and innovative solutions with better logistics service levels and lower costs. The idea of this Special Issue is to provide an overview of the status quo in research and possibilities to effectively implement blockchain-based solutions in business practice.

This Special Issue contains well-prepared research reports concerning recent advances in blockchain technology around logistics processes to provide insights into realized maturity. It is a genuinely, internationally crafted edition with contributors from all over the world:

Abderahman Rejeb, Karim Rejeb, Steve Simske, and Horst Treiblmaier reported on findings about blockchain technologies in logistics and supply chain management based on a bibliometric review. Additionally, Moritz Berneis, Devis Bartsch, and Herwig Winkler conducted a systematic literature review and analyzed applications of blockchain technology in logistics and supply chain management. Houssein Hellani, Layth Sliman, Abed Ellatif Samhat, and Ernesto Exposito investigated blockchain integration with supply chain and provided an overview on data transparency. Christian Straubert and Eric Sucky answered the question of how useful a distributed ledger is for tracking and tracing in supply chains based on a systems thinking approach. Horst Treiblmaier, Abderahman Rejeb, Remko van Hoek, and Mary Lacity analyzed the intra- and interorganizational barriers to blockchain adoption, developed a general assessment, and provided coping strategies for the agrifood industry. Serkan Alacam and Asli Sencer showed how blockchain technology can be used to foster collaboration among shippers and carriers in the trucking industry based on a design science research approach. Elnaz Irannezhad showed what the architectural design requirements of a blockchain-based port community system are. Bernard Aritua, Clemens Wagener, Norbert Wagener, and Michał Adamczak provided an overview of blockchain solutions for international logistics networks along the New Silk Road between Europe and Asia. Hana Trollman, Guillermo Garcia-Garcia, Sandeep Jagtap, and Frank Trollman presented a blockchain for ecologically embedded coffee supply chains. Moritz Berneis and Herwig Winkler showed the results of a value proposition assessment of blockchain technology for luxury, food, and healthcare supply chains. Mubashir Hayat and Herwig Winkler explore the way from traditional product lifecycle management systems to blockchain-based platforms. Abderahman Rejeb, John G. Keogh, Suhaiza Zailani, Horst Treiblmaier, and Karim Rejeb elaborated a review of potentials, challenges, and future research directions of the blockchain technology in the food industry. Last, but not least, Saša Malešević, Michael Lustenberger and Florian Spychiger gave insight into applying distributed ledger concepts to a Swiss regional label ecosystem.

This edition contains 13 articles that are of interest for researchers, students, and practitioners, with a focus on management aspects and implementation possibilities of blockchain solutions.

Herwig Winkler
Editor

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Article

Blockchain Technologies in Logistics and Supply Chain Management: A Bibliometric Review

Abderahman Rejeb [1], Karim Rejeb [2], Steve Simske [3] and Horst Treiblmaier [4,*]

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Abstract: The emergence of blockchain technology has sparked significant attention from the supply chain management (SCM) and logistics communities. In this paper, we present the results from a thorough bibliometric review that analytically and objectively identifies the intellectual structure of this field, the seminal papers, and the most influential scholars. We employ a knowledge domain visualization technique to generate insights that go beyond other review studies on blockchain research within logistics and SCM. The analysis starts with selecting a total of 628 papers from Scopus and the Web of Science that were published during 2016–2020. The bibliometric analysis output demonstrates that the number of blockchain papers has rapidly increased since 2017. The most productive researchers are from the USA, China, and India. The top academic institutions contributing to the literature are also identified. Based on network analyses, we found that the literature concentrates mainly on the conceptualization of blockchain; its potentials for supply chain sustainability; its adoption triggers and barriers; and its role in supporting supply chain agility, trust, protection of intellectual property, and food/perishable supply chains. Besides systematically mapping the literature, we identify several research gaps and propose numerous actionable research directions for the future. This study enriches the extant blockchain literature, provides a timely snapshot of the current state of research, and examines the knowledge structure of blockchain research in logistics and SCM with the help of evidence-based scientometric methods.

Keywords: blockchain; supply chain management; logistics; bibliometrics; network analysis

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1. Introduction

Modern supply chains have recently witnessed tremendous changes, extending a formerly operational function to an independent supply chain management (SCM) function [1]. Supply chain processes contain numerous logistics operations, including planning, implementing, and controlling the effective flow and storage of goods, services, and related information from the source to the point of consumption to satisfy customer requirements [2]. Integrating and streamlining these activities bring a competitive advantage in visibility, revenue optimization, inventory turnover, supply chain speed, and efficient customer service delivery [3]. However, achieving these objectives is challenging since the complexities of supply chains have significantly increased due to the interplay of multiple geographically dispersed entities operating independently and frequently competing to serve their respective customers [4–7]. Besides complexities, supply chains also face numerous uncertainties and risks [8–10], such as the engagement of trading partners in opportunistic behavior (e.g., distorting information, cheating) [11,12], privacy leakage [13], fraud and cybercrime [14], and counterfeit product identification.

To overcome these issues, corporate managers across many industries attempt to improve SCM through digitalization [15]. The digitalization of supply chains refers to the process of organizations adopting inter-organizational systems to collaborate and transact with their trading partners (e.g., key suppliers and customers) along their respective chains. In total, the SCM market is anticipated to reach revenues of $19 billion by 2021 through the digitalization of its operations [16–19]. The digitalization of supply chains offers increased business velocity and agility and contributes to the formation of supply chain networks that are highly interconnected, inclusive, trustworthy, and secure [20]. Digitalization has also played a key role in maximizing the speed of business transactions and supporting the development of traceability mechanisms that enable the identification and recording of products and processes [21]. Through digitalization, Kuhi et al. [15] argue that firms can obtain better visibility over key information, events, and collaborations across organizational boundaries, thereby maintaining competitiveness in the supply chain network. Firms can also rely on the digitalization of supply chain processes to better meet customer demands for a wide variety of individualized products through higher efficiency and lower costs.

Firms have recently begun deploying blockchain technology to sustain their activities and improve the management of their supply chains [22–24]. Blockchain can be defined as a "*digital, decentralized, and distributed ledger in which transactions are logged and added in chronological order with the goal of creating permanent and tamperproof records*" [25] (p. 547). The decentralized ledger contains a chain of time-stamped blocks that are linked by hashes using cryptography [26]. Each block comprises a set of entries (e.g., data, transactions, records) to be included in the network, and each new block is chained to the preceding block. Once blocks are added to blockchain, they are immutable and have been verified through sophisticated automation and governance protocols [27]. Blockchain is built using peer-to-peer (P2P) networks, and it necessitates agreement between all parties to validate transactions. This eliminates inaccurate or potentially fraudulent transactions from the database. Unlike conventional information technology (IT) platforms, blockchain alleviates the reliance on a single centralized authority and facilitates secure and pseudo-anonymous transactions and agreement among transacting partners [28]. A specific blockchain solution, according to Rejeb et al. [29], is seen as a combination of various methods, technologies, and tools that addresses a particular problem or business use case. This means that the technology is versatile and enables many solutions, while spanning multiple industries [30]. The concept of an online blockchain was introduced by the pseudonymous Satoshi Nakamoto [31] in 2008 with the cryptocurrency Bitcoin, representing a novel technological approach to develop trustless systems [32]. In the context of cryptocurrencies, the tamper-resistant nature of blockchain serves as an effective solution to prevent 'double spending' and assure that transactions are carried out properly without the risk of the same funds being allocated more than once [33]. Beyond flourishing in the finance industry, the spectrum of blockchain applications extends to other sectors, such as logistics and SCM [34–36], social media and marketing [37,38], e-commerce [39,40], tourism [41–43], and healthcare [12,44,45]. Likewise, research on blockchain technologies has gained global traction, particularly from the logistics and SCM community [46]. The reasons for this increasing interest in the technology are diverse. First, blockchain has emerged as a new boundary condition that gives rise to new frameworks and concepts for business models, organizational forms, and governance structures [47], while facilitating improvements in resource management, traceability, security, and data transparency [48]. Second, blockchain changes the relationship between parties in transactions [34] and allows the integration of participants within a supply chain network while reinforcing collaboration between them [49]. Third, blockchain technology offers the potential to radically transform current business operations in logistics and SCM by fostering sustainability and streamlining organizational operations, including distribution, order fulfillment, payment for intermediate goods, and information transmission [50].

Despite the fact the blockchain technology has been covered thoroughly in the logistics and SCM literature, there is a dearth of studies that focus exclusively on analyzing the intellectual structure of blockchain research within this stream of literature. By closing this gap, the current study offers several contributions to the existing literature. Besides being the first attempt to use knowledge domain visualization, this study reviews the structure of blockchain knowledge through the analysis of information related to networks of co-citation and core content (i.e., keywords). This study is motivated by the study of Portugal Ferreira [51], who points out that, when fields of research become more complex and enter their maturity phase, scholars should periodically attempt to draw insights from the accumulated knowledge in order to identify new contributions, detect trends and research traditions, and reveal future research directions. By exploring the network structure and dynamics of blockchain knowledge and identifying prominent authors, we provide depth to the blockchain knowledge base from the perspective of logistics and SCM. In this respect, our research aligns with the view of Wang et al. [52], who argue that the rapid growth of emerging technologies (i.e., cloud computing in their study) requires periodic review to keep researchers updated on the latest progress. By conducting a thorough analysis of blockchain research in logistics and SCM, we seek to accelerate the conceptual development of this rapidly evolving research area. More precisely, our investigation answers the following research questions (RQ):

RQ1: How has blockchain research within logistics and SCM progressed since its emergence?
RQ2: Which countries/regions contribute most to the formation of a geographic atlas of blockchain research in logistics and SCM?
RQ3: Which scholars and studies are most impactful in the blockchain logistics and SCM field?
RQ4: What are the thematic trends of blockchain research in logistics and SCM?
RQ5: What are the key research discussions and hotspots in the literature?

RQ1 is relevant since blockchain is constantly expanding its scope; RQ2 considers how research could affect particular supply chains originating or terminating in specific locales; RQ3 identifies thought leaders that should be tracked to see where the field is heading; RQ4 detects key points of profitability and helps to anticipate important future developments; and RQ5 highlights the most likely adjacencies to current technologies.

This paper is structured as follows: Section 2 briefly summarizes existing literature reviews; in Section 3, we outline the methodology used in this study; Section 4 provides a detailed summary of the descriptive quantitative analysis; Section 5 discusses the study findings and presents key research implications; in Sections 6 and 7, we present several theoretical and managerial implications and conclude the paper.

2. Literature Reviews on Blockchain in Logistics and SCM

Numerous research studies have recently discussed the applications of blockchain in logistics and SCM. Several dimensions of deploying blockchain in logistics and SCM have been examined, varying from conceptualizing the promises of the technology [53] and exploring successful use cases for companies [54–56] to examining the impact of blockchain's connectivity inhibitors on supply chain interaction and resilience [57]. For example, Cole et al. [58] investigate the implications of blockchain for the field of operations SCM (OSCM) and find that the technology could reshape several practices, including product safety and security, quality management, inventory management and replenishment, disintermediation, new product development, and supply chain cost transactions.

The studies listed in Table 1 predominantly employed a systematic literature review (SLR) or bibliometrics to summarize the literature and derive new insights. For example, Queiroz et al. [53] study existing applications, the main challenges, and future research directions of the literature at the intersection of blockchain and supply chain integration. The authors find that the electric power industry tends to have a relatively mature understanding of blockchain and its ability to increase supply chain integration through smart contracts. Chang et al. [59] analyze 106 articles to explore the use of blockchain and smart contracts in SCM. Their findings reveal several areas that can benefit from blockchain adoption, namely: traceability and transparency, stakeholder involvement and collaboration, supply chain integration and digitalization, trust and performance, process automation, and distributed governance. Similarly, Wang et al. [54] investigate how blockchain could impact supply chain practices and argue that the technology brings extended visibility and traceability, supply chain digitalization and disintermediation, improved data security, and smart contracts. Vivaldini and de Sousa [57] review the inhibitors of connectivity during blockchain implementation in supply chain interaction and resilience. The study details the technical and organizational influences that determine the adoption of blockchain in the supply chain as well as identifying barriers to interaction between the involved agents and supply chain resilience.

Since its inception, companies in the food industry have been scrutinizing blockchain as a game-changing logistics and SCM technology. Recognizing its strengths in meeting several food supply chain requirements, several SLRs have been conducted to better understand the development of blockchain and its value-creation potential. For example, Nurgazina et al. [56] summarize the insights from 69 articles to identify existing applications of blockchain and IoT in food supply chains and the challenges of their implementation. Challenges related to scalability, security, privacy, cost, standardization, regulation, interoperability, and energy consumption, for instance, are highlighted as highly relevant barriers to integrating these technologies in food supply chains.

When it comes to bibliometrics, a few review studies have sought to examine the application of blockchain in logistics and SCM. For example, Pournader et al. [60] conduct a co-citation analysis of blockchain applications in supply chain, logistics, and transport management, and identify four main clusters which center on technology, trust, trade, and traceability/transparency. In the same vein, Muessigmann et al. [55] provide a bibliometric analysis of blockchain technology using 613 selected articles collected from several academic databases. Based on co-citation analysis, the authors classify the literature into five distinct research clusters, including theoretical sensemaking, conceptualizing blockchain and experimenting with applications, framing the technology within supply chains, the technical design of blockchain applications for logistics and SCM applications, and the possibilities of blockchain in digital supply chains. Lastly, Tandon et al. [61] conduct a bibliometric analysis of 586 articles identified on Scopus to study the use of blockchain in management.

Although several reviews have been carried out to systematize the literature about the use of blockchain in logistics and SCM, the use of SLRs is not always the best strategy since they are somewhat subjective, labor-intensive, and impractical for analyzing larger bodies of literature [62]. The current array of research streams employing bibliometric techniques to investigate blockchain is still very limited. Additionally, existing bibliometric studies either draw on a relatively small sample of articles [60] or a single academic database [61], and use different bibliometric tools that lead to different clustering outcomes and insights [55]. In order to address these shortcomings, in this study, we carry out a comprehensive bibliometric analysis of the blockchain literature in the logistics and SCM field. We aim to guide researchers, practitioners, and decision makers from the emergence of blockchain towards its future potentials. The study's findings will enrich the current literature and contribute to an increased understanding of the interplay between blockchain and SCM.

Table 1. Review studies on blockchain in the logistics and SCM field.

Article	Review Method	Database(s) Used	Sample	Time Span	Type of Reviewed Publications
[53]	SLR	Multiple (except WoS)	27	2008–2018	Journal articles
[54]	SLR	Multiple	29	2016–2018	Journal articles Conference papers
[55]	Bibliometric	Multiple	613	2016–2020	Journal articles Conference papers Book chapters

Table 1. *Cont.*

Article	Review Method	Database(s) Used	Sample	Time Span	Type of Reviewed Publications
[56]	SLR	Multiple (except Scopus and WoS)	69	2016–2020	Journal articles Conference papers Book chapters
[57]	SLR	Scopus WoS	89	2015–2020	Journal articles
[58]	Narrative review	-	-	-	-
[59]	SLR	Multiple	106	2016–2019	Journal articles Conference papers
[60]	Bibliometric	Scopus WoS	48	2016–2018	Journal articles
[61]	Bibliometric + content analysis	Scopus	586	2015–2019	Journal articles
[63]	SLR	Multiple (except Scopus and WoS)	187	2017–2020	Journal articles
[64]	SLR	Multiple (except Scopus)	22	2010–2020	Journal articles
Our study	Bibliometric	Scopus WoS	628	2016–2020	Journal articles Conference papers

3. Methodology

3.1. Data Collection

An initial search in the Scopus database was carried out using the following search string: blockchain* AND ("supply chain*" OR logistic*). Scopus was chosen because of its extensive coverage in comparison to other academic databases (e.g., the Web of Science) [65] and its specific functionalities that allow researchers to efficiently pull and aggregate references from a sample of articles [66]. Similarly, Scopus is recognized for its reliability and the large amount of scholarly publications that it indexes, including academic journals published by leading publishers such as Elsevier, Emerald Insight, Taylor and Francis, Springer, IEEE, and the ACM [67]. Besides Scopus, Web of Science (WoS) was used to complement the searches and capture all potentially relevant publications that are not indexed in Scopus. Initially, the search keywords were sought in the abstract, title, or keywords fields. This resulted in a total number of 2583 publications. The subject areas were then limited to Management and Accounting, Business, Decision Sciences, Social Sciences, and Economics, Econometrics and Finance. To ensure the academic nature of the retrieved literature [68], only peer-reviewed articles and conference papers in English language were considered. The selection procedures finally resulted in 628 publications being retrieved for further analysis. The references and citations of these articles were saved in CSV format. The search and selection procedure is outlined in Figure 1.

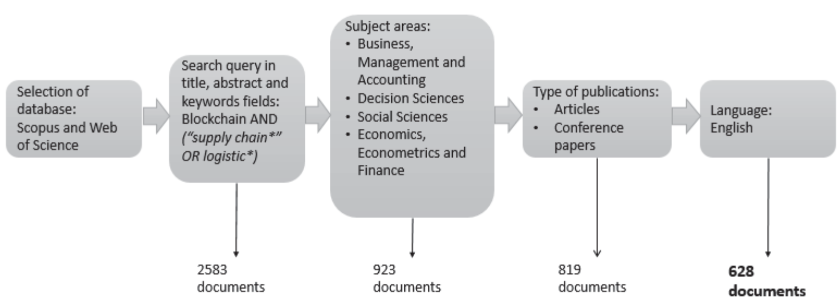

Figure 1. Search and selection process.

3.2. Research Method

According to Tranfield et al. [69], the main goal of a literature review is the identification, specification, mapping, and assessment of the existing body of pertinent literature in a systematic, objective, and easily reproducible manner. A structured literature review covers a wide range of publications and methodologies, resulting in a thorough and detailed analysis that considers clear and contextual relationships [70]. The use of bibliometrics in our study has three main justifications. First, as opposed to other methods for text analysis such as content analysis, a bibliometric analysis is more reliable and scalable. Second, bibliometric techniques help to deeply and thoroughly analyze relations among selected publications, citations, keywords, and co-citations, and can therefore provide valuable and comprehensive information. The last reason is that bibliometric techniques enable researchers to visualize important clusters of research topics in an intuitive and interpretable way.

3.2.1. Quantitative Analysis

We first analyzed the evolution of blockchain research in the field of logistics and SCM by plotting the selected publications according to their annual distribution. Next, following the process of Fahimnia et al. [71], we investigated several quantitative measures such as publications per author, citations per publication, as well as the location of publications to evaluate the impact and quality of the research. To facilitate data input and manipulation, we used the software package BibExcel to analyze the bibliometric data. The main benefit of BibExcel lies in its extensive compatibility with numerous academic databases (e.g., Scopus) and visualization tools (e.g., Gephi, VOSviewer).

Scholars attracting many citations are considered to be influential in their respective fields. We also ordered the authors of all selected papers according to their frequency of appearance. The authors' affiliation information was retrieved from the papers and imported into BibExcel to identify the leading academic institutions and the countries in which these institutions are situated. To gain a better understanding of the foci of blockchain research in the field of logistics and SCM, we carried out a keyword analysis to identify the most commonly used keywords in the selected publications. Tracking citations and understanding their trends are crucial for evaluating the impact and influence of research. The number of times a single paper is cited reflects its degree of importance within the academic community and provides an indication of its impact and influence [72]. We measured the frequency of local citations by considering the number of citations each publication received from other articles in our sample. The number of global citations per publication drew on the citation counts in the Google Scholar database. Given that Google Scholar covers major academic databases like Scopus, Web of Science, and EBSCOHost, the difference between local citations and global citations for a given paper indicates the amount of interest attracted within its own versus other research domains.

3.2.2. Network Analysis

After the descriptive analysis of the selected publications, we conducted a thorough analysis of the inner patterns and trends among these studies. We employed network analysis using bibliometric data and the visual software Gephi to depict the network structure of blockchain research in the field of logistics and SCM. The strength of network relations between two papers can be detected by keyword co-occurrences or co-citations [73].

Co-citation analysis was originally introduced by Henry Small in 1973 [74] to evaluate the semantic similarity of papers that share the same references. This is referred to as bibliographic coupling, wherein two papers share at least one common reference, and thus exhibit one co-citation. The co-citation frequency quantifies how many co-citations exist between two papers, whereby a higher frequency indicates that the two papers are closely related to each other. In order to identify the topic clusters, we rely on the references of each paper for the co-citation analysis.

The input data from BibExcel were imported into the visualization software Gephi to generate a co-citation network. We followed several steps to produce a map of co-citation clusters. Before using Gephi, we pre-processed the bibliometric data and fixed the co-citation frequency at an appropriate threshold. Too high a threshold value may lead to only a few articles being clustered, whereas too low a threshold value may result in too many clusters being generated. Therefore, to generate a meaningful visualization in the Gephi layout, the circle pack layout recommended by prior studies [75,76] was applied in our research to create a simple and readable graph. Each node represents a paper, and each edge linking two nodes reflects a co-citation relation. To generate the network, we manually adjusted the hierarchies, node size, and other parameters (e.g., color). This can be considered a form of manual regularization of the clustering.

To obtain an in-depth understanding of blockchain research within the logistics and SCM field, we created a keyword co-occurrence network. Akin to a co-citation network, a keyword co-occurrence network indicates that author-supplied keywords co-occur and shows the respective relationships [77]. According to Lee and Su [78], keyword co-occurrence analysis allows researchers to detect research topics and monitor the transitions of research frontiers in a particular knowledge domain. In a keyword co-occurrence network, two keywords have a closer relationship if they appear in the same papers more frequently. By generating the keyword co-occurrence network, we analyzed the core content from the used keywords and described the current structure of the blockchain research. The software selected for generating this network was VOSviewer because it is highly compatible with the BibExcel tool. The radius of the node reflects the frequency of each keyword, while the width of the edges indicates how often each pair of keywords were used together. By visualizing the mutual relationships between keywords, it is possible to reveal the topics addressed in blockchain research within the field of logistics and SCM. Figure 2 summarizes the research approach applied in this study.

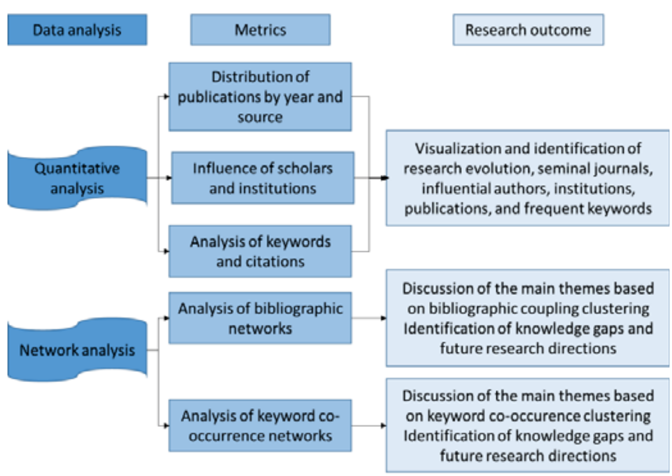

Figure 2. Research approach.

4. Results of Quantitative Analysis

4.1. Destribution of Publications by Year and Source

The final sample contained 628 papers. To answer the first research question, we traced the evolution of blockchain research in the field of logistics and SCM. Figure 3 shows a trend of consistent growth since 2016. A substantial increase in publications occurred during 2018–2020, when the number of papers on blockchain technology mushroomed. The earliest paper was published in 2016 and focused on the design of traceability in agricultural supply chains using Radio Frequency Identification (RFID) as well as blockchain technology [79].

This research is seminal because it inspired researchers and paved the way for them to investigate the potentials of blockchain for logistics and SCM. Overall, the results show that blockchain has garnered a lot of attention from scholars, especially from 2019 onwards. This finding also reflects the increasing popularity of blockchain within the logistics and SCM academic community.

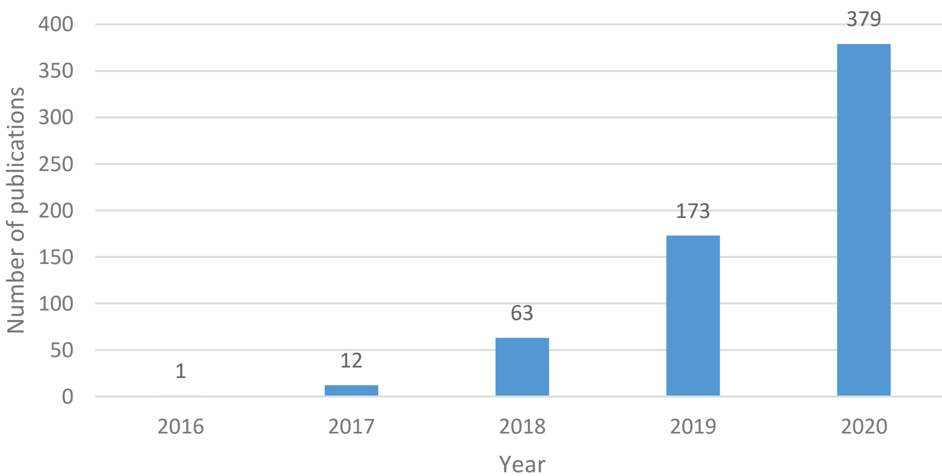

Figure 3. Blockchain research in the field of logistics and SCM.

Table 2 shows the top ten journals publishing articles relating blockchain technology to logistics and SCM. Overall, these journals published 156 articles, representing 24.8% of the 628 identified papers. As can be seen from Table 2, Sustainability tops the list by publishing a total of 25 articles on the topic. Next in the list, the International Journal of Production Research published 24 articles, Lecture Notes in Business Information Processing published 18 articles, and Transportation Research Part E Logistics and Transportation Review published 15 articles. The journal-wise distribution of articles indicates that blockchain research was published in a wide variety of top-tier journals that focus on the implications of the technology for business, management, production operations, sustainability, and logistics. That papers appear in such a diversity of journals reflects the interdisciplinary nature of blockchain and the versatility of its applications throughout logistics and across other fields.

Table 2. Top ten journals in terms of number of publications.

Journal Title	Count	%
Sustainability	25	16%
International Journal of Production Research	24	15%
Lecture Notes in Business Information Processing	18	12%
Transportation Research Part E Logistics and Transportation Review	15	10%
IFIP Advances in Information and Communication Technology	14	9%
International Journal of Information Management	13	8%
Supply Chain Management	9	6%
IEEE Transactions on Engineering Management	8	5%
International Journal of Production Economics	8	5%
International Journal of Supply Chain Management	8	5%
International Journal of Recent Technology and Engineering	7	4%
Frontiers of Engineering Management	7	4%
	156	100%

4.2. Scholars' Influence and Institution Statistics

Table 3 depicts the ten most productive scholars in the field. T.M. Choi published 13 papers to rank as the leading author with the highest number of publications in blockchain research within the field of logistics and SCM. J. Sarkis published seven papers, while A. Gunasekaran and M.M. Queiroz contributed equally to the literature with six papers each. The majority of the scholars listed in Table 3 have a background in SCM, operations management, and sustainability. Their studies employed theoretical and empirical methods such as literature reviews, surveys, and case studies.

Table 3. Top ten most productive authors according to number of published papers.

Author	Author's Institution	Count	%
Choi T. M.	Hong Kong Polytechnic University, Kowloon, Hong Kong	13	24%
Sarkis J.	Worcester Polytechnic Institute, Worcester, MA, USA	7	13%
Gunasekaran A.	California State University, Bakersfield, Bakersfield, USA	6	11%
Queiroz M. M.	Universidade Paulista, Sao Paulo, Brazil	6	11%
Fosso Wamba S.	TBS Business School, Toulouse, France	5	9%
Kouhizadeh M.	Foisie Business School, Worcester, MA, USA	5	9%
Casino F.	University of Piraeus, Piraeus, Greece	4	7%
Ravishankar B.	B.M.S. College of Engineering, Bengaluru, India	4	7%
Van Hoek R.	Sam M. Walton College of Business, Fayetteville, NC, USA	4	7%
		54	100%

Table 4 shows the top academic institutions according to the number of papers published, along with their locations. Scholars affiliated with Hong Kong Polytechnic University top the list with 16 published papers, followed by Worcester Polytechnic Institute, National Institute of Industrial Engineering, and Universidade Paulista. Table 5 lists the ten countries whose academic institutions have contributed most prolifically to blockchain research in the field of logistics and SCM. Overall, the top ten countries are responsible for the publication of 545 out of the 628 papers in our sample (87%). Researchers from the USA and China published the most papers, 113 and 100, respectively, while India ranks third with 88 publications. The number of publications from these countries has grown rapidly over recent years, reflecting the increasing popularity of blockchain and its relevance to both developed and developing countries. For example, the Government of the Indian state of Kerala has considered the implementation of blockchain technology in the food supply chain to reduce food wastage and increase overall transparency [80]. Similarly, Walmart has piloted the use of blockchain to track the exact origin of pork originating from China and its processing in the USA [12]. The remainder of the papers were primarily contributed by researchers from European countries such as the UK, Germany, France, and Italy, as well as from Australia, Russia, Canada, and Hong Kong. This illustrates that research relating blockchain to logistics and SCM has gained interest worldwide. When it comes to geographical distribution, North America and Europe contributed more than Asia.

Table 4. Academic institutions with over five publications.

Institutions	Count	Location
Hong Kong Polytechnic University	16	Hong Kong
Worcester Polytechnic Institute	8	United States
National Institute of Industrial Engineering	8	India
Universidade Paulista	8	Brazil
University of Derby	7	United Kingdom
California State University, Bakersfield	7	United States
Foisie Business School	7	United States
B.M.S. College of Engineering	6	India
TBS Business School	6	France

Table 5. Top ten countries according to the number of publications.

Country	Count	%
USA	113	21%
China	100	18%
India	88	16%
UK	61	11%
Germany	43	8%
Australia	31	6%
Russia	23	4%
Canada	22	4%
France	22	4%
Italy	22	4%
Hong Kong	20	4%
	545	100%

4.3. Analysis of Keywords and Citations

Table 6 lists the top 20 keywords by frequency. In addition to the search terms used to identify papers for analysis, smart contracts, IoT, and DLT are the most popular keywords, which underlines the potential of blockchain-based smart contracts in reforming supply chain operations [81]. Unsurprisingly, the term IoT is also often used in the blockchain research, indicating that these two technologies are often applied together. This technological interplay, according to several studies, is supposed to have a significant impact on SCM and logistics [82], since it enables resilient and truly peer-to-peer distributed systems [83] by offering supply chain partners increased openness, transparency, neutrality, reliability, and security [84]. In addition, "*traceability*", "*transparency*", and "*trust*" appear in the list, which suggests that these supply chains' characteristics are among the goals of blockchain technology. These elements are essential to create a healthy and sustainable business ecosystem. Similarly, trust and transparency are necessary in supply chain networks to ensure compliance with legal regulations, reduction of risks, and mitigation of fraud [54]. The high frequency of keywords such as "*food supply chains*" and "*additive manufacturing*" indicates that the current industrial focus of blockchain technology lies in the food and additive manufacturing sectors. The food industry has been under increasing pressure to meet traceability requirements, overcome issues of product perishability, and enhance productivity [85–87]. "*Additive manufacturing*" is applied in SCM to leverage three-dimensional (3D) printers throughout the different stages of the SC with the goal to boost manufacturing flexibility, shorten lead times, support product individualization, and reduce inventory [88]. Additionally, it is typically more distributed than traditional manufacturing, which may require greater collaboration and trust assurance.

Table 7 shows the top ten publications according to the total number of global citations. Local citation counts are also presented. A closer look at the citation analysis reveals that F. Tian and N. Kshetri are the most influential scholars, both in terms of the number of articles and total citations received. Tian has the highest number of global citations among all publications. Kshetri received the second-highest number of global citations and was ranked second on local citations. These findings indicate that these two scholars have made seminal contributions and laid the foundations for later research. Several other studies revolved around the technical aspects of blockchains necessary for different application scenarios and the critical role of the technology for provenance tracking. A closer look at the ten most productive authors in Table 3 reveals that M. Kouhizadeh, J. Sarkis, and S. Saberi were members of the same author team, whose background was blockchain and sustainable SCM.

Table 6. Top 20 most frequently occurring keywords.

Keyword	Frequency
Blockchain	520
Supply chain	145
Smart contracts	94
SCM	89
IoT	66
DLT	50
Traceability	39
Logistics	30
Ethereum	29
Sustainability	27
Industry 4.0	21
RFID	20
Transparency	19
Bitcoin	18
Technology	14
Trust	14
Digitalization	14
Food supply chains	13
Security	13
Additive manufacturing	13

Table 7. Top ten papers according to global citations.

Publications	Global Citations	Local Citations
Tian [79]	416	81
Kshetri [12]	354	105
Saberi et al. [6]	326	94
Ivanov et al. [88]	233	35
Tian [84]	215	49
Wüst and Gervais [89]	182	25
Kim and Laskowski [90]	182	43
Kshetri [91]	172	19
Queiroz et al. [92]	146	50
Wang et al. [54]	130	54

5. Findings from Network Analysis and Discussion

5.1. Bibliographic Coupling Network

Following the example of previous studies [71,73], we chose a threshold of 2 for co-citation frequency. The generated bibliographic coupling network contains 296 papers. The nodes of a network can be grouped into different clusters or partitions in which the density of links is greater among nodes of a similar cluster versus those of different clusters [93]. Each cluster in the network constitutes a group of well-connected papers on blockchain in SCM and logistics, with these papers having only a limited association with papers grouped in the other clusters (see Figure 4). The clustering of papers enables analysis of the topology of the network and reveals topics, connections, and collaboration patterns.

To generate the co-citation network, we used Gephi's default modularity tool, which uses the Louvain algorithm. This is an iterative optimization model, whose algorithm can identify the optimal number of clusters to maximize the so-called modularity index [94]. The modularity index of a specific partition adopts a value between -1 and 1 that measures the density of edges inside of communities as compared to links between distinct communities [95]. The application of this algorithm led to the generation of six main clusters. The quantity of papers in each cluster ranges from 2 in cluster 6 to 101 in cluster 1, the latter representing the largest community. The modularity index in Figure 4 equals 0.151, revealing the important interrelationships between the six clusters. This result can be seen by comparing the left (Figure 4A) and the right side of the figure (Figure 4B), with and without the links/edges depicted. Since closely connected papers share similar characteristics, a cluster with strong co-citation relations indicates similar subject areas [96]. A careful examination of each paper within a certain cluster helps to identify the main research focus of that specific cluster. Because of the high volume of papers in each cluster, we decided to consider only the top ten articles of each cluster for further content analysis. The lead papers were determined according to their co-citation PageRank. Based on these papers, we identified the research focus of each cluster and labeled them accordingly. The lead papers from each cluster are shown in Table 8.

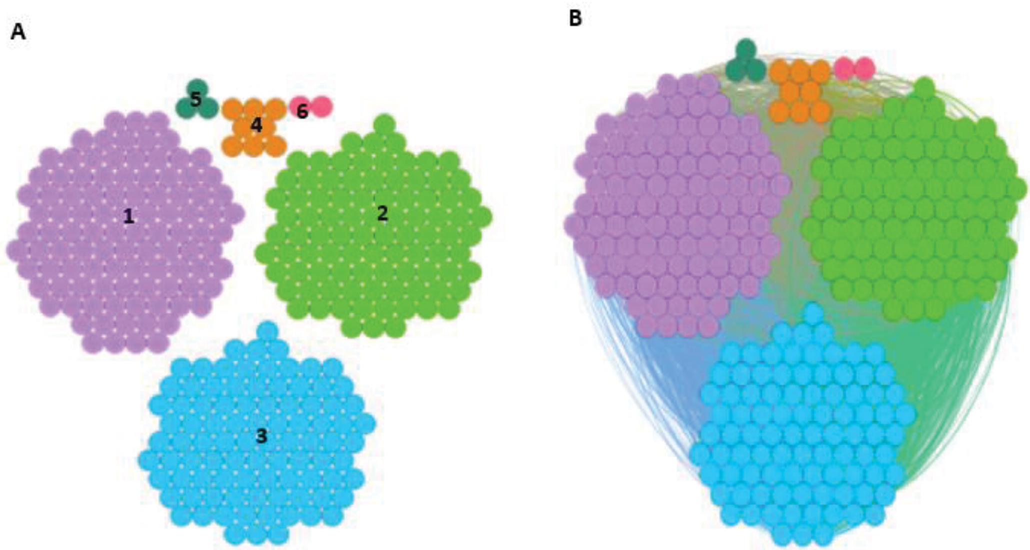

Figure 4. Clustering network for the co-citation analysis (**A**: without edges; **B**: with edges).

5.1.1. Blockchain for Supply Chain Sustainability

The classification of research foci summarized in Table 8 reveals that blockchain research in the logistics and SCM field frequently focuses on sustainability aspects of supply chain ecosystems. In this regard, Bai and Sarkis [50] argue that the technology can coordinate order fulfillment, payment of goods, information flows, and distribution. By adopting blockchain, firms can achieve real-time transparency, reduce networking costs, and realize substantial cost savings in their manufacturing activities [117]. The need for cost efficiencies arises from a variety of pressures faced by companies, including competition. In response to these pressures, firms can gain economic benefits from the use of blockchain. For example, Hastig and Sodhi [111] point out that blockchain can be an effective option for companies trading in commodities (e.g., cobalt, timber) as the origins of products can be easily verified, resulting in higher operational efficiencies, elimination of illegal practices, and increased sustainability. Allen et al. [130] note that blockchain can result in substantial reductions in the cost of trading food products in global supply chains. Similarly, Yadav and Singh [107] argue that blockchain can increase customer and end-user awareness of supply chain activities, thereby increasing customer trust and satisfaction.

Table 8. Lead papers from each cluster according to their PageRank.

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Blockchain for supply chain sustainability	Conceptual development of blockchain research in the field of logistics and SCM	Adoption triggers and barriers of blockchain technology in supply chains	Blockchain as an enabler for supply chain agility and adaptability	Blockchain for the protection of intellectual property	Blockchain for the management of food/perishable supply chains
Bai and Sarkis [50]	Wang et al. [54]	Kouhizadeh et al. [97]	Kamble et al. [98]	Holland et al. [99]	Mondragon et al. [100]
Yadav and Singh [101]	Behnke and Janssen [102]	Di Vaio and Varriale [103]	Sheel and Nath [104]	Holland et al. [105]	Mondragon et al. [106]
Yadav and Singh [107]	Saberi et al. [6]	Kamble et al. [108]	Sheel and Nath [109]	Engelmann et al. [110]	
Hastig and Sodhi [111]	Kim and Shin [83]	Fosso Wamba et al. [112]	Miraz et al. [113]		
Muller et al. [114]	Schmidt and Wagner [47]	Wong et al. [115]	Gunasekaran et al. [116]		
Ko et al. [117]	Divey et al. [118]	Karamchandani et al. [119]	Delafenestre [120]		
dos Santos et al. [121]	Cole et al. [58]	Batwa and Norrman [122]	Srivastava et al. [123]		
Lustenberger et al. [124]	Wang et al. [125]	Ghode et al. [126]	Denis et al. [127]		
Lu et al. [128]	Palas and Bunduchi [129]	Wong et al. [46]			
Allen et al. [130]	Caldarelli et al. [131]	Pournader et al. [60]			

Blockchain can be used to ensure that products are certified by authorities throughout various supply chain stages without compromising the privacy of the company [121]. Therefore, the main insight from cluster 1 is the opportunity for additional research on the role of blockchain in improving the environmental performance of supply chains by, for example, increasing green supply chain transparency, supporting green sourcing strategies, and facilitating the development of eco-design practices in logistics and SCM. The extant literature is remarkably silent on how the increased process integration due to blockchain transparency and information availability can improve the speed of green product development, the sales of environmentally friendly products, and the responsiveness of firms to stakeholders' environmental concerns. Although the economic implications of blockchain have been repeatedly reported in prior studies, the importance of the technology to promote socially responsible operational practices in logistics and SCM is still missing. Increasing customer awareness of social conduct through blockchain transparency may impose additional pressure on firms to fulfill their corporate social responsibilities and improve their corporate citizenship [132]. The social performance of supply chains can benefit from the ability of blockchain to enhance the alignment of exchange partners' business strategies with social/ethical standards [133]. Thus, the investigation of cooperative mechanisms by means of which firms can acquire knowledge, augment alignment, and establish higher levels of mutuality and trust in the supply chain presents a promising avenue for future research. Researchers may also empirically investigate the impact of blockchain on the social performance of supply chains, thus extending previously suggested performance models [134].

5.1.2. Conceptual Development of Blockchain Research in the Field of Logistics and SCM

Although clusters 2 and 3 overlap when it comes to theory development, the leading papers in cluster 2 focus on advancing the conceptual underpinnings of blockchain technology. The existing studies are exploratory in nature, laying the theoretical foundation of blockchain and structuring the field [125]. The set of review and conceptual papers [6,47,54] is indicative of the need for researchers to define and explain the possibilities of blockchain for logistics and SCM.

5.1.3. Adoption Triggers and Barriers of Blockchain Technology in Supply Chains

Cluster 3 revolves around applications of well-established theories such as the force field theory, the technology, organization, and environment (TOE) theory [97,115,135], technology acceptance model (TAM), technology readiness index, theory of planned behavior [108], and the unified theory of acceptance and use of technology (UTAUT) [46,112]. These theories were challenged and advanced through empirically oriented testing methods, including surveys. According to the previous studies, the adoption triggers of blockchain technology in logistics and SCM consist of facilitating conditions (e.g., regulatory support), technology readiness, and technology affinity [46].

In a recent study, Wong et al. [115] found that cost was not statistically supported as an inhibitor, but rather a driver for blockchain adoption. In general, the barriers to blockchain adoption have received more attention from scholars than the motivators. For a novel technology, the expectations are high, but the challenges are also enormous. In this context, Ghode et al. [126] reported that organizational challenges (i.e., inter-organizational trust, relational governance), technological challenges (i.e., data transparency, data immutability), operational challenges (i.e., interoperability, product type), and social challenges (i.e., social influence, behavioral intention) all hamper willingness to adopt blockchain into supply chains.

While the technology has been hyped for years [136], many constraints stand in the way of mainstream adoption of blockchain. These include data immutability, security risks, implementation costs, privacy concerns, and lack of governance [60]. Although empirical studies have investigated the drivers and barriers of blockchain adoption in both developed and developing countries (e.g., India and the USA [112], Malaysia [47,116], and

India [108]), there is scope for confirming and extending the results of these investigations in other geographical contexts such as Africa, Europe, and Latin America.

To date, there are no observational studies applying a longitudinal approach to examine the responses to blockchain adoption in various industries across the technology adoption life cycle. Moreover, additional empirical research using more comprehensive models for the inter-organizational drivers of blockchain adoption and other theories (e.g., institutional theory, contingent resource-based theory) are required to help firms use blockchain technology more efficiently and effectively. The results of such research may provide clearer guidelines for practitioners who are eager to make informed and evidence-based decisions regarding the key characteristics of the blockchain into which they will commit their efforts and limited resources.

A key question for scholars to examine is the role of culture in blockchain adoption and use. Supply chain scholars should consider the cross-cultural testing of technology adoption models or theories, recognizing the likelihood of cultural differences. Although TAM has been previously tested as a tool for predicting technology use [108], so far there are scant attempts by scholars to look into the antecedents of perceived usefulness and ease of use in the case of blockchain. A better understanding of these antecedents will help firms to devise appropriate strategies that will accelerate the uptake of blockchain in logistics and SCM.

5.1.4. Blockchain as an Enabler for Supply Chain Agility and Adaptability

We labeled cluster 4 as "blockchain as an enabler for supply chain agility and adaptability". Agility commonly refers to the ability of firms to sense and respond to environmental changes in a timely manner [137–139]. In the context of logistics and SCM, agility represents a key competitive advantage that allows firms to quickly adapt to continuously changing demand patterns, short product lifecycles, dynamic markets, competition, and demand for customized products [140]. Supply chain partners can increase agility by using blockchain to further automation and facilitate data integration across their business processes [116].

A key feature of an agile firm is flexibility, and blockchain can improve supply chain alignment, adaptability, and agility, which, taken together, sustain competitive advantage and firm performance [113]. Blockchain can also boost capabilities to respond effectively to the changing and dynamic nature of the business environment because the technology facilitates supply chain efficiency and responsiveness [98]. Using the technology, firms can better respond to the dynamics of customer demand fluctuations and abrupt changes within the supply chain.

Even though the extant literature has highlighted an enabling role for blockchain in shaping future agile manufacturing practices [116], a specific focus on the implications of the technology for supply chain agility is, so far, missing. Therefore, further research is required to truly understand the impact of blockchain on supply chain agility and the influence of this agility on firm performance. It is vital that supply chains are continually assessed with respect to competitiveness; blockchain-enabled agility is a paradigm that may allow managers to redesign their competitive strategies.

Blockchain's ability to improve supply chain agility depends on the integration of firms and suppliers into the blockchain ecosystem. Thus, examination of inter-organizational processes, trust, and other determinants of blockchain's ability to improve supply chain agility generates valuable insights when it comes to devising strategies and effective investments that optimize blockchain's impact on agility and, eventually, on business performance.

5.1.5. Blockchain for the Protection of Intellectual Property

Cluster 5 contains articles that discuss the enablers of blockchain for the protection of intellectual property. For instance, scholars contend that blockchain can protect 3D print supply chains and prevent intellectual property (IP) theft [99,105]. The encryption and licensing of data can be significantly facilitated by blockchain and the technology can also address the need for traceable, digital administrative data relevant for 3D printing [105].

One compelling avenue for future research involves investigating the role of blockchain-enabled IP protection as a mediator in the collaborative relationships between supply chain partners and their efforts to launch new products and create new markets. The enforcement of IP rights with blockchain can constitute a strategic and competitive asset, and thus researchers should examine how blockchain can support IP rights policies, particularly for industries with high-value-added products and creative content. The use of blockchain to protect IP rights illustrates its potential for knowledge generation and innovation among supply chain partners. The evaluation of this impact may help to open new doors for innovation research in logistics and SCM.

5.1.6. Blockchain for the Management of Food/Perishable Supply Chains

Cluster 6 focuses on the application of blockchain in food/perishable supply chains. Mondragon et al. [100] argue that blockchain enables better responses to the increasing requirements for compliance in the food chain through tamper-proof records and provenance tracking. The combination of blockchain with specialized IoT devices (e.g., intelligent sensors/containers) can provide the necessary synopsis to control the status of perishable foods throughout transportation, handling and storage, and delivery to final consumers [106].

Among the numerous opportunities for future research in food logistics and SCM, scholars could analyze how blockchain-enabled traceability can enhance food safety through the reduction of information asymmetries and the allocation of incentives encouraging upstream suppliers to ensure they provide quality and safe food raw materials. Empirical investigations are needed to evaluate the impact of blockchain-based systems in the food industry in terms of costs, benefits, barriers, and changes to consumer purchasing decisions and habits.

5.2. Keyword Co-Occurrence Network Analysis

Before generating the keyword co-occurrence network, we set a frequency threshold of 3 to obtain a better visualization. As a result, the number of keywords considered for the keyword co-occurrence network analysis was 71. The algorithm used by the VOSviewer software generated five significant clusters. Each node in Figure 5 represents a keyword, and the radius of a node relates to the occurrence frequency of the keyword in each paper. According to the number of nodes, the red cluster, which constitutes the center, comprises the most frequently used concepts that attracted greater attention from researchers. We listed the ten most common keywords in each cluster as shown in Table 9 (except for the purple cluster on the bottom, which only contains five keywords, as shown in the visualization map). Each cluster in the network was labeled according to the main theme emerging from the keywords.

5.2.1. Blockchain Fundamentals and Technical Aspects

The red cluster revolves around the early implementation of blockchain in the finance sector through cryptocurrencies such as Bitcoin and Ethereum, and their potential to disrupt other industries and all sorts of business operations, including logistics and SCM [33,141]. Therefore, we labeled this cluster as "*blockchain fundamentals and technical aspects*". The most relevant keywords in this cluster are "*blockchain*", "*supply chain*", "*smart contracts*", and "*IoT*".

Researchers have further argued that smart contracts and IoT can support continuous improvements in supply chain processes [6] and augment sustainability through improved coordination, cooperation, and communication between supply chain actors [142]. Moreover, the role of blockchain to strengthen the security and privacy of supply chain data has been emphasized in the literature, implying that the technology can improve the function of smart contracts by implementing real-time quality monitoring and control of processes [143] and guarantee data security without compromising the privacy of participants [144,145].

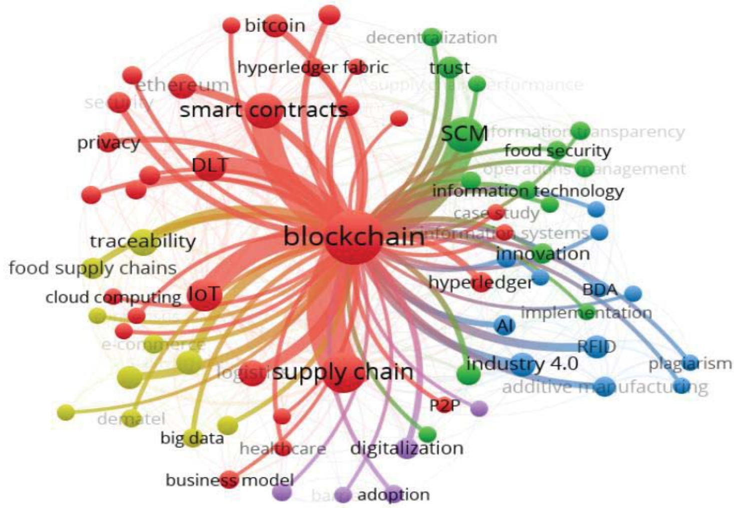

Figure 5. Keyword co-occurrence network.

Table 9. Top ten ranked keywords based on frequency in the cluster.

Red Cluster	Green Cluster	Blue Cluster	Yellow Cluster	Purple Cluster
Blockchain Fundamentals and Technical Aspects	Blockchain for Digitally-Enabled Supply Chains and Trust Mechanisms	the Combination of Blockchain with Industry 4.0 Technologies	Blockchain for Traceable and Sustainable Supply Chains	Barriers to Blockchain Adoption
blockchain	SCM	industry 4.0	traceability	digitalization
supply chain	technology	RFID	sustainability	adoption
smart contracts	trust	additive manufacturing	transparency	survey
IoT	innovation	AI	food supply chains	barriers
DLT	decentralization	food safety	big data	literature review
logistics	food security	BDA	e-commerce	
Ethereum	information technology	food traceability	supply chain finance	
Bitcoin	information transparency	intellectual property	DEMATEL	
security	operations management	license management	agriculture supply chain	
cryptocurrencies	systematic literature review	plagiarism	visibility	

5.2.2. Blockchain for Digitally-Enabled Supply Chains and Trust Mechanisms

The green cluster in the upper right corner discusses and reviews the importance of blockchains for increasing supply chain trust, stimulating innovation, and promoting information transparency. Therefore, we labeled this cluster as "*blockchain for digitally-enabled supply chains and trust mechanisms*". In the supply chain context, trust is a necessary yet insufficient condition for repeated business transactions [146]. The architecture of blockchain and its tamper-proof nature helps to overcome trust issues in the supply chain [12] because it eliminates the need to evaluate the trustworthiness of intermediaries or other network participants [147].

Keywords such as "*innovation*", "*decentralization*", "*food security*", and "*information transparency*" appear in the cluster. The high frequency of "*innovation*" in this cluster indicates that blockchain serves as an impetus to unlock the potential for innovation across the supply chain. For instance, Liao and Wang [148] note that blockchain is one of the key innovation drivers in logistics that can revamp logistics operations and magnify the impact of ICT on supply chain integration. Due to the growing importance of innovation in logistics and SCM, future research is needed to understand the dynamics and processes of blockchain-induced innovations and their impact on firm performance. Research in this direction can provide managers with guidelines on the innovation paths that firms should follow to sustain and accelerate their supply chain digitalization efforts and initiatives.

5.2.3. The Combination of Blockchain with Industry 4.0 Technologies

Another research focus of the reviewed literature regards the integration of blockchain with other technologies. Accordingly, we labeled the blue cluster on the right as "*the combination of blockchain with industry 4.0 technologies*". Industry 4.0 is an evolutionary concept that originated in Germany and aimed to bring to firms novel perspectives on enhancing services and production methods [149], largely through computerized manufacturing [150,151]. The industry 4.0 initiative has sparked several discussions concerning the digitalization of organizational processes through the use of advanced technologies like cyber-physical systems, wireless sensor networks, the IoT, big data, cloud computing, and blockchain technology [15]. The shift toward smart, data-driven, and highly integrated supply chains and logistics can be significantly facilitated by the blockchain. For example, blockchain can be incorporated with RFID tracking to verify transfers of ownership [34], improve food safety and traceability [58,84,152], and increase the automation of supply chain processes.

Interestingly, additive manufacturing is a commonly used term in this cluster, gaining increasing attention from both academics and practitioners [153]. As opposed to subtractive manufacturing methods, additive manufacturing (AM) is conceptualized as the formation of complex components by continuously adding layers of material [154]. AM involves a complex network of automated and manual workflows that depend on a secure cyber-physical-system (CPS) to ensure reliable physical (e.g., material) and informational hand-offs between multiple partners in the manufacturing process to ultimately produce a high-quality component. The implementation of this technique could benefit from blockchain as it would make AM documentable from a design perspective [105], resulting in increased efficiencies, lower risks, and higher manufacturing flexibility [88].

Blockchain use cases are often associated with other forthcoming technologies such as artificial intelligence (AI) to optimize the collection and parsing of data [155], develop fast learning expert systems [156], and help firms develop sophisticated strategies for the real-time monitoring of changes in their supply chains and the swift formulation of effective responses. In addition, firms that recognize the potential benefits of big data analytics (BDA) for logistics and SCM can expand the value of this technology by the use of blockchain to streamline flows of supply chain data, derive actionable insights, and enhance decision-making [98].

Notwithstanding the benefits promised by the implementation of blockchain, more in-depth studies on its interplay with industry 4.0 technologies are needed. For example, future studies should investigate how firms can use blockchain to positively influence changes and improvements in the workflows of their supply chains. It is of interest whether blockchain can enable artificial neural network models to help managers identify and improve targeted aspects of supply chain activities to bring higher returns to the firm and improve customer satisfaction. Effective quality improvement strategies and policies are becoming ever more important in the context of increasingly dynamic market conditions. Another interesting avenue for research is to examine the contribution of blockchain in establishing reliable analytical infrastructure for logistics and SCM.

5.2.4. Blockchain for Traceable and Sustainable Supply Chains

The lower left cluster in yellow contains articles with a focus on the effectiveness of blockchain in enhancing supply chain traceability, transparency, and visibility for sustainability. Mounting consumer concerns over food safety and quality are pushing for increased transparency regarding the origin of products. As a result, we labeled this cluster as "*blockchain for traceable and sustainable supply chains*". Traceability is a key requirement that enables consumers, regulators, producers, and marketers in food supply chains to mitigate potential risks and deliver high-quality and safe products [121].

Thanks to the tracking capabilities of blockchain and its ability to provide a complete audit of transactions, firms can develop more traceable supply chains, quickly identify the provenance and authenticity of products, and demonstrate environmental and social sustainability credentials to their trading partners. As shown in Table 9, articles in this cluster mainly conducted survey-based studies using the DEMATEL methodology to visualize the complex causal relations between various blockchain enablers. For example, Kamble et al. [108] identify the major drivers for sustainable supply chains following the integration of blockchain [107], and explore significant barriers that hinder blockchain adoption in the agri-food supply chain [157]. Another notable result from this cluster is that keywords pertaining to practical blockchain applications for services such as "*e-commerce*" and "*supply chain finance*" are included. There are several challenges facing e-commerce, such as lack of security and trust in online transactions [158]. These concerns could be alleviated by the use of blockchain since enhanced trust between trading partners would enable transactions to be conducted directly and without involving third parties [159,160]. The integration of blockchain in e-commerce could also enable the secure storage of documents and the transfer of data during transactions [161].

Furthermore, blockchain can be used in supply chains to integrate financial and logistic services more efficiently. Previous studies have established that blockchain coupled with smart contracts can support the development of highly secure and convenient supply chain financial systems [162], coordinate collaboration data sharing between parties [163], and improve capital availability for businesses [164].

Empirical research into the behavior of customers engaging in blockchain-based e-commerce is necessary to understand their value concepts and how to design and deliver better customer experiences with matching value propositions. There is a need for blockchain solutions addressing the pressures caused by surges in e-commerce activities and just-in-time deliveries. The benefits of blockchain for e-commerce have been examined, yet the impact of blockchain-based platforms on supply chain performance is still neglected in the literature. For supply chain finance, researchers may be interested in empirically investigating how blockchain can contribute to the reduction of upstream and downstream supply chain costs. The potential of blockchain to improve cash management and identify the risk preferences of supply chain partners is also an intriguing research direction.

5.2.5. Barriers to Blockchain Adoption

The last cluster examines the challenges that limit the widespread implementation of blockchain in logistics and SCM. We labeled this cluster "*barriers to blockchain adoption*". For example, despite many promising use cases, the adoption of blockchain has not seen rapid acceptance [97] because of regulatory uncertainty, lack of stakeholder awareness and ease of use, and the high complexity of blockchain-based systems [157]. In the AM sector, Kurpjuweit et al. [153] posit that the shortage of blockchain-skilled specialists, governance mechanisms, and firm-internal technical expertise represent key barriers to blockchain adoption.

Due to scalability and speed issues, technological access limitations [6], and security and privacy concerns [157], the mainstream adoption of blockchain in the logistics and SCM field is not imminent. The exploration of these barriers has been conducted from both theoretical and empirical perspectives using literature reviews and surveys. However, there is a lack of studies looking into technical solutions that could overcome scalability issues in logistics and SCM. The causal relationships among the technical, organizational, and regulatory barriers are often blurred and therefore further empirical research is needed. Similarly, there are additional research opportunities in determining the organizational mechanisms that can facilitate and accelerate the uptake of blockchain in supply chains.

6. Discussion

6.1. Theoretical Contributions

Scholars have recently begun to apply bibliometric analyses to investigate the applications of blockchain in the logistics and SCM field. However, most of the bibliometric studies on the technology have relied on datasets with a relatively small number of articles. A more holistic approach was needed to expand understanding of the topic and inform gaps in the literature. Our study accomplished this by examining blockchain in a broader context. Specifically, we focus on the works published in the last five years (2016 to 2020) to enlighten bibliometric indicators such as the influential authors, journals, and academic institutions that have contributed to the evolution of blockchain research and advanced its applications in logistics and SCM. Moreover, the network analysis of selected publications provides insights that serve to inform an agenda for future research.

Our study offers several contributions to the logistics and SCM literature. First, we unearthed the core research foci of related blockchain research, which span three major themes: (1) blockchain for supply chain sustainability, (2) conceptual development of blockchain research in logistics and SCM, and (3) triggers and barriers of blockchain adoption in supply chains. The findings from the co-citation analysis indicate that most of the influential papers focus on the conceptualization and review of blockchain possibilities and challenges for supply chains. Empirical works mainly employ surveys to identify the drivers and barriers of blockchain adoption. The early works on blockchain tended to define the technology, present its technical features, and suggest opportunities and challenges. More recently, scholars have become more focused on specific research topics such as the application of blockchain for digitally enabled supply chains and trust, its combination with industry 4.0 technologies, traceability, and barriers in the transition toward blockchain-based supply chains. Unlike previous reviews on blockchain, this study employed an objective method to structure the related research themes and reveal avenues for future research. Our findings provide logistics and SCM scholars with a thorough understanding of the current status of blockchain research in the field, and our suggestions for future research will direct them towards noteworthy topics when they dig deeper into this auspicious but still uncharted research area.

6.2. Managerial Contributions

Leveraging digitally-enabled supply chains presents several opportunities in the context of fierce competition, market instability [116,165], demands for reduced time-to-market, and challenges associated with access to critical technologies. The main challenges in today's supply chains include a lack of data visibility and transparency, extended supply chain traceability, and the validation of claims regarding sustainability. The ability to identify and verify critical information related to products transitioning along the supply chain can be facilitated by the deployment of blockchain. The technology provides a unified way to monitor the entire supply chain and streamline information processes among the parties involved. Data discrepancies and inconsistencies [108] arising from the lack of IT platform integration along the supply chain may lead to inefficient management and poor performance [15]. As a result, this study recommends that managers consider blockchain to improve transparency, achieve fair pricing, enhance product qualities, and reduce business costs.

Organizations can use blockchain to enhance traceability and make information about products' origins or content more accessible, thereby meeting the growing expectations of consumers, associations, and regulators [166]. With the support of blockchain, complete supply chain traceability is possible as managers can maintain the required amount of detailed information and degree of precisions [167]. Other supply chain stakeholders can similarly capitalize on blockchain to develop unified approaches addressing concerns over product quality traceability. Defective products are hard to trace back in supply chains featuring numerous stages and production lines [160], yet blockchain's traceability enables transparency and empowers trust even along geographically dispersed and disconnected supply chains [108].

Organizations and regulatory bodies can obtain additional insights from this review. First, managers can grasp the development of blockchain research in logistics and SCM, the potentials of the technology for supply chain sustainability, and the challenges hampering the transition toward blockchain-enabled business models. The findings of the study clarify expectations about blockchain deployment and highlight trends and opportunities on the path towards a comprehensive blockchain ecosystem. Decision makers and regulatory bodies must also understand blockchain as they tackle regulatory barriers such as the lack of legal frameworks related to smart contracts, which would enable managers to improve compliance and adherence to regulations such as food traceability and safety standards.

6.3. Study Limitations

This study provides meaningful support for understanding the present state of blockchain technology and potential directions for future research. However, several limitations should be addressed in further investigations. This study only considered journal articles and conference papers for the bibliometric analysis. Hence, other documents such as books and chapters could potentially be included in future work. Another limitation is that bibliographic coupling provides a static and retrospective view that requires periodic renewal to keep track of recent advances in blockchain deployments in logistics and SCM. Therefore, researchers may address this shortcoming by replicating the co-citation network analysis presented in this paper. Finally, the exact keywords used for the retrieval of studies can influence the sample and subsequent analysis. Accordingly, the use of different keywords in the search query may result in novel insights.

7. Conclusions

The goal of this paper is to present a structured review of blockchain research in the field of logistics and SCM. The number of papers published in this area is rapidly increasing as blockchain applications begin to revolutionize aspects of supply chains and reshape their structures. Even though several literature reviews on the potentials of blockchain for logistics and SCM have previously been published, this bibliometric review provides a timely snapshot of the current state of research and objectively identifies the intellectual structure of the field as well as the influential publications and scholars.

Overall, 628 papers published between 2016 and 2020 were selected from the Scopus and Web of Science databases for our analysis. Blockchain attracted little attention in the years prior to 2017, but since then the technology has become increasingly popular in the scholarly press. The academic outlets publishing the most blockchain studies in logistics and SCM are Sustainability, International Journal of Production Research, Lecture Notes in Business Information Processing, and Transportation Research Part E: Logistics and Transportation Review. Meanwhile, several articles were published in other top-tier journals, such as Supply Chain Management, the International Journal of Production Economics, and the International Journal of Supply Chain Management. This indicates that leading journals have significantly contributed to the advancement of research into the business implications of blockchain.

In terms of national contributions, both developed countries including the USA and UK along with emerging economies such as China and India have devoted significant attention to the investigation of blockchain applications. The geographic distribution of papers revealed that authors affiliated with European and North American academic institutions dominated early contributions, yet a noticeable diffusion of research efforts into Asia is underway.

For those seeking a better understanding of blockchain research in logistics and SCM, the identified influential papers in this study may prove a good starting point to grasp the conceptual foundations of the field. In addition, the co-citation analysis helps to capture the more recent publications that have the potential to make enduring contributions and trigger further research. Being aware of the prominent scholars within the academic community may inspire future developments, motivate collaboration, and stimulate further research. Recent studies from influential scholars have focused on the nexus of blockchain, supply chain management, and sustainability, and the adoption drivers and barriers to blockchain implementation in logistics and SCM.

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logistics

Review

Applications of Blockchain Technology in Logistics and Supply Chain Management—Insights from a Systematic Literature Review

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Abstract: The most successful applications of Blockchain Technology are still in the area of crypto-currencies, although both scientists and practitioners have discovered the potential of Blockchain Technology in Supply Chain Management. There is a significant theoretical literature on Blockchain Technology, but there exists a lack of published case studies and concrete examples. This paper discusses whether this shortcoming is due to insufficient added value of the technology and identifies other possible reasons. Furthermore, this paper introduces Blockchain Technology, describes the origins of Bitcoin, the structure and core properties of the Blockchain, and examines smart contracts. A comprehensive and structured literature analysis identifies concepts for the use of Blockchain Technology in logistics in terms of economic benefits. Additionally, a cluster analysis regarding the topics of the relevant literature was conducted. One finding of the study is that Blockchain Technology is particularly worthwhile for goods with a high value. Moreover, if the trade volume of the respective goods is low, the advantages of BCT are maximized. At the same time, the demand for transparency and immutability of data must be more important than the protection of sensitive data. In addition to concrete use cases of Blockchains, an exemplary logistics process will be presented within the Luxury Supply Chain, showing the advantages of Blockchain Technology for each individual process step.

Keywords: Blockchain Technology; Smart Contracts; logistics; Supply Chain Management

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1. Introduction

In 2008, an individual using the pseudonym Satoshi Nakamoto published the basic concept of the first crypto-currency, Bitcoin [1]. Bitcoin is a cryptocurrency, which does not require a central institution such as a central bank or a trusted third party, like PayPal. The Bitcoin network is based on Blockchain Technology (BCT) [2] (p. 22). The Blockchain (BC) is a distributed peer-to-peer database that consists of a network of equal nodes [3] (p. 1). Because the data is tamperproof and firmly integrated into the BC, the BC can reduce human intermediaries. Currently, BCT is mainly used in the field of crypto-currencies, but researchers and companies have recognized the potential of BCT for other areas, such as logistics [4] (p. 263). This paper examines the application of BCT in logistics with the aim of identifying its economic benefits and practical applications.

With globalization, logistics is confronted with new challenges stemming from a world-wide network that has to be planned, guided, optimized and controlled. This network consists of a multitude of different companies, which are currently controlled individually with different central systems [5] (p. 19). Holistic controlling of the Supply Chain (SC) could increase its transparency and both generate and maintain competitive advantages over other SCs [6]. Logistics and Supply Chain Management (SCM) could benefit tremendously from BCT's decentralized structure, high transparency and security against manipulation [7] (p. 7). The following comprehensive literature analysis demonstrates the growing interest of logistics and SCM in BCT. The aim of the paper is to answer the following two research questions: (a) What is the international state of research regarding BCT in SCM?; (b) Which areas of SCM are covered by current publications? Furthermore, the paper aims to provide insights into selected case studies and real world examples.

2. Fundamentals of Blockchain Technology

2.1. Origin of the Blockchain Technology

In 2008, during the global economic crisis that began in 2007, and presumably triggered by the bursting of the speculative bubble of the American real estate market, the pseudonymous Satoshi Nakamoto published the concept for Bitcoin in a white paper [1]. The Bitcoin network is very similar to conventional payment services, such as PayPal, in terms of its functionality for the user [2] (p. 22). However, Bitcoin has little in common with traditional currencies, which can be available in digital form through financial services providers such as PayPal. When digital currencies rely on a central node, a hostile attack can cause serious damage [8] (p. 1).

Bitcoin, on the other hand, has a decentralized structure. With a public BC, anyone can become a user of the network. Since the network is stored on many devices worldwide, an attack on the network is almost impossible [9]. Time has proven this, as the Bitcoin network has been online almost continuously without major problems since its launch in early 2009. The market capitalization reached a peak of around USD 300 billion in 2017 (See: coinmarketcap.com (last accessed on 10 June 2021)), which has aroused public interest and attracted the attention of new investors.

Bitcoin's enabling technology is the BCT. However, Bitcoin cannot exist without the BC and is inseparably linked to the BC [2] (p. 26). The BC has enormous potential for large-scale improvements in many different areas [2] (p. 22). This is a new type of decentralized data structure that enables the unique properties of the Bitcoin network. The following section describes the basic structure of a BC and explains its most important properties and key features.

2.2. Basics and Structure of the Blockchain

A BC is, as the name implies, a chain of blocks. Each block has an identical structure, consisting of a head and a body. Each block contains an exact reference to the previous block, so that a chain is formed (see Figure 1). The only exception is the so-called Genesis block. This is the first block of the BC, defined by a software. All transactions are combined and stored in the next block, a process that is called mining [9] (p. 244).

The header of a block contains the obligatory reference to the previous block, as well as other information, such as a timestamp and the version of the block. To make the blocks uniquely identifiable, they are assigned a unique name by an algorithm. The reference to the previous block results in a chain of blocks that becomes longer and longer. The deeper a block is contained within this chain, the more participants have to be manipulated for a change, which reduces the probability of manipulation. The most important feature of the BC is that the previous blocks cannot be changed without having to rebuild the entire BC [10].

The main part of each block is the body. All transactions that did not make it into the last block are transferred into the current block. The size of each block is fixed, and therefore the number of transactions per block is strongly limited. In the body, these transactions are stored, as well as all related information. In the Bitcoin example, this is the data about the sender, the recipient and the amount in Bitcoin [11] (p. 561).

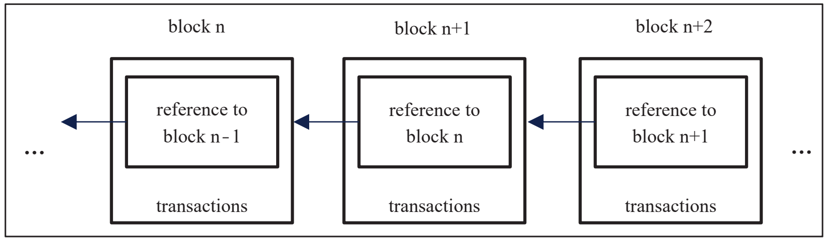

Figure 1. Schematic representation of the structure of a Blockchain [12] (p. 2293) (slightly modified).

As mentioned above, the BC has a decentralized structure and is not based on a central server or a central institution. Instead, the BC consists of a network of so-called nodes. Each user can keep a complete copy of the BC and check the new blocks. The more nodes that carry the network, the more copies there are of the BC and the more secure the network becomes. However, for a strong unique network, there must also be agreement on the BC. This is achieved by so-called consensus mechanisms; the BC of Bitcoin uses the Proof-of-Work (PoW) algorithm [11] (p. 559).

The PoW algorithm consists of a mathematical problem. In the example of Bitcoin, the first correct solution to the problem will be rewarded with Bitcoin and published, together with the new confirmed transactions. The solution can be verified very quickly by all other nodes and, if correct, can be attached to the BC, including the transactions. An alternative to the PoW algorithm is the Proof-of-Stake (PoS) algorithm. Here, the miners are liable for the authenticity of a block with a part of their assets. Since no complex mathematical problems have to be solved, this algorithm is much more power-efficient and scalable. This means that the network is cheaper to operate, but, on the downside, the security of the network is lower than with the PoW algorithm [13] (p. 3).

2.3. Key Features of the Blockchain Technology

The BC is structured as described above to enable the most important feature of BCT, the decentralized structure. This is a very important security feature, because all changes have to be adopted by all participants of the network. Since each participant is allowed to hold a copy of the BC, and there is consensus on the BC between the participants, the transactions in the previous blocks are unchangeable. This transparency means that all transactions can be checked by all participants. The more nodes the network has, the more fail-proof it is; in the case of Bitcoin, even satellites (See: blockstream.com/satellite/ (last accessed on 10 June 2021)) are a part of the network [14] (p. 2).

The specific structure of the BC and the high level of security gained also has its price. Each node holds every transaction ever made, must validate new transactions and must attach them to the stored BC. This very inefficient procedure (compared to conventional databases), in addition to the limited block size, results in very limited scalability. The Bitcoin network can process approximately seven transactions per second (TPS) [11] (p. 561). A centralized payment network like Visa claims to be able to process up to 65,000 TPS (See: Visa Factsheet. https://usa.visa.com/dam/VCOM/download/corporate/media/visanet-technology/aboutvisafactsheet.pdf (last accessed on 10 June 2021)). Scalability can only be improved at the expense of decentralization or security. To improve the scalability, consensus mechanisms can be used with less security or they can be switched to private, permissioned BCs [15] (p. 6). Another problem is the dilemma between the highest possible transparency and the highest possible data protection. In the example of Bitcoin, the transactions are transparently visible to every participant in the network, which is necessary for a complete documentation of the ledger. Each Bitcoin can be traced back to its creation, and the true identity of the Bitcoin owner is often revealed at the interfaces to reality, e.g., the exchanges. Further technical challenges and barriers in implementing the technology are discussed in Section 4.2 [13] (p. 7).

In summary, the BCT is a decentralized, transparent data structure and therefore it is also a very secure data structure. It functions without a central control system and stores information, such as transactions or programs, in chained blocks [16] (p. 5).

2.4. Smart Contracts

Currently, contracts are drafted by lawyers according to current law, in the case of disputes the contracts are judged by the judges of courts. If necessary, the executive power then enforces the contracts [17] (p. 265). Smart Contracts do not need all this, they enforce themselves independently according to previously defined, unambiguous rules. With Smart Contracts, the program code is stored on the BC. Smart Contracts are contracts because they are an agreement between two or more parties and contain fixed conditions. They are smart because the Smart Contract automatically recognizes which case of the contract has occurred and then automatically carries out the contractually agreed actions for this case. In most cases, these actions are transactions in which a pre-determined amount is sent to a specific address. Ethereum is measured by market capitalization, the second largest crypto-currency, and is therefore the most famous public BC supporting Smart Contracts [18] (p. 93).

The following example, based on the work of Asadi Bagloee and colleagues (2019), is intended to illustrate the principle of Smart Contracts, by means of a bet on the weather between two friends. Neither of the two friends knows what the weather will be like tomorrow, and they agree that the winner gets €100 from the loser. The two friends could hire an unbiased, trustworthy third party, like a lawyer, which they do not want. A Smart Contract can solve the bet cheaply and easily. First of all, it is defined at which weather conditions who wins and where the Smart Contract should get the weather information from. Then both deposit €100 into the Smart Contract and leave their addresses. The Smart Contract automatically determines the winner at the agreed time and initiates the corresponding transaction [19] (p. 3).

Nick Szabo already developed the idea of automated contracts in the 1990s [20]. Prior to the BCT, there was no suitable secure technology on which Smart Contracts could have run safely. The core characteristics of the BCT mentioned above enable unchangeable, decentralized and therefore secure, Smart Contracts. In summary, Smart Contracts can automate payments between two parties and ensure that the two parties do not have to trust each other, because both can trust the Smart Contract, due to its predictable behavior. Smart Contracts can provide higher security at lower costs. Therefore, Smart Contracts are assigned an important role in the application of BCT in SCM [16] (p. 21), [21] (p. 21).

3. Structured Literature Analysis

The comprehensive and structured literature analysis was conducted in six steps in order to analyze the topic of BCT and SCM as objectively as possible. The seven steps of Freels and Onwuegbuzie (2016) serve as the basis of the six steps [22]. For this purpose, the seven steps were interpreted and adapted to the topic. In this section, the procedure shall be explained as comprehensibly as possible.

1. Development of a thorough understanding of the topic;
2. Identification of two main topics, a subject area and subsequent definition of keywords;
3. Performing a preliminary research in selected databases;
4. Performing the research in several available/suitable databases;
5. Conducting a prior evaluation of the quality of the literature;
6. Performing a detailed analysis and classification of the selected literature.

In order to identify two main topics and a subject area, a thorough understanding of the topic is necessary. After that, the keywords needed for the search are defined. By conducting a preliminary search in selected databases, the keywords can be tested and adjusted, if necessary. The actual research was then carried out at Science Direct (SD) and Web of Science (WoS). Based on the titles and, if applicable, the abstracts, the literature was evaluated thematically; search terms and impact factors were also used for this purpose. Thereafter, the exploration phase of the literature analysis—the so-called literature research—is completed and the interpretation or analysis of the literature found is begun. The final literature found can subsequently be analyzed and classified in detail.

3.1. Preparation of the Literature Analysis—Defining the Keywords

Exploration of the subject matter is a prerequisite for formulating targeted search terms and thus initiating the literature research. In this phase, the title for this literature analysis was worked out and a research question was posed. Then the work here was divided into subtasks. The focus of the analysis has already been defined in the first section of this paper. The aim is to answer the research questions mentioned above with the help of the systematic literature analysis. In addition, an overview of the current state of the art of the possible applications of BCT in the SCM is to be provided.

In order to answer the research questions, sources have to be identified that deal with BCT as well as logistics and SCM. The following three themes are relevant for this paper. First is the BCT, the focus of this paper. Since there is disagreement in the literature about the exact wording of this term, different variations were searched for ("Blockchain", "Block Chain" as well as "Block-Chain"). Some authors also use the term "distributed ledger." It denotes the underlying technology for which the BC is an example. Second, advantages or possible improvements that the implementation of the BCT may be able to provide are the focus of research. The third complex of themes refers to the use cases of BCT. The examined application area of BCT is logistics or SCM. Therefore, "Supply Chain" and "Logistics" were used as search terms. Sources containing the term "Supply Chain Management" were found from the first term. For each complex of themes, technical terms were derived, which in turn were transformed into keywords (see Table 1).

Table 1. Definition of the keywords based on three complexes of themes.

Complex of Themes	Technical Terms	Search Term
Blockchain Technology	Blockchain Distributed Ledger	"Blockchain", "Block-Chain", "Block Chain" "Distributed Ledger"
advantages or possible improvements	advantage, advantages economics, economical, economically . . . process, processes challenge. Challenges problem, problems example, case study, project	"advantage*" "econom*"; (*) represents any group of character, including no character "process*" "challeng*" "proble*"
Logistics	Supply Chain Supply Chain Management Logistik, Logistic, Logistics	"Supply Chain" "Logisti*"

The search terms of the themes were each linked with the Boolean operator OR. The actual complexes of themes were linked with the Boolean operator AND. The query used for WoS is the following: "TS = (("Blockchain" OR "Block-Chain" OR "Block Chain" OR "Distributed Ledger") AND ("advantag*" OR "econom*" OR "proces*" OR "challeng*" OR "proble*") AND ("Supply Chain" OR "Logisti*"))".

3.2. Selection of the Relevant Literature

In this step of the systematic literature analysis, the publications relevant for this work are filtered out manually, out of all the publications found. The search was conducted on 24 May 2021 on the databases SD and WoS. Since SD produced significantly fewer hits on the topics of BCT and SCM, due to the limitations of SD, only these two topics were combined (Note: Science Direct did not support wildcards—status 2021). Therefore, the query for SD has been changed as follows: Title, abstract, keywords: ("Supply Chain" OR "Logistic" OR "Logistics"); Title: ("Blockchain" OR "Block-Chain" OR "Block Chain" OR "Distributed Ledger"). Overall, a preliminary result set of 440 publications was found.

First, all publications were removed if they were duplicates or not written in either German or English. Subsequently, both the titles and the abstracts of the other sources were evaluated. With the help of this information, each source was assigned a score. The title and the abstract were evaluated in terms of their relevance to the topic of this paper. Furthermore, the literature was evaluated thematically. An indication of quality was provided by the ranking of the journals on various journal ranking platforms (Scimago Journal and Country Rank and the ranking of VHB). The literature selected was evaluated on a scale from 1 to 10. All sources with a rating below 5 were immediately excluded. A score of 10 was not assigned, which means that no paper was found that perfectly answered the research question. This resulted in a total of 32 relevant publications (see Figure 2).

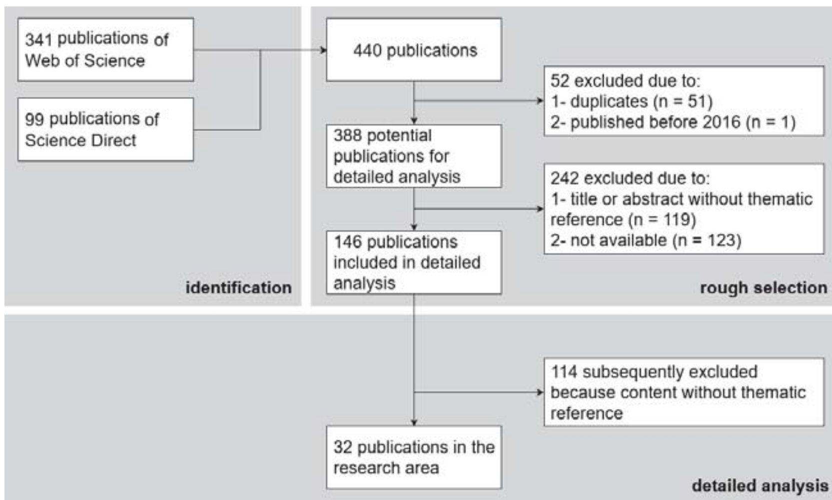

Figure 2. The literature filtering process [23] (p. 3) (greatly modified).

3.3. Analysis and Synthesis of the Identified Literature

As already described, the aim of the systematic literature analysis was to identify economic benefits of applying BCT in SCM, as well as real-world examples.

For this purpose, the relevant publications were first synthesized into thematically related clusters (see Figure 3). To form these clusters, the bottom-up approach was applied. After a first analysis of the titles, as well as the abstracts of the publications, two superordinate clusters were identified.

The first group of sources generally deals with the functionalities of BCT. The conditions under which a BC can be used in SCM were discussed. These sources also deal with the advantages and disadvantages of the BC and the adoption barriers. This cluster is referred to as "Overview of BCT in SCM." A more detailed analysis of this cluster is provided in Section 4. The second cluster consists of sources in which the authors deal with the concrete application possibilities of the BCT. This group can be divided into three subclusters: Food SC, Healthcare SC and descriptions of logistics processes within the luxury SC. In Section 5, these application possibilities are analyzed in more detail. In addition, an exemplary logistics process will be described. Due to the high number of publications, the use cases "Food SC" and "SC in Healthcare" are considered separately. One application case will be presented for each of the two clusters in which BCT is already in use.

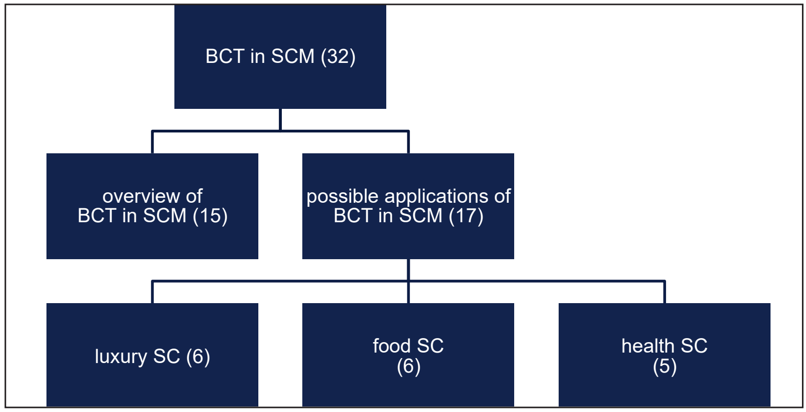

Figure 3. Number of relevant publications in the distinguished clusters.

4. Blockchain Technology in Supply Chain Management

In this section, it will be demonstrated which features the BCT can offer to the SCM and which of them are relevant for the SCM. The implementation of the BCT will be explained and the related weaknesses of the BCT will be pointed out. Therefore, the first cluster "Overview of BCT in SCM" is evaluated regarding the functionalities and application areas of the BCT in SCM. Subsequently, the barriers and weaknesses of BCT and the factors to be considered when implementing the BC will be discussed. Finally, from the knowledge gained, the conditions are derived under which the use of a BC in the SCM makes sense. It is already known that BCT can provide more than just the two functionalities discussed below. However, the paper deliberately focuses on the two functionalities that have the highest potential for the SCM. Wang et al. (2019) name the general advantages of BCT in SCM as first, the improved transparency of SC, second the creation of trust and secure information exchange and third the improvement of processes [3] (p. 226), [24] (p. 34993).

4.1. Functionalities of the Blockchain Technology in Supply Chain Management

The possible applications of BCT are very diverse. However, for a meaningful economic use, this technology must solve existing problems of SCs or lead to process improvements. From the analyzed literature of the first cluster "Overview of BCT in SCM," two fundamental functionalities of the BCT have been identified which may be beneficial for SCM. The two identified functionalities of the BCT that have a high potential for the SCM are its functionality as a transparent database and the application of Smart Contracts written on the BC.

4.1.1. BCT with the Functionality of a Database

For the first functionality, the BC acts as a database, whereby the data must be stored permanently and without contradiction along the SC. In this way, a complete, cross-company data and information flow along the entire SC can be ensured. Thus, the SC can be strengthened, since functional problems of the SC can be found or searched for in a targeted manner. Because nowadays it is not only individual companies that compete with each other, but entire SCs, a SC can generate or secure a competitive advantage over other SCs by increasing its efficiency. Since the data in the BC cannot be manipulated by the participants at a later time, the individual companies along the SC can gain an advantage because cooperation is more transparent and therefore fairer [25] (p. 5). When acting as a database in SCM, there are two possible advantages that BCT can provide: on the one hand, BCT can provide process improvements and, on the other hand, BCT can offer added value to the customer [26]. In the first case, competitive advantages arise from lower costs and in the second case, customers are willing to pay a higher price.

With regard to process improvements, it can be stated that a database based on BCT differs from a conventional database in that each participant in the network may have a complete copy of the database. In this way, everyone can copy the current changes to his database and check if it is consistent with the previous blocks [25] (p. 2). BCT is a suitable solution when trust is required and transparency needs to be created. According to Giungato and colleagues (2017), this may be the most important advantage of BCT in SCM and could be applied in many areas of SCM [27] (p. 8). Tijan and colleagues (2019) point out that the developments around Industry 4.0 already offer many possibilities to improve processes that can be supported or enabled by BCT. The goods remain traceable along the entire SC for all participants. Applying Big Data is a necessity for Industry 4.0. Big Data and BCT can benefit each other, because with BCT the data can be collected along the SC, which generates deeper insights through Big Data. This includes a large amount of structured, but also unstructured, data that are often only collected in order to obtain more data. The amount of this data is growing exponentially [7] (p. 6).

Traceability of processes or goods can be of great interest for SCs. Traceability can be implemented on the basis of BCT, which is why Business Process Management conducts research in the area of BCT. Due to the high degree of specialization of companies, SCs are becoming more and more complex and contain more participants, which can lead to trust problems in certain processes within an SC. This is especially problematic if critical goods, such as pharmaceuticals, are part of the SC; regulations and laws require full traceability of origin and processing for some critical goods [28] (p. 56). BCT in SCM could also prevent time delays and significantly reduce human error. Every transport within the SC can be documented reliably with BCT. In the best case, this traceability starts with the mining of the respective raw materials and ends with the purchase by the end customer [7] (p. 6).

The second possibility of BCT generating a competitive advantage in SCM is to offer the customer added value. The increase in transparency does not only provide an advantage for the SC companies, but can also create more trust in the product among final customers [29] (p. 2125). This increased trust could lead to higher customer satisfaction [4] (p. 264) and greater willingness to pay, especially for critical products such as food or pharmaceuticals [30] (p. 36505).

4.1.2. BCT with the Functionality of Smart Contracts

Smart Contracts have been identified in the literature as a second way in which BCT could provide advantages in SCM. In Section 2.4, Smart Contracts were presented theoretically. In summary, Smart Contracts are automated, secure contracts that are written to the BC and only trigger a transaction under previously known conditions. No support of a centralized execution authority is necessary. Smart Contracts enable the automation of complex multi-step processes [12] (p. 2301). For these reasons, the functions of Smart Contracts are very relevant to SCM. Traditional contracts often require a central, trusted third party. This trusted third party often charges high transaction fees and can become a weak point in the process; failure of this party can lead to security problems and a cancellation of the transaction. Furthermore, the decision of a trusted third party is not always objective and understandable for all the parties involved. Smart Contracts are different in that they function as autonomous actors and their behavior is completely predictable [12] (p. 2297).

Smart Contracts come with many problems, which is one reasons why there are hardly any real applications of Smart Contracts in SCM in the literature. The problems can be divided into four categories, which are described in more detail in the next section: programming, security, data protection and performance problems [18] (p. 94).

4.2. Implementation of Blockchain Technology in Supply Chain Management—Barriers and Weaknesses

To implement a BC in an SC, it is important that all parties involved agree on a BC and that everyone is involved in the process of implementation. As the average number of participants in a SC has increased, reaching an agreement is becoming more and more important, but also more complex and difficult. Some companies gain a greater advantage from the implementation of BCT than others. Therefore, many decisions have to be taken together by the participants. A public BC is the most secure and has the highest transparency and can therefore offer the end customers the best and most trustworthy information. With a public BC, sensitive company data also becomes public. This extensive disadvantage overrides the advantages of a public BC for most companies. In most cases, a private, permissioned BC is used to which only certain parties have access. Only a small part of the data is subsequently released to the final customer [15] (p. 6).

One problem with Smart Contracts is that the legal enforceability is still limited. The problem is made worse by the fact that Smart Contracts in SCM are supposed to be valid across national borders. Efforts are being made to make the technical rules of smart contracts legally enforceable and binding for all parties. As an interim solution until these problems are globally solved, a so-called "Dual Integration" is proposed (See: https://erisindustries.com/components/erislegal/ (Last accessed on 7 June 2021)). This involves drawing up two contracts between companies that refer to each other. On the one hand, a real contract is drawn up that is legally binding for all parties. On the other hand, a Smart Contract is drawn up which refers to the real contract between the companies.

If a function of the Smart Contract contains errors (logical or content-related), the decisions made in the Smart Contract cannot be reversed, which is problematic. For example, a Smart Contract in its simplest form can function as a lockbox. It may happen that depositing money into this safe deposit box is possible without any problems, but there is an error in the code for the payment of the funds or the "withdrawal function" (See: https://solidity.readthedocs.io/en/latest/introduction-to-smart-contracts.html (Last accessed on 7 June 2021)). This means that the deposited crypto-currencies are irrecoverably lost and cannot be recovered by any party [12] (p. 2300).

The problems of Smart Contracts can be classified into the following four categories: programming, security, data protection and performance problems. Programming Smart Contracts requires accurate contracts, but programming them is a challenge, because the contracts cannot be changed or cancelled. Another challenge is the complex programming language. Smart contracts should be more secure than traditional contracts that are monitored by third parties. Unfortunately, there are still conceptual problems that might affect security. There is a dependency on time stamps; at Ethereum, for example, the execution of the contract may depend on Miner if two dependent transactions update the same Smart Contract in the same block. Other problems include transaction dependency, criminal activities and untrusted data feeds [18] (p. 94).

Smart Contracts, due to their transparency, give away more information than traditional contracts. The problem becomes more manageable through private BCs, but it still remains. If transparency becomes limited for the protection of company data, the security and trustworthiness of the data is simultaneously reduced. With BCT, the number of executable transactions or Smart Contracts is limited. This can be particularly problematic when executing Smart Contracts sequentially, since with BCT one contract is executed after another. The BCT is only limited and can be scaled at high expense, which can lead to performance problems if the number of contracts to be executed is very high [31] (p. 183).

In summary, BCT is a secure, transparent and decentralized database for monitoring the product flow. The increased transparency can either offer added value to the end customer, or it can help to comply with regulations and laws and provide the companies along the SC with opportunities to increase the efficiency of the SC. The greatest economic potential results from the tracking of critical goods, such as food or pharmaceuticals. In order to make tracking easier for Smart Contracts and to automate the processes, sensors can be used to document the transport of the goods. Due to sensible company data, private, permissioned BCs are better suited than more secure, and more transparent, public BCs.

5. Applications of Blockchain Technology in Supply Chain Management

This paper aims to present real applications of BCT in SCM. First, a logistic process is described and then two use cases are presented, where BCT is already in use. The specific added value of the BCT for the respective use cases will be shown. In order to achieve this goal, the second cluster "Possible applications of BCT in SCM" will be analyzed. This consists of 17 publications in which the authors deal with the practical applications of this technology in SCM, and whose evaluation resulted in a multitude of different applications. The majority of the publications in the second cluster examine an application of BCT in the food SC (six publications) and an implementation in the SC of the healthcare sector (five publications). For these two major clusters, a concrete use case, where BCT is already in service, will be given. BCT is already used in many areas (e.g., financial engineering and crypto-currencies), but virtually no financially self-sustaining applications exist in the real world [32] (p. 10).

5.1. An Examplary Logistics Process in Detail—Inside the Luxury Supply Chain

In the literature, there are various ways that BCT can support a so-called Luxury SC. A current application is the authentication and certification of diamonds, on the one hand to prevent the acquisition of so-called "blood diamonds." On the other hand, conventional certificates can be faked, or a real certificate can be used for a fake diamond, since BC certificates are permanent [33] (p. 17).

Platforms like Everledger offer a unique digital thumbprint for high value and hard-to-replace goods, such as diamonds and fine wine [15] (p. 9). This thumbprint is made by using the BCT that is unalterably stored in the BC; the thumbprint consists "of 40 metadata points, the laser inscription on the girdle, and the stone's four Cs—color, clarity, cut, and carat weight." (See: https://www.altoros.com/blog/a-close-look-at-everledger-how-blockchain-secures-luxury-goods/ (Last accessed on 7 June 2021); Primary source: https://youtu.be/GAdjL-nultI?t=202 (Everledger, Last accessed on 7 June 2021)).

In addition to the already existing BC-certificates [33] (p. 27), the transport of the diamond could be documented completely by means of the BCT (tracked and traced). The TrustChain™ from IBM can already track and authenticate diamonds [34] (p. 587) (Source: https://www.trustchainjewelry.com (Last accessed on 7 June 2021)). Transports usually involve several transshipments (processes in which the mean of transport is changed). The diamond is transported by different transport service providers. Ideally, the diamond would have to be checked for its digital thumbprint at each transfer point and the result would have to be stored in the BC. For one thing, checking the diamond takes time and for another, special measuring technology is required.

One way to speed up the process is to mandate that only the final receiver checks the digital thumbprint. The seller and the sender are responsible for the quality of the diamond, and can authenticate and certify it using the BCT. The shipper seals a transport box and is responsible for the fact that the diamond matching the digital thumbprint is in the box. Inside the box, there is an RFID chip beside the diamond, and a barcode is attached to the outside of the box. Inside the box, further sensors can be installed, which can be connected (e.g., via Bluetooth), such as temperature sensors or acceleration sensors, which might be able to detect shocks [34] (p. 587). The shipment could be refused on the basis of the sensor data.

In this example, the diamond is transported as follows: from the shipping point, the diamond is transported by truck to the freight port by a forwarding agent. There the diamond is transshipped into a cargo ship; at the final port, the diamond changes the means of transport (from the ship to the truck) and the responsible party. The truck then transports the diamond directly to the recipient. During the actual transport, the diamond can be shipped in a properly sealed package (e.g., a hard-plastic box). Opening the box is thus visible to the person next in the transport chain. The condition of the package is documented with each handling and saved in a block of the BC. For this purpose, the following transfer protocol could be processed for each transfer:

- Is the package intact and in a flawless condition?
- Is the seal undamaged?
- Do the barcode and RFID match the shipping note?
- Confirmation that the package has been passed.

As soon as the recipient of the package confirms that the package has been delivered, a transaction can be triggered by means of a Smart Contract. One advantage of BCT is that it can be used across different companies, which means that the transportation means of different companies can be used, as long as they agree to use the same BC. No one can change the data in the BC retrospectively. As the BC is law, the currently responsible party for the diamond is always visible to all parties; this currently responsible party is liable for any damage or loss. The responsible persons can individually insure themselves. In the case of a public block certificate, there is a risk that criminals could gain access to the current location of the valuable diamond, which makes a private, permissioned BC suitable [15] (p. 6). However, a residual risk remains because all companies along the SC have access to the BC.

5.2. Food Supply Chains

Although the literature analysis found quite a number of publications in the field of food SCs, no case was found in which a company actively used the BCT to earn money and gain a competitive advantage. Many feasibility studies have been found, but only few have tested the prototypes in the real world; this finding matches the findings of Hinckeldeyn (2019) [16] (p. 32). In the following section, several projects are briefly mentioned as examples, followed by a more detailed description of one application.

First, there is the cooperation of Walmart and Hyperledger Fabric, a BC platform for companies, which is intensively supported by IBM [16] (p. 24) and has been found referenced numerous times (See: https://fortune.com/2017/08/22/walmart-blockchain-ibm-food-nestle-unilever-tyson-dole/ (Last accessed on 7 June 2021)). In a field test, Walmart and IBM were able to demonstrate that the origin of mangoes and pork could be determined via BC within a short time [16] (p. 32). The IBM Trustchain can track tomatoes from the farm to the pot, to the jar, to the table, but is not yet in use, although a working prototype is (Source: https://www.trustchainjewelry.com (Last accessed on 7 June 2021)). Bumble Bee Foods cooperates with SAP to document tuna fish products from Indonesia. The size of the fish, fishing location and time, freshness during its processing and the company's certificate of production are stored within a BC (See: https://cointelegraph.com/news/north-american-seafood-firm-to-use-blockchain-tech-in-supply-chain/amp (Last accessed on 7 June 2021)). Other examples deal with the traceability and certification of Extra Virgin Olive Oil [35] (p. 173) or describe how eggs can be traced in the USA using BCT [36] (p. 1).

On the one hand, these examples demonstrate the increased interest of food manufacturers in the trustworthy documentation of their products in a BC [37]. Many companies are already trying to gain the trust of consumers with the help of seals, such as the Fairtrade label, which is given by a Fairtrade organization under certain conditions. On the other hand, the examples also show the interest of the large IT groups. Whether the interest comes from the Research and Development department or the Marketing department is not always identifiable. Food scandals have led to manufacturers generating competitive advantages by providing reliable proof of the origin and processing of goods. The BCT might be able to strengthen the confidence of the consumer [16] (p. 32).

In the following section, a prototype that has been tested in the field will be discussed. Zhang and colleagues (2020) have developed a new system architecture along the entire Grain SC based on BCT. Compared to traditional methods of the SCM, their system is characterized by high data security, real-time exchange of relevant information (such as hazardous material information) and trustworthy grain tracing along the entire SC [38] (p. 36398).

The Grain SC starts with grain cultivation and production, primary grain processing, grain product cycles, and deep grain processing and ends with transport to the consumer (see Figure 4). Zhang and colleagues (2020) have identified five typical links in the traditional Grain SC (see Figure 4): the link of grain production (G1), the link of grain storage (G2), the link of grain processing (G3), the link of grain logistics and transport (G4) and the link of grain marketing (G5) [38] (p. 36400).

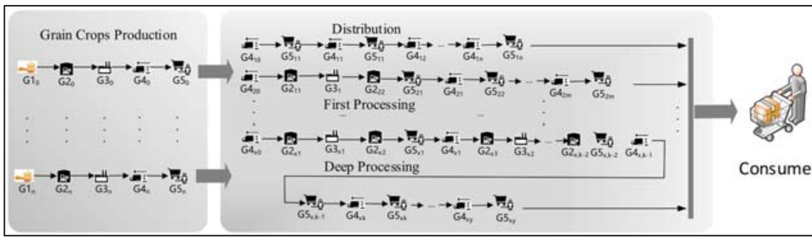

Figure 4. Structure of the Grain Supply Chain [38] (p. 36401).

Smart Contracts define the conditions for the execution of the transactions in advance. The system collects data about the grain, which is then stored within the BC. The data are collected mainly by electronic tags and various sensors such as code-scan guns, cameras, smoke detectors, humidity sensors, light sensors, etc. When the parameters of the grain meet the requirements and all other requirements are met, the transaction is automatically triggered [38] (p. 36404).

A special use case was applied to validate the proposed system. An Information Management System for the Grain SC was established with grain companies in the province of Shandong. This field test was conducted on the BC platform of Hyperledger Fabric with the cloud database MySQL. The system was able to provide reliable information in the SC for participants, consumers and third parties, and the data provided a good basis for assessing, predicting and early warning of hazards [38] (p. 36407).

5.3. Supply Chains in Healthcare

The company Modum, a Swiss start-up, is to be shown as an example for SCs in Healthcare. Modum has initiated several studies and has developed and tested prototypes and offers its services in the field of BCT in SCM. The goal of the company is the secure tracking and tracing of pharmaceutical products. To this end, the company relies on the public Ethereum BC. For tracking, IoT sensor devices (IoT = Internet of things), QR codes and barcodes are used to clearly identify the items handled.

The Good Distribution Practice Regulation (GDP 2013/C 343/01) requires proof that the transport conditions (in particular the temperature) could not have affected the quality of the pharmaceutical products transported [39]. The company Modum.io enables other companies to meet the GDP requirements with the help of BCT. At the same time, it should be possible to generate significant cost savings for the transport of pharmaceuticals that do not require active cooling [40] (p. 5). The system is based on the components shown in Figure 5.

Figure 5. Components of the system from Modum are a dashboard, a temperature logger and a mobile application [40] (p. 6).

To monitor the temperature during the transport of medicines, a calibrated temperature sensor in the package stores a measured value every 10 min. When receiving the package, the customer can scan the ID number on the package and then request the temperature data via Bluetooth, without having to open the package [40] (p. 5). The customer then sends the data to the Smart Contract (see Figure 6). The data are stored in PostgreSQL because the collected data is too large or too sensitive to be stored in the Ethereum BC [34] (p. 588).

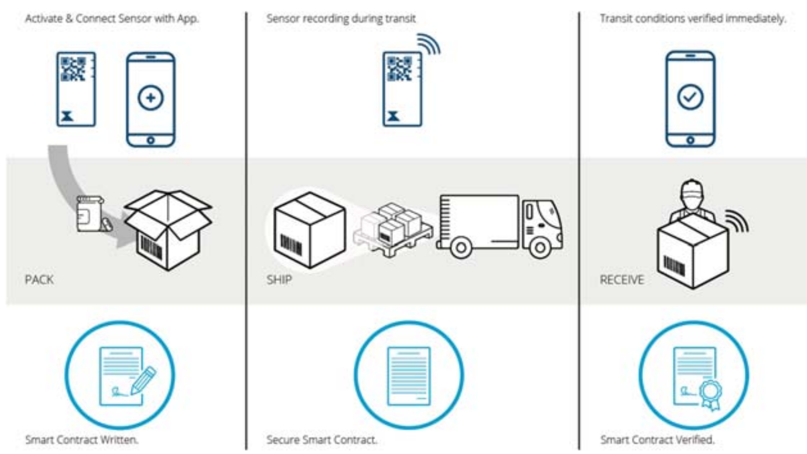

Figure 6. Logistics process of the company Modum [40] (p. 8).

6. Conclusions and Outlook

This work aimed to identify the economic benefits of implementing BCT in logistics by means of a structured literature review. In order to do this, this paper introduced the BCT, described its origins in Bitcoin and the structure and core properties of a BC. A comprehensive and structured literature analysis was performed to identify concepts for the use of BCT in logistics in terms of economic benefits. The cluster "Possible applications of BCT in SCM" and the sub-clusters of Food and Healthcare SC were identified, among others. In addition to two concrete use cases, an exemplary logistics process was presented, showing the advantages of the BCT for each individual process step.

Based on this study, new insights into the added value of BCT can be perceived. Companies that do not have expertise in BCT can use this paper to assist them in their technology selection. In addition, this paper provides managerial insights by identifying current possible applications of the technology, examining them for their benefits, and thus highlighting possible research gaps. The applications found highlight opportunities and can inspire companies.

In summary, the main advantages of a BC are that, unlike traditional distributed databases, no intermediary or central point of account is required, because the participants in the network control each other. In this way, the BC creates a consensus on the current state of the network without requiring the individual partners of the SC to trust each other. It also guarantees the integrity and immutability of the information stored on it.

The BCT is considered a new technology with many weaknesses and adoption barriers. The main feature is the decentralized structure, which, in combination with transparency, sets new security standards. Compared to conventional central databases, BCT is quite complex, and the high level of security is paid for with high hardware and energy costs. This effort is only worthwhile if the advantages resulting from the transparency can outweigh the disadvantages. For critical goods, such as food or pharmaceuticals, or in luxury SC, the BCT could be used more and more frequently.

A finding of the study is that BCT is particularly useful for goods with a high value. In addition, the advantages of BCT unfold best when the trading volume of the respective goods is low. The demand for transparency and immutability of data must be more important than the protection of sensitive data. This work has some limitations which should be considered when looking at the results. Initially, two databases were used in the systematic literature analysis. Therefore, it may happen that some relevant papers were not found.

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Article

On Blockchain Integration with Supply Chain: Overview on Data Transparency

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Abstract: Data transparency is essential in the modern supply chain to improve trust and boost collaboration among partners. In this context, Blockchain is a promising technology to provide full transparency across the entire supply chain. However, Blockchain was originally designed to provide full transparency and uncontrolled data access. This leads many market actors to avoid Blockchain as they fear for their confidentiality. In this paper, we highlight the requirements and challenges of supply chain transparency. We then investigate a set of supply chain projects that tackle data transparency issues by utilizing Blockchain in their core platform in different manners. Furthermore, we analyze the projects' techniques and the tools utilized to customize transparency. As a result of the projects' analyses, we identified that further enhancements are needed to set a balance between the data transparency and process opacity required by different partners, to ensure the confidentiality of their processes and to control access to sensitive data.

Keywords: DLT; Blockchain; supply chain; IoT; smart contract

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1. Introduction

Supply chain transparency is emerging as a fundamental feature of business continuity and high product quality. Effective collaboration among the different stakeholders requires a supply chain with a high degree of transparency [1]. In fact, transparency enables the different participants in the supply chain to obtain full visibility in terms of the data, services, and products being introduced and exchanged. Different works in the literature have used the terms transparency and traceability to describe this feature. However, these two terms designate two related yet different features [2]. Data transparency is defined [3] as the ability to easily access and work with data, independently of where they are located or what application has created them. On the other hand, traceability in a supply chain is described by ISO 9000:2005 as the ability to identify a product at any stage in the supply chain. It is also defined as a process of tracking the products' provenance and their inputs from the start phase to the end-use. From our perspective, transparency in the supply chain refers to the disclosure of information to trading partners, shareholders, customers, consumers, and regulatory bodies. It captures high-level information along the supply chain, such as product components, suppliers' names, the different locations involved, and associated certificates. Referring to the previous definitions, we conclude that traceability is a prerequisite to transparency realization. Traceability provides opportunities to determine supply chain efficiency, meet regulatory requirements, and verify sustainability claims. To this end, many modern supply chain projects use a different technical solution to achieve traceability, and hence achieve a high level of transparency.

In addition, trust is an essential requirement in a transparent supply chain. Research studies [4–6] show that mistrust among the partners of a supply chain is a significant issue, which hinders collaboration [7,8]. The supply chain is composed of independent partners, each of which represents a standalone centralized system. Consequently, data transparency may be compromised by a lack of trust among the partners and require more solid trust to be developed [9,10]. Furthermore, consumers may request details concerning the products, including manufacturing origin, quality of service, and proof of safety. Thus, building trust is achieved by enabling transparency along the chain so that individuals and companies can trace their products back to their origin. This can be achieved using Internet of Things (IoT) technology [11,12]. IoT technology is used to deliver the collected data over the network to enhance supply chain performance and traceability. However, the supply chain becomes constrained by additional data loads within the partners' independent systems.

In order to overcome the issues related to trust, Blockchain and, more generally, Distributed Ledger Technology (DLT), is a good candidate which enables the full transparency of data records. It enhances trust between partners through a cryptographic-based, peer-to-peer decentralized platform that underlies a supply chain [13]. Using the Blockchain platform for the supply chain eliminates the ambiguity behind the group of independent databases of traditional supply chain systems, as all records are stored within the ledger on every stakeholder system. Furthermore, Blockchain is immutable against the altering or removal of any records without leaving traces. This is because all partners have a copy of the same updated ledger that leads to a clear vision over the ledger contents. According to many studies [14–16] that have surveyed the critical aspects of implementing Blockchain solutions, Blockchain is a convenient tool to overcome trust and collaboration issues in a supply chain. It is called the "truth machine" [17], and discourages companies from any misconduct. Moreover, many proofs-of-concept (POCs) or piloting schemes have been developed in recent years using technology to study supply chains for traceability and transparency purposes [16]. Data transparency is a built-in feature of Blockchain due to the decentralized nature of the platform. In this context, the ability to control data privacy or opacity within the public Blockchain is questionable, while stakeholders in the supply chain have sensitive data that should not be disclosed to the public. Supply chain projects go far beyond the offered transparency and add their enhancement preferences in addition to the current Blockchain transparency feature. Despite its high importance in building the modern supply chain, there are no comprehensive studies that categorize and analyze the Blockchain-based supply chain's data transparency. To the best of our knowledge, a few of the intended projects have shed light on this topic. The contributions of this paper are:

- We surveyed the existing DLT-based supply chain projects leveling data transparency;
- We investigated the techniques utilized in the data transparency enhancement process;
- We shed light on the importance of transparency and borders between transparency and opacity through access control to successfully integrate Blockchain into a supply chain;
- We highlighted the smart contract and IoT technology roles in achieving controllable data transparency, and call for further investments.

The rest of this paper is structured as follows: Section 2 presents the methodology adopted in this survey. The supply chain transparency requirements and challenges are shown in Section 3. The benefits of using DLT technology in supply chain systems, including transparency, are discussed in Section 4. Section 5 summarizes the existing DLT techniques for supply chain transparency. In Section 6, different projects that employ the DLT in their supply chain are analyzed, with a specific focus on their transparency and traceability features. A discussion is detailed in Section 7 and Section 8 concludes the paper.

2. Methodology

This paper contributes to the provision of knowledge about the supply chain's data transparency. The increasing necessity of obtainable transparency in the supply chain encourages investigations in this area of research. The integration of the supply chain with Blockchain and the great evolution towards decentralization are considered by many studies. However, research works that investigate data transparency in the supply chain are limited. Table 1 enlists the existing surveys and studies that discuss the transparency topic and its effectiveness in the supply chain.

Table 1. Existing studies related to Blockchain-based supply chain data transparency.

Sources	Roles
[18]	Elaborates the role of NGO's brand collaboration in enhancing the supply chain transparency
[19]	Develops system architecture to integrate Blockchain, IoT, and data analytics to provide sustainable products
[20]	Studies the relevance of supply chain transparency to supply chain sustainability governance
[21]	Conducts the adoption of Blockchain for supply chain transparency
[22]	Reviews transparency/traceability of Blockchain-based supply chain in the literature
[23]	Develops smart contracts to directly directly the supply chain transparency
[24]	Proposes multi-chain platform to enhance cross-border e-commerce supply chain traceability

The integration of Blockchain with the supply chain is a relatively new approach. This new approach was adopted to attain immense product traceability and sustainability among companies and individuals. This paper sheds light on the efficiency of Blockchain data transparency and traceability within the supply chain, and illustrates the evolution of data transparency in the modern decentralized system compared to its presence in the traditional centralized system. It also investigates the major transparency challenges encountered in any supply chain and highlights the significance of utilizing the new decentralized platforms.

The research points are summarized in the following questions:

Q1: What are the challenges related to data transparency in the supply chain?
Q2: What are the influences of Blockchain over data transparency in the supply chain?
Q3: What are the existing DLT techniques to achieve transparency in the supply chain?
Q4: Which supply chains are integrated with DLT? How do they tackle transparency?
Q5: What are the logistic obstacles that would affect the achievement of controllable transparency?
Q6: What additional measures should be taken to enhance supply chain transparency?

Our study addresses these questions by investigating the related surveys and studies mentioned in Table 1. However, additional work is required to address the research questions and present the techniques and frameworks which are accountable for building the supply chain transparency based on DLT and IoT technologies. To make progress in this direction, we first considered the papers that entirely or partially tackle supply chain transparency, hosted in scientific databases such as ACM, Elsevier, IEEE, etc. Secondly, we studied the 24 available projects and pilots that decentralize their supply chain and highlighted the used techniques. We also explored many available white papers related to the investigated projects. Some of the projects mentioned in this paper have no detailed technical background. However, we shed light on their contributions and targets.

The novelty of this paper lies in the following aspects: Elaborating on answers to the above questions; showing the different techniques that help the researchers and developers adopt the expedient supply chain platform, regarding their utility; directing future researches towards the topic of transparency access control. This paper can be considered as guide to data transparency researchers. It helps them to build and develop additional transparency techniques for their projects because it analyzes and illustrates the existing up-to-date projects, as well as their innovative techniques, which are utilized to achieve the required supply chain transparency.

3. Supply Chain Transparency Challenges and Processes

3.1. Data Transparency Challenges

At present, the global supply chain consists of a complex network of stakeholders across industries to coordinate collaborative tasks and achieve mutual agreements. Figure 1 depicts the significant supply chain challenges: centralized systems, lack of transparency, scalability, challenges to IoT integration and the upcoming technologies.

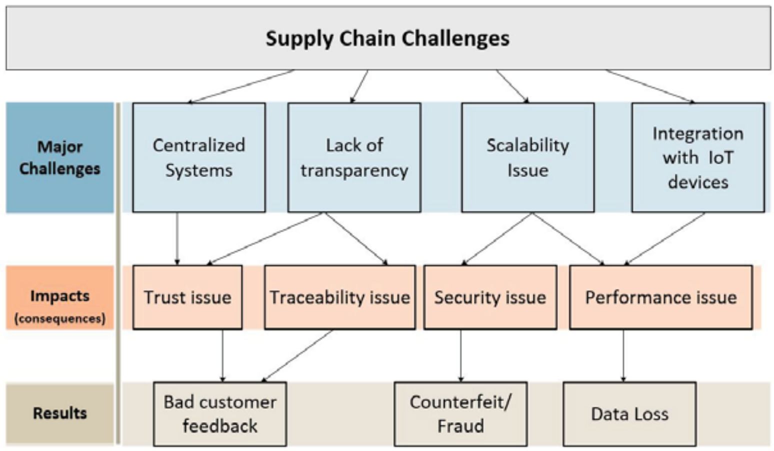

Figure 1. Technical Supply Chain Challenges.

The existing centralized supply chain systems struggle unproductively to provide a portion of the vital requirements using workarounds and trusted third parties [25], in addition to the great integration of new technologies. Such independent databases have trust issues resulting in negative customer feedback and dissatisfaction. In addition, there is no reliable shared information within most of the supply chain, and that is the main transparency issue with a centralized system. Lack of transparency leads to traceability and trust issues, in addition to negative feedback from customers. Furthermore, scalability is a major problem when the product travels across many geographical regions. It comes with crucial documents such as ISO certificates, invoices, customs, letters, proofs, etc., and requires hundreds of communications among stakeholders. A study showed that 200 communication processes are necessary to achieve a single product delivery [26]. Hence, the occurrence of scalability challenges leads to security and performance issues. Therefore, these cause counterfeits in the data of the intended products and, in many cases, data loss. This may cause trust issues among partners and result in customer dissatisfaction. Moreover, the current network infrastructure cannot exploit IoT's full potential and manage/analyze the massive incoming data well within the centralized circumstances [25]. In this way, a considerable portion of the IoT power is dismissed. Currently, there are unreliable frameworks and infrastructures designed to connect billions of heterogeneous and disparate IoT devices and their associated services, as well as data aggregation and data analysis [27].

3.2. Data Transparency Motivation

The supply chain has encountered enormous changes over time due to the high demands for supply chain transparency and traceability. These demands represent the main motivation for creating transparent systems. For example, when consumers increasingly wonder about where and how their clothes are made, or just how sustainable their potential new electric vehicle might be, given the raw materials required to make it, transparency in global supply chains becomes a notable issue, whicg needs to be addressed [28]. Moreover, the supply chain has become increasingly involved in the diversity of partners, products, and customer desires. Recently, the challenges have ranged from the heterogeneity of the systems to the additional technological requirements. Thus, besides the above challenges, the motivations behind supply chain transparency are the following:

- Independent Database: The current supply chain infrastructure is a group of centralized-based systems where each stakeholder represents a centralized system which belongs to one or more supply chains. These systems rely heavily on centralized, often disparate, and standalone information management platforms [15]. The group of databases involved in the production process is distributed, heterogeneous, and autonomous [29]. Therefore, data interchange between different databases is inflexible, due to the hard-coded nature of different data standards; Walmart and Cisco are two obvious examples [30]. Practically, the organizations' tendency to use their platform and control their data would limit collaboration.
- Lack of cooperation: The supply chain challenges are mainly related to the heterogeneity of the involved stakeholders, different data forms and lack of communications among the involved systems. Collaborative relationships determine how data are shared between companies, and project them to the underlying business processes. Collaboration is an opportunity for modern businesses to optimize their relationships with their trading partners. However, achieving collaboration poses complex contests between the supply chain actors. In this setting, there is a broad spectrum of collaborative initiatives, disparate standards for communication, and various levels of trading partner competencies and business processes [31].
- Data Loss: The widespread of IoT adoption triggers profound changes in global manufacturing [32]. The IoT systems are usually heterogeneous and categorized under different administrative domains [33]. IoT technology ameliorates the production progress and provides a high level of control, but it charges servers and peripheral devices with a high data volume [34]. The current network infrastructure cannot exploit the full IoT potential and cannot thoroughly manage/analyze the massive incoming data well within the centralized circumstances. Investing in IoT technologies in the current supply chain infrastructure surcharges these traditional systems with high data load, so part of the information is considered lost [25]. Moreover, most valuable products are controlled and tagged electronically; these tags may be cleared/replaced during the transition between stakeholders without leaving traces, leading to trust and security concerns. The probability of data alteration is very high through the current supply chain processes [35,36], where data loss and fraud are likely to happen in many situations.
- Product Complexities: Today's products and services' dispersed natures require their supply chains to be adequately visible to avoid obscurity and provide transparency and traceability features [16]. However, many manufacturers and sellers encounter information insufficiency, and therefore fail to provide customers with the required information due to lack of transparency. Hence, the supply chain complexity is increasingly evolving, as the diversity of the products and requirements requires the integration of many multi-tier supply chains. The availability of high transparency achieves a multi-tier supply chain and manages the different supply chain network parties Thus, the centralized system's uncontrolled informational data lead to massive counterfeit, massive trade losses and bad business reputations.

3.3. Security Challenges

Many different security factors challenge the supply chain in a way that may hinder the whole production processes.

- IoT technology proliferation: It is involved in most supply chain chain productions and processing tasks. Their proliferation will exceed half-trillion within the next few years [37]. The IoT devices communicate among themselves, servers and storages, producing massive transaction numbers along with supply chain production lines,

leading to to numerous security challenges to protect the devices and the sensitive data from any leakage or attack.
- Data opacity requirement: Usually, the manufacturing processes are accompanied by several private aspects, including proper planning, recipes, manufacturing intelligence, etc. Data privacy is one of the apparent concerns of the supply chain areas. Therefore, all systems may face data breaches, theft, leaks, unauthorized access, eavesdropping, etc. Accordingly, data opacity must be maintained by all the stakeholders that form a supply chain. By definition, a system is opaque if an external observer is unable to infer a "secret" about the system behavior [38]. Consequently, the decentralized platform that manage the supply chain should consider the opacity requirements.

3.4. Supply Chain Policy Enforcement

To achieve the supply chain transparency target as planned, a deep understanding of the intended goods and their requirements is desired. Furthermore, it is required to map suppliers and processes and clarify information gaps. Unfortunately, there is unclear description of the transparency processes that illustrate the road-map of a supply chain project in the literature. In [39] a practical guide to defining, understanding, and building supply chain transparency in a global economy is presented. It is done by: identifying and visualizing risk, using transparency levers to close information gaps, managing, and finally monitoring. In the below, we set the transparency processes for a supply chain to be well employed within better conditions:

- Self-identification: this is the first step that should be settled for a supply chain to identify the environment's overall components, including suppliers and sub-suppliers. Consequently, they should define each component issue and the common intersection among the partners. Accordingly, the risks and the goals are determined afterward, based on the different regulations and rules of the internal/external stakeholders in addition to the common factor impact on the business success.
- Collect information: Collecting data about the production processes, goods, gaps and others, practically on sites, is the most sensitive step. Nowadays, companies increasingly require more data from their suppliers. Collecting accurate data, in this step, is significantly crucial and impacts directly the overall supply chain transparency.
- Expose: the decisions are taken in the last step where the company has a complete picture of the supply chain. The decision takes into account meeting the relevant regulatory requirements and internal/external stakeholders' demands. Furthermore, the company should clarify how the information is disclosed.

4. DLT-Based SUPPLY Chain Benefits

Blockchain is a good candidate to address the above supply chain issues. It is a technology used for storing and transmitting data, which guarantees its integrity and transparency. A DLT platform that works without a trusted third party contains the history of the data exchanged in the network. This secure database is replicated in all the network nodes. Blockchain contains a chained set of blocks; each block contains a list of transactions and some other specific data. It is a fully decentralized P2P (peer-to-peer) system that guarantees trust between the non-trusted partners [40]. The main features of Blockchains are their decentralization, shared ledger, tamper evidence, tamper resistance, record-keeping, immutability, distributed trust, multiple-party consensus and independent validation [41].

There are four main types of Blockchain as shown in Table 2: Public Blockchain (permissionless) is available for anyone, such as bitcoin. Public Blockchain (permissioned) is open to anyone for data reading but restricted for data input, consortium Blockchain is a network of predefined organizations, and private permissioned is limited to one enterprise. The Blockchain serves the supply chain against many limitations and improves its functionalities in reference to the features mentioned below:

- Decentralization: The distributed ledger of a Blockchain-based supply chain empowers the involved partners to detect any deterioration of information. Thus, Blockchain tackles data corruption, hacking, or crashing issues in the centralized and independent systems and increases the information validity [42]. Moreover, this decentralized system can be inexpensively implemented among the suppliers [43];
- Trust: transparency is the main consequence of the distributed ledger technology where participants have a complete vision of the current contemporary information. Furthermore, privacy and anonymity are enabled because of the cryptography system [44]. Thus, it is unnecessary to evaluate the trustworthiness of the participants in the network with a decentralized supply chain. Evaluating trust between participants is due to the Blockchain's underlying technology, which guarantees the integrity of data records even in the presence of fraudulent nodes. Therefore, participants recognize that the information is accurate because each involved party has the same data, which cannot be altered or deleted. For this reason, resolving trust issues is discussed as one of the main arguments of the implementation [45];
- Automation: Blockchain applications are mainly based on smart contracts to verify the execution of transactions between two or more parties relying on predefined rules and conditions. The smart contract is a self-executed program or script, which is located on Blockchain ledger [46]. It executes its code once triggered, either from a participant node or from another smart contract. Then, it broadcasts the content to all network nodes for validation and updates the ledgers accordingly in case the contractual terms agree. This automated process reduces the apprehension behind the traditional contract of a supply chain where there is no need for human intervention and trusted intermediaries [47].

Table 2. Blockchain types, source: [48].

			READ	Write	Commit	Example
Blockchain Ledger Types	Open	Public Permission	Open to anyone	Anyone	Anyone	Bitcoin, Ethereum
		Public permissionned	Open to anyone	Authorized participants	All or subset of authorized participants	Supply chain platforms viewable by public
	Closed	Consortium	Restricted to an authorized set of participants	Authorized participants	All or subset of authorized participants	Multiple banks or chain of restaurants operating a shared ledger
		Private permissioned	Fully private or restricted to a limited set of authorized nodes	Network operator only	Network operator only	Enterprise ledger shared among head office and branches

5. Existing DLT Techniques for the Supply Chain Transparency

The emerged DLT-based supply chain proposals involve several techniques and solutions on top of their decentralized platforms. These techniques are presented in this section to be reused solely or unitedly by researchers for their under-construction supply chain systems. Then, in Section 6, we explore existing projects, and we show how they use the existing techniques related to data transparency and traceability to achieve the modern supply chain requirements. Below are the most valuable techniques:

5.1. Blockchain Core Improvement

The peer-to-peer system surcharges IoT devices with computing tasks and high storage demands. Many nodes are designed and prepared with top resources for computing and transaction validation in the mining and cryptocurrency field, which is not the case with heterogeneous IoT devices. Modifying some critical Blockchain characteristics boosts the integration of IoT devices with the DLT technology. Block size, creation time, and consensus algorithm are the areas where altering and adjusting the Blockchain in accordance with IoT requirements occur. In terms of data transparency, the enhancements of the transaction format have a significant impact compared to the others. The transaction in its current status lacks many essential details. Thus, developing the transaction format to include some real identity, references, blockinfo, etc., will increase the challenges related to the data transparency.

5.2. Smart Contract

Smart contracts are automated contracts embedded in the Blockchain, which make the entire process decentralized. Upon the deployment of the smart contracts, it is almost impossible to alter its code. Smart contract is a recent term that is widely used to refer to low-level code scripts running on an Ethereum Blockchain Smart contracts have recently attracted interest due to their importance in business applications and supply chains. In addition to the smart contract's role in ensuring the contract progress, it is also considered an excellent tool to enhance the data supply chain transparency [23]. When a smart contract is executed, all the intended parties within the supply chain are informed of the result and, therefore, they can trace and monitor their products, which increases the transparency level.

5.3. Involvement of IoT Device

At present, IoT technology represents one of the core elements of any modern supply chain. It has two main functions: capturing data from media and transmitting them to their destination. Moreover, IoT devices play a central role in ensuring the success of the supply chain's product traceability. Exerting additional efforts has an extensive role in improving the IoT functionalities, to make them suitable for Blockchain-based manufacturers' requirements. Considering the IoT side by the DLT system and its application is the best practice. Some projects [49–52] mentioned in this study have contributed to the IoT improvements in terms of detecting data accurately, to improve the visibility of the data. The transparency is enhanced, and the traceability will be more efficient with the IoT technology involved in the DLT-based supply chain [15].

5.4. Merkle Tree Tool

The Merkle tree structure [40] is a binary tree with an associated value for each node, where each one is the hash of its children. These data structure trees are created by repeatedly hashing pairs of nodes until only one hash is left. The last node of a tree (leaf) is a hash of transactional data where other nodes are hash of their previous hashes. This allows any party to quickly verify the validity of data in a branch or leaf using the tree's root hash. Blockchain, and especially Bitcoin and Ethereum, fundamentally use it. Merkle tree has three main advantages over transactional processing. First, it guarantees the integrity and validity of the data. Second, it consumes less memory and CPU resources, as the proofs are computationally easy. Third, Merkle processing requires tiny data to be sent over the network and stored on disks. We involved the Merkle tree in the list of transparency techniques due to its importance in traceability within a supply chain.

5.5. Zero-Knowledge Proof

Zero-knowledge proof (ZKP) [53] is an encryption scheme where service providers do not recognize the data stored on their servers. The Prover can prove that a specific statement is true to the other verifier party without revealing any additional information. It can be used in messaging, authentication, storage protection, and for any other sensitive information. ZKP can also be integrated with Blockchain and, more specifically, with the private Blockchain, so that whatever the number of Blockchain nodes, ZKP adds a robust layer of security to the data ledger. Integrating ZKP with Blockchain encourages the supply chain to increase its transparency level, while their data confidentiality is preserved [54].

6. Existing DLT-Based Supply Chain Solutions

The supply chain is essential to all businesses. Therefore, the integration of DLT into legacy industries and different stakeholders aims to revolutionize the global supply chain with decentralization features, smart contracts, and IoT technology. Currently, many DLT-based projects seek to acquire trust, transparency, collaboration, and cost/time-saving throughout their innovative DLT platforms. The authors in [55] listed all the 105 DLT-based projects integrated with IoT since 2008 and categorized them into four types without revealing their technical sides. Most of them consist of API interfaces run on Ethereum, the well-known global Blockchain, but they do not have explicit technical references or detailed publications. This section sheds light on the DLT-based supply chain projects and displays their technical parts while focusing on data transparency and traceability. Below are the intended projects that employ DLT in their supply chain:

- Dietrich et al. [23]: proposes an academic framework designed to tackle supply chain transparency by employing a new smart contract approach. The authors achieve their goals by following three steps. In the first step, the framework identifies and enlists all the partners involved in the manufacturing process. The first step is not an easy mission in a complex supply chain, but it is necessary to simplify the manufactured product's concrete process affiliation and composition. This framework assumes that each asset should have a unique identifier. Accordingly, a link is established between each physical asset and the Block-chain platform by generating smart contract's unique identification numbers. These numbers are called virtual identities or Hash'ID, where each one is mapped to a unique physical asset. Hash IDs can also refer to licenses, certificates, or other types of non-physical assets. They are attached to a bar-code form such as Radio Frequency Identification (RFID) or Quick Response (QR) code to link these numbers to the Blockchain. The proposal introduces two types of players in the framework, the supplier and the Certifier. The certifier's role is to assign certification to suppliers in order to create the Hash'IDs. Depending on the supply chain's characteristics, the Certifier's role can be taken over by the manufacturer and other independent organizations. In the second step, they logically attach all the supply chain processes logically into the Blockchain platform through the smart contract. Furthermore, the last step makes the final decision based on a multiple smart contract recorded on the immutable Blockchain ledger.
- Ambrosus [56] is an industrial project utilized to track products throughout their circulation in the market. It is a Blockchain-based supply chain dedicated mainly to protecting and controlling pharmaceutical and food quality. This platform solution is mainly composed of a customized version of Ethereum Blockchain integrated with a data storage solution named the interplanetary file system (IPFS). To avoid the high cost of running transactions on the central Ethereum platform, Ambrosus develops its independent customized version of Ethereum. Moreover, Ambrosus does not rely on Ethereum storage to store the supply chain data, as it is limited in capacity. Instead, it uses IPFS as the primary storage for their large transactions to provide scalability and high throughput for the clients. Ambrosus has advanced sensitive sensors to detect and analyze particular cases related to food and medicament. Ambrosus takes advantage of the Merkle tree in their transactional processes, since it is based on hash cryptography. With this tree algorithm, users can quickly find its data and filter out the wrong inputs. Two types of smart contract are introduced: the requirement smart contract describes quality standards directly compared to items inside the measurements' smart contract, while the measurement smart contract stores the list of ambrosus-certified devices, the root hash of the Merkle tree, and the collected attributes throughout the supply chain to note the variation in composition quality, if any. The Merkle tree data are uploaded periodically to the leading Ethereum network to assist users with further visibility and quickly achieve the tracking process. Ambrosus uses IoT hardware and sensors to tag products, therefore allowing goods

to be tracked through the supply chain and assuring the complete integrity of data comprehensions and transparency.

- Modum [52] is a supply chain for monitoring solutions, which controls the distribution of immense volumes of sensitive goods, especially pharmaceutical ones. It comprises the Ethereum network, the API applications, and a specific sensor called a modum temperature logger. Modum architecture is constituted of front-end and back-end phases. The back-end is composed of an Ethereum network, smart contracts, and a specific server, connected directly to the external users. The front-end is composed of sensors and mobile applications, connected to the HTTPS server in the back-end via REST API and JSON. The logger or SensorTag is the top added value used to measure the shipments' environmental conditions. In detail, each logger has a unique MAC address represented in the QR code, and each shipment has its unique QR, named "track and trace". Both QR codes should be scanned with the user's mobile applications and sent to the server. Once the combination of QR codes is received, the server broadcasts the smart contract and then stores the smart contract ID on the sensor. The client scans the "track and trace" code and requests the sensor's temperature measurements via Bluetooth low energy (BLE). The smart contract receives the data for verification purposes and sends a report back to the client's mobile. When using the smart contract, data authenticity is confirmed at every ownership alternation. The results of the evaluation are then immutably stored in as a proof-of-existence. Using the Modum technique, the data transparency is well-tackled, and there is no need to physically verify the product content.
- OriginTrail [51] is a supply chain solution composed of a combination of off-chain and Blockchain networks. It implements the off-chain network on DLT-based nodes within a new type of decentralized environment. The Blockchain platform runs on different nodes and interacts with the non-DLT network. The off-chain network, known as OriginTrail Decentralized Network (ODN), comprises data and network layers. Thus, the architecture is the stakeholders' applications, the non- decentralized ODN, and the platform. OriginTrail uses Zero-Knowledge encryption to prove private information without revealing it. Moreover, the smart contract is involved in the different off-chain nodes to guarantee the execution of a set of predefined conditions. The aim of using this platform is to store the data fingerprint, ensure the integrity and transparency of records and provide an immutable supply chain system.
- Vechain [57] is a supply chain solution composed of vechain supply chain projects and a vechainthor Blockchain-based platform. Vechainthor is an enhanced version of Blockchain, forked and improved based on the Ethereum codebase. The enhancements cover the transaction format in many directions. The new transaction format includes four fields: independent ID, DependsOn, Blockref, and Expiration. Thereby, the application deal with a single transaction instead of a bundle of transactions. Blockref provides more information about the previous, current, and next blocks. Furthermore, it provides information on the transaction creation time. This will be helpful for financial purposes in case of an acceptance delay, for example. An expiration is added to the transaction to avoid stacking for a long time. Multi-task transaction: a transaction is composed of many small transactions to address complex business payments. Vechain connects the technologies RFID, QR codes, Near-Field Communication (NFC), and bar codes to Blockchain to tag the items with a universally readable identity. The combination of new transaction fields and the IoT technology allows for the accurate tracing of the origin of items and prevents counterfeiting, since Blockchain records cannot be alternated or duplicated.
- Waltonchain [49] is a Blockchain platform designed to track the RFID-based transactions with multiple supply chain partners. It comprises a central network called the parent chain and many other sub-chains networks, which are connected and mined to the parent chain. A sub-chain works independently after being created and registered in the parent chain. The parent chain ledger contains only information related to

sub-chain details, while each sub-chain has its ledger. At any time, a sub-chain can be created and registered to the parent one. The parent chain runs independently of sub-chains, so it does not store the different sub-chains' data. The smart contract is the foundation of waltonchain that builds and maintains the underlying logic platform. Furthermore, it develops an RFID IC tag to be suitable for Blockchain applications. The supply chain sustainability and transparency are managed through the default Blockchain Ethereum platform and the IoT enhancements that help collect accurate data.

- Devery [58] is an open-source protocol based on the Ethereum network, used to build applications for verification purposes where retailers can assign unique signatures to their products. These signatures are stored on Ethereum and used to verify a product throughout the application queries. Devery protocol consists of three data structures, which interact with Ethereum through DeveryRegistery.sol and DeveryTrust.sol smart contracts. The data structure is based on the registration of a product public key with an application's unique identifier. The hash of the product information determines each product's identifier and allows for a lookup via a check method. Devery uses the Entry Verification Engine (EVE) token for payments and charges. The application consumers must pay the application host for the product verification service using Bokky's Token Teleportation Service' (BTTS), which does not permit consumers to directly deal with EVE or gas tokens. This protocol allows for supply chain verification throughout the Blockchain smart contracts without directly interacting with the decentralized environment. This protocol enrolls the transparency over applications by referring to the default Blockchain features.
- CoC [59] refers to "Chain on Blockchain", a supply chain management platform based on hybrid Blockchain to mainly tackle the trust issue of multiple entities. In general, in an authorized network, some nodes are promoted for block creation and validation. CoC distinguishes between the record submission and block-building using a hybrid model to organize the underlying distributed ledger. Submitted records are limited to users, third-party users, and supporting entities only, while building blocks are opened to the public users, named helpers. CoC invented an approach to build a distributed ledger called "Two-Step Block Construction" within their hybrid platform. Step 1 is the generation of reservation blocks by users, and step 2 is to generate data blocks. In step 1, a user submits a request to reserve predictive blocks. The request includes requester information, the fee the user wants to pay for the block, the helper's identity and who creates it, and other essential information. The helpers have to reach a consensus to reserve the block. In step 2, the user uses their reserved block(s) to send data to the ledger. There is no proof-of-work computation effort for the reserved block in this step, since helpers already validate it at the reservation time. The two-step block reservation does not reduce the latency for the overall performance. It provides a mechanism to shift the latency as long as a user has enough reservation. The latency of adding a new supply chain record can be very low. In short, CoC proposes a new DLT hybrid mechanism, but in terms of transparency, it relies on the embedded Blockchain features only.
- Shipchain [60] is a fully integrated system of the entire supply chain that enables tracking shipments from the moment of leaving the factory to the final receiver doorstep. It is based on Ethereum Blockchain using side-chain and smart contract techniques. Records are stored on the Ethereum network, while the side chains can be used by organizations to store and validate their data on their own for cost-saving. Thereby, data is fully decentralized, and located in either Ethereum main ledger or side chain ledger where no mediator is engaged. Additionally, Shipchain contains a web platform that enables shippers to connect directly to carriers without passing the traditional brokerage model. Although the smart contracts run on the Ethereum network, they can be duplicated and operating on Ethereum forks (ShipChain protocol) and used by side-chains for cost-saving. As a result, each shipment has a unique smart contract

that gives shippers more visibility across their supply chain, allows carriers to communicate quickly reducing delays and miscommunications, and achieves the overall required transparency.

- Aqua-Chain [61] is a traceable system for the water supply chain management based on Blockchain and can be implemented by either Ethereum or hyperledger Blockchains. The data transparency is guaranteed, since IoT devices collect data along the supply chain and store them within the Blockchain ledger. Therefore, Aqua-chain software is adapted to provide full traceability to their customers under the classical notion "from-supplier-to-buyer." It is composed of a layered architecture that relies on Blockchain and IoT to achieve traceability. Aqua-chain can be integrated into existing traditional systems such as ERP and CRM. The front-end layer is composed of API REST applications that can easily be integrated with other software. The middle layer is called the controller. It is responsible for transforming the high-level function call into a low-level Blockchain call, and vice versa. Aqua-Chain enables integrating IoT and DLT technologies, and creating transparent, fault-tolerance, immutable and auditable records that can be used for the water traceability system.
- Tael (WaBI) [50] is a decentralized application that permits creation a secure link between Physical and Digital assets through RFID labels with anti-copy functionality. It is independently installed on the user mobile so that they can authenticate their product via mobile app. The user is incentivized through the mining represented by the scanning process, where they perform proof-of-purchase for every scan. Wabi refers to the Walimai organization and supports the "Walimai label," which is applied at a designated point of origin along the supply chain. The registered products under the "Walimai system" consume WaBI tokens. The Walimai label technique provides transparency by being attached uniquely and securely to the product throughout its journey to the consumer. Linking physical products with a unique encrypted code allows the consumer to scan its unique code via mobile applications to check the physical product against its digital state.
- TE-FOOD [62] represents one ecosystem that integrates all food partners (farmer, producer, transporter, and consumer) equally, for successful farm-to-table food traceability, to fight against food frauds and mistrustful supply chains. TE-FOOD introduces a utility token called TFD, Blockchain protocol, smart contracts, plastic security seals, and RFID identification tools. Two types of Blockchain are involved in the progress: the public Ethereum used for the payment process with a TFD token and a private Blockchain to store the transactional data. Accordingly, supply chain companies must have two wallet types: a wallet on the Ethereum network, which can be accessed directly or through the TE-FOOD mobile app, and the transaction wallet on the private network, which TE-FOOD can access The public Blockchain mediates the consumers and the suppliers' private Blockchains. The consumer buys traceability services via the public Blockchain to track its product from different suppliers. TE-FOOD deposits then the purchased transactions to the suppliers' wallets. The contribution of this project can be seen as "traceability as a service", where achieving transparency is an investment for suppliers;
- Cargox [63] is a decentralized solution involved in global transportation, which is implemented on the Ethereum Blockchain. It tackles the bill of lading documents and avoids the supply chain's logistic trading. Users interact through the API of the dApp to create their smart bill of lading. They can either consume cargo token "CXO" directly or utilize the USD/CXO conversion mechanism. Since dApp, based on the public Ethereum with a smart contract enabled, participants can benefit from the DLT transparency feature. Thus, exporters, carriers, importers, or any other parties involved in the transportation, can use their mobiles to manage the shipments. Cargox emerges a full dApp, which allows the carrier to initiate the smart bill from scratch. The carrier sends the bill to the exporter's address once the latter pay the shipping costs, and transfers the bill's ownership to the importer after paying the price of goods.

The importer claims ownership of the goods at the destination port, using the smart contract technology embedded with the dApp. The Cargox dApp empowers users to create smart bills quickly. Besides this, only the involved parties can read these documents, which enforces transparency along with global trade;

- CargoCoin [64] is a decentralized supply chain platform based on the Ethereum network, which aims to encapsulate all types of transport cargoes into a single platform, then connect it to the traders of goods. The services' platform and the smart contracts are both utilized within the platform to achieve this objective. The platform offers a range of communication channels between the partners involved in the supply chain process, providing a method of sending, receiving, rejecting, approving, or signing documentation. CargoCoin introduces smart utilities represented by smart contracts and payments to provide a transparency advantage to the EcoSystem participants and save time and money. The participants, including shipper, carrier and consignee, interact and set terms and conditions using the same decentralized platform;
- ProductChain [65] is a consortium Blockchain, introduced to enhance the traceability of the food supply chain (FSC), taking into account the speeding up the transaction rate into less than one second. It mainly relies on a three-tiered sharding architecture to improve scalability and ensure data availability to consumers. It also introduces the Access Control List (ACL) to limit access to competitive partners, collectively managed by consortium members, and provides read and write access. In addition to its improvement over scalability, it introduces transaction vocabulary to store different types of information and interactions, which encompass all FSC processes. The transaction vocabulary can link the final product to multiple raw ingredients relevant to a broad range of SCs. Productchain enhancements provide data transparency so that a user can quickly trace it back to specific key ingredients and a consortium-governed access control, which guarantees that no participant controls the Blockchain;
- Bext360 [66] is a supply chain platform used to enhance the global food commodities and provide full transparency from farmer to table. It is a software as a service (SaaS), which integrates Blockchain and sustainability measurements to provide a traceable fingerprint from manufacturers to consumers. It runs a RESTful API that allows retailers and wholesalers to insert the technology into their websites, point-of-sale systems, or supply chain management tools. The SaaS platform allows each stakeholder to track food products independently throughout each phase of their supply chain and enhances its overall transparency;
- FarmaTrust [67] provides a robust cloud-based platform to track pharmaceuticals through a supply chain that links digital systems to pharmaceuticals moving in the physical world. It is based on Ethereum Blockchain with a POA consensus algorithm to enhance the scalability. The FarmaTrust platform named "Zoi" is shared among the global community, including suppliers, logistics and shipping companies, wholesalers, distributors, pharmacies, and hospitals. This global network uses the FamraTrust platform to ensure data transparency to ensure that medicines and related medical products are genuine. As a final step toward complete transparency, the consumer is allowed to use the FarmaTrust mobile app to verify the product's authenticity via a QR code scanner;
- BlockGrain [68] is an agriculture supply chain that allows farmers, brokers, and companies to track the path of grains from the place of harvest to consumer destination. It is a decentralized platform using Ethereum Blockchain for the agriculture supply chain. It is structured into three layers: public Blockchain, Private Blockchain, and applications. The main data, smart contracts, and transaction Agri tokens are stored on the public Blockchain, while buyers use the private Blockchain to reduce the transaction costs and waiting times associated with the public. Both Blockchains are managed through the BlockGrain Platform (Applications Layer). BlockGrain automates the delivery process end-to-end. The data are collected and stamped

at each point, along with the product circulation. Using this process, BlockGrain increases visibility and improves transparency;

- ZERO defects [69] is a platform specialized in creating digital twins through an innovative investigative framework for traceability purposes, detecting and mitigating defects early during the production. It is a data acyclic graph (DAG)-based platform managed by the IOTA Foundation with the collaboration of Pickert (an ISO-certified company). DAG is an alternative DLT technology of Blockchain. It has good adaptation with high incoming data loads, and has nominal transaction fees and computation. As a decentralized application, the IOTA platform enriches Zero defects with full transparency and visibility for its board's immutable records. With Zero defects, each product is identified using its unique serial number, which is immutably stored and accessible in the IOTA Tangle;
- Blockverify [70] is an anti-counterfeit Blockchain-based solution for luxury supply chain items. Blockverify tracks each product, which has a unique special tag along the supply chain, where the customer itself determines the transparency level. Blockverify consists of public Bitcoin and an authorized Blockchain to successively store public and private information within the public and private ledgers;
- Chronicled [71] is an industrial supply chain project to gain trust and automation among companies by integrating the Mediledger network. The MediLedger Network combines a secure peer-to-peer messaging network and a decentralized Blockchain network as the ultimate transparent bridge between trading partners. It uses smart tags and the Chronicled App to track the physical products and link them to Blockchain using "identity inlays and tamper-evident cryptographic seals". A Smart Tag is a cryptographically secured chip containing details about the physical good and linked with a private key, which guarantees additional data transparency among all involved parties;
- Everledger [72] comnis a Blockchain platform specializing in protecting the integrity of worthy products, such as diamonds, based on a hybrid Blockchain system. It uses hyperledger as a private Blockchain and Ethereum as a public Blockchain to focus its target on the immutability of the diamond transaction history rather than the system scalability. Everledger combines artificial intelligence (AI), nanotechnology, and IoT to create a digital twin of every single product. This technique provides a secure and permanent digital record of an asset origin, characteristics and ownership. This technologies combination enhances transparency along customer supply chains to enable traceability in a secure, immutable and private platform;
- Fr8 [73] is a supply chain network that aims to modernize logistics with an improved solution for the industry in general, leveraging Blockchain technology at its core. It is based on coupling shipment tracking IDs, RFIDs, and other documentation to create meaningful relationships among multiple datapoints. The Fr8 protocol is composed of five layers. The transport document layer contains the data and metadata of a shipment. The permission & ID Layer manages data integrity and permissions. The interface Layer exchanges data between the document layer and the service Layer. The service Layer connects the Fr8 Protocol with applications. The application Layer works with services and interface layers to display the data. To ensure transparency, Fr8 relies heavily on the Blockchain principle as a single source of truth for shipment data. All of the involved stakeholders will have unprecedented visibility into shipments and their associated data;
- NextPakk [74] is a delivery service that tackles the last mile issues based on Stellar's Blockchain due to its speed and scale. It allows customers to schedule delivery within an hour at home when the package arrives. Furthermore, NextPakk uses Blockchain technology to track packages while protecting customer identity and ensuring a punctual delivery This adds transparency to the delivered goods, where customers can instantly track their packages online. Nextpakk involves Blockchain in elaborating

the entire last mile, so that the consumers can track the driver and obtain complete transparent information on their packages' exact arrival time.

7. Discussion

Production stakeholders seek collaboration to optimize the supply chain processes and maintain robust relationships with trading partners. Collaboration among different independent systems challenges the supply chain partners, as there is a broad range of collaborative initiatives, disparate communications, and numerous levels of trading competencies and business processes. A collaborative supply chain requires suppliers and sub-suppliers to share data within a fully transparent environmental media to entirely realize the benefits of collaborative business. Before Blockchain, one of the well-known methods used to achieve transparency is called one step up, one step down. Many supply chains use this principle for traceability purposes [75]. This principle requires each supplier to share their information between the other adjacent ones. In other words, it is a chain of shared information where each supplier receives enough information on the incoming commodity, and then they thoroughly deliver the complete information to all the involved suppliers. It is a neighboring process for actors to share the information among themselves. However, this method is limited to two strides of visibility and, therefore, the transparency is not fully achieved. Furthermore, FarmaTrust [67] finds that technologies, such as holographic tamper-proof labels and unique serial numbers, are not sufficiently effective within the current centralized supply chains. In addition, the challenges mentioned in Section 3 necessitate the intervention of a decentralized Blockchain, coinciding with the development of many other technologies, such as IoT and others. Certainly, Blockchain is a quantum leap toward a new supply chain concept. The new supply chain data are collected differently and added to the decentralized chronological system, which is immutable, anti-counterfeit, transparent, and trusted. Nevertheless, as transparency represents the core of a successful supply chain, what else can be done to the standard traits of any Blockchain network?

We have previously mentioned various solutions targeting the modern supply chain improvements integrated with Blockchain, which enriches the system with trust, transparency, and traceability. These projects integrate the Blockchain within their platforms to overcome the trust issue at the first stage and obtain the other DLT systems' added values. Besides the excellent facilities of Blockchain, the listed techniques in Section 5 are used/introduced by several projects, and they are implemented in various ways to achieve more flexibility in data transparency and traceability. Table 3 shows that these projects' techniques are used to enhance product traceability and data transparency. Referring to the above classification, the most utilized techniques involve IoT device and the smart contract. Most of the projects use these two techniques differently based on their requirements. IoT technology is often used for tracking and tracing items using technologies, such as QR codes, smart tags, RFID tags, NEC, and mobile applications. Moreover, there are some additional IoT devices which are essentially constructed for supply chain transparency purposes. Some projects utilize the smart contract as it was programmed with Blockchain, such as Ethereum. Furthermore, the smart contract is developed to ensure the transparency of off-chain networks outside the Blockchain environment. Some smart contract enhancement tools are represented by assigning different roles or defining multiple smart contracts within the same project, such as setting the standard requirements and measurements of Ambrosus [56]. The Merkle tree algorithm is a technique used to quickly and accurately filter out the wrong data inputs using the crypto-hash functions. The zero-knowledge proof is used to protect sensitive data and enhance transparency. At the level of Blockchain core improvements, one of the techniques used is changing the Blockchain transaction format to include additional fields, which enhance transparency and facilitate traceability.

Table 3. Transparency techniques of supply chain DLT-based Projects.

Project Name	Transparency Technique	Tool
Ambrosus [56]	Merkle Tree Algorithm	Hash-based data structure
	Smart contract	Measurement and requirement smart contracts
Modum [52]	IoT device involvement	"track and trace" QR code
	IoT device involvement	Modum temperature logger
	Smart contract	Normal utilization
Vechain [57]	Blockchain core improvement	Block transaction format (ID, DependsOn, Blockref)
	Smart contract	Normal utilization
Chronicled [71]	IoT device involvement	Smart tag (cryptographically secured chip)
WaltonChain [49]	IoT device involvement	RFID tag IC
	Smart contract	Manage parent chain and sub-chains contracts
Devery	Smart contract	Smart contracts for registration and verification
OriginTrail [51]	Smart contract	Off-chain utilization
	Zero-Knowledge Proof	Sensitive data protection
Cargocoin [64]	Smart contract	Normal utilization
Bext360 [66]	Smart contract	Normal utilization
Shipchain [60]	Smart contract	Normal utilization
WABI [50]	IoT device involvement	RFID cryptographically secured chip
TE-Food [62]	IoT device involvement	Plastic security seals (1D/2D barcodes)
	Smart contract	Normal utilization
FarmaTrust [67]	Smart contract	Normal utilization
	IoT device involvement	QR code scanner via mobile SMS/voice label code on traditional mobile
ProductChain [65]	IoT device involvement	Transaction vocabulary
BlockGrain [68]	Smart contract	Public/private Blockchain managment
Zero defects [69]	Blockchain core improvement	IOTA DLT platform
Everledger [72]	IoT device involvement	Inteliggent Labelelling: RFID, NFC
FR8 [73]	IoT device involvement	Combines RFID, ID, product information

The DLT integration with the supply chain radically solves the data transparency and provides end-to-end traceability, with clear visibility of all the platform components. Moreover, some of these projects employ extra efforts and propose an additional layer of transparency. They target data traceability, by introducing mechanisms with added values over the current Blockchain features. Different enhanced tracking methods are deployed, ranging from involving new sensors to tags and tracers, as shown in Table 3. Vechain and Ambrosus are notable projects, which employ different methods. Ambrosus takes advantage of the Merkle tree in their transactional processes, since it is based on hash cryptography. With this tree algorithm, users can immediately find their data and filter out the wrong inputs. The tree algorithm can also be used with other IoT devices or mobile scanner applications that distinguish between massive Blockchain records. In other terms, it enhances the tracing function of the supply chain and speeds up the transparency process. Vechain is moving towards the improvement in the core of Blockchain for additional service refinements. This modifies Blockchain's transaction format by defining new fields: ID, DependsOn, Blockref, and Expiration for each transaction. From a logical standpoint, the Vechain proposal can be commonly used within any DLT-based supply chain. The new fields of vechain can be classified under tracking parameters that can be used with any DLT platforms without challenging their functions. These parameters improve the data transparency and aid in the perfect traceability achievement.

7.1. IoT for Transparency Enhancement

The importance of IoT integration with Blockchain to enhance supply chain transparency and traceability rises with IoT technology development. The IoT devices' prominent features are represented by collecting accurate data, quick adaptation, and always-on availability services compared to traditional manual methods. Under the current central structure, IoT experiences the difficulty of achieving a genuine cooperation because the relevant parties of such cooperation often belong to different suppliers with complex or uncertain trust relationships. Therefore, the collaboration of the current IoT devices can only be employed in a trusted environment. As a technology that offers the service of trust, Blockchain can ensure the authenticity of data on the network. IoT ensures the true effectiveness of information when uploaded from the original source. The combination of IoT with Blockchain opens up a road of innovation, with unlimited possibilities. It can be used primarily to track the history of different goods. Thus, IoT technology is essential for new business systems. Furthermore, the IoT helps to establish a harmonious relationship between Blockchain and the world, as IoT devices are the physical interfaces that collect data. In addition, the IoT technology can reduce the disturbing factors from the source to ensure the data's actual effectiveness. Mainly there are five IoT techniques involved in the industrial field [34]: RFID, wireless sensor network (WSN), middleware, cloud computing, and IoT software. In contrast to human abilities, IoT techniques assist producers in collecting data accurately, such as perceiving temperature variation, calculating the elapsed time, and the color degree [76].

Many projects enforce the transparency of the supply chain by introducing the IoT technology within their projects, as illustrated in Table 4. Each project utilizes this technology differently. Waltonchain is directly related to the inventor of RFID technology. It introduces an enhanced RFID version for a Blockchain-based supply chain that provides tamper-resistance, reliability, anti-counterfeiting, and traceability to the business system. Thus, in addition to Blockchain features, the Waltonchain project includes an RFID tag IC and reader IC, appropriate for Blockchain applications. The ICs are characterized by integrating an elliptic curve and decryption acceleration module based on the existing RFID technology and a communication interface protocol for Blockchain applications. Waltonchain solves major IoT problems in Blockchain-based applications. It exempts tags from data storage and limits its responsibility to signature verification. Tags automatically generate random public keys private keys to ensure that the IoT application tag is unique, authentic, and tamper-resistant. Thereby, tags can reduce the amount of information stored to solve overload with large amounts of data in IoT applications. Moreover, tags solve the problem of slow encryption and decryption in asymmetric encryption technology. Modum fabricates another RFID IoT device called Modum logger temperature. The logger is an IoT temperature sensor designed for medical products that do not require active cooling during transport. During the shipment process, the monitored temperature is stored in the logger memory. Using Bluetooth technology, the shipment can be checked without opening it. The results of each evaluation are stored in a smart contract inside the immutable Blockchain. This combination of IoT, Bluetooth and smart contract demonstrates that drugs have not been exposed to conditions which may compromise their quality and integrity. Vechain upgrades the chip layer of a traditional IoT component by adding personal identification with an asymmetric key algorithm. It generates random IDs of 20 bytes, hashes and transforms them into In this way, every IoT equipment is defined by a unique ID and asymmetric key. These IDs are managed by smart contracts and permanently stored on the Blockchain. Different technologies can be used to achieve the same goal. Wabi and Everledger are both interested in linking digital and physical assets through IoT and Blockchain. However, they use different IoT tag devices.

Table 4. IoT-enabled DLT-based supply chain projects.

Project	IoT Technology	IoT Role	Technology Base
Modum [52]	Modum temperature logger	Trace drug temperature instantly	Smart contract and BLE
WaltonChain [49]	IOT-RU20 (RFID tag IC and reader IC)	Upload data direct to Blockchain and realizes Anti-counterfeit	UHF Android Smart RFID Reader/Writer
Vechain [57]	Encrypted chips tag technology development	Monitor and trace	Adds ID and asymmetric keys to IoT devices
Wabi [50]	Walimai	Links digital and physical assets through RFID labels	Secure RFID label Authentication is done through mobile consumers
Everledger [72]	Intelligent Labeleing	Links digital and physical assets through RFID, NFC,	NFC, RFID beacons, and synthetic DNA

7.2. Smart Contract for Transparency Enhancement

The complex manufacturing networks' structures challenge the supply chain transparency and affect the overall collaborative system. The smart contract can reasonably tackle the transparency gap and organize the collaboration. In addition to its central role in drawing legal contracts among Blockchain members, a smart contract enforces the tracking and monitoring of the content of the intended product's data. Some of the Blockchain-based supply chain projects listed in Table 3 use smart contracts for transparency enhancement purposes. They integrate it differently, based on their infrastructure needs. In [23], a smart contract is used for transparency by proposing a framework that interconnects the smart contracts and the manufacturing supply chain' assets. In this proposal, each asset is assigned a unique identification number by generating a particular smart contract stored on the Blockchain. Therefore, the Blockchain ledger can be seen as a database of timestamps that offers anyone the ability to notice that a certain thing has occurred. Ambrosus involves smart contracts in a novel way by introducing two types of smart contracts: measurement and requirement. All the assets and standards are periodically used in the measurement contracts, and the smart contract requirements determine whether a product continuously meets the standards defined by an interested participant in the network. In this framework, the smart contract is utilized as a new protocol to set quality standards and compared directly to the Measurements Smart Contract items. Vechain uses Ethereum virtual machine (EVM) with additional extensions on the contracts called built-ins. It has six smart contract extensions for further data reliability.

Generally, the complexities of attaining transparency are caused by the stakeholder's incompatibility in rules and conditions, leading to difficulties in reconciling transparency requirements. The partners experience the obstacle of not revealing private data while attaining intended transparency. The smart contract is a trusted tool that plays a significant role in achieving transparency and some data privacy. All regulations, rules, and conditions related to different supply chain partners should be collected at the first step to identify the risks and goals. Hence, a smart contract transcribes/records and stores all the regulations, conditions, and risks on the immutable Blockchain ledger. It is committed to executing the partners' recommendations by literally and intelligently following their predefined code content. The smart contract can then help achieve the planning requirement, and can assist it in reaching its targets successfully. Coupling smart contracts with IoT technology interacts directly with the sensors to ensure precise execution. The registered data represent a source of trust for all partners, since it is recorded on an authentic ledger. Finally, the decisions to expose data are taken through a dynamic and trusted platform, considering all the supply chain' network complexities.

7.3. Transparency Versus Opacity: Access Control

In addition to the above-mentioned technical limitations, there are further obstacles that would affect the ability to achieve full transparency. Full (uncontrolled) transparency goes against the opacity and privacy required by stakeholders that intend to hide sensitive information such as plans, cost, secret ingredients, etc. In a Blockchain-based supply chain, and since its introduction, Blockchain ensures the use of multiple keys for signing transactions so that, each time, a new key is generated and used once. This method protects user privacy on the cryptography level. However, it requires an advanced method to enable parties to customize their transparency and opacity levels based on their requirements and regulations. For example, some sensitive data are shared among partners/companies only for collaboration purposes in a supply chain. Thus, the decentralized platform is requested to protect such data from leakage and provide certain opacity using access control. At this level, questions are raised about the effectiveness of the aforementioned techniques on transparency control. How can we mitigate the gap behind Blockchain data transparency and obtain access control?

In this context, the fully decentralized system (public Blockchain) prevents partners from controlling their data as if it were in the centralized systems. This inability to control opacity leads the partners to prefer the private Blockchain to the public one, knowing that the latter is much more recommended for the global supply chain. Hence, there is a need to accomplish the access control feature within the global Blockchain. Table 5 depicts the techniques' impacts on the transparency access control, their advantages, and limitations. Starting with the public Blockchain, the ZKP promises to preserve their privacy, encouraging them to go public. Other cryptographic proposals would also have a large impact on data privacy, such as homomorphic encryption integrated with Blockchain [77]. These algorithms protect privacy and advance public Blockchain usage. However, they have a medium impact on data transparency and opacity control. The Merkle tree technique facilitates traceability without exerting a significant impact on the control side. Regarding transparency, smart contracts and IoT techniques can significantly provide access control if employed precisely. The recent projects listed above, which investigated smart contract development, ignore the transparency access control and concentrate on their functionality part only.

Table 5. Current techniques impacts on transparency access control.

Techniques	Transparency Access Control Impact	Benefits	Limitations
Zero-Knowledge-Proof	Medium	Ensure privacy in public Blockchain and encourage merging supply chains	Unable to recover lost user credentials
Merkle tree	Medium	Facilitate extract and tracking data	Hash collision and overhead syncing
Blockchain core improvement	Low	Facilitate the access control in case of improving transaction format and roles	Have no direct impact unless the improvements become related to data transparency
Smart Contract	Very High	Apply conditioning access control and automate the traceability process	Complexity in a scalable environment
Involvement of IoT devices	High	Rapid data correlation and facilitate automation	Unable to be managed in a vast centralized system

To satisfy both transparency and opacity requirements, a hybrid Blockchain is an appropriate solution to regain partners' confidence in the supply chain decentralization. On the one hand, partners are able to run and store their sensitive data off-chain, thus achieving opacity. On the other hand, partners could publish different data to the Blockchain to ensure transparency. In addition, a hybrid smart contract [78] was recently proposed, which permits the control of off-chain data and lets partners build smart contracts that cover both on-chain and off-chain data.

7.4. Summary and Open Issue

As a result of these analyses, the Blockchain offers an attractive embedded transparency feature to the entire supply chain and improves the overall processes. Furthermore, the techniques presented in this paper assist in the achievement of further transparency and support supply chain actors in building their platforms. The current Blockchain-based supply chain solutions lack transparency access control. Thus, restructuring their platform is required. The techniques that could be used are very different: The smart contract technique has the highest impact on transparency access control. The IoT technology integrated with smart contract automates the traceability process to enhance transparency and reduce the overall risks. Besides, other cryptographic techniques, such as the ZKP, encourage enterprises to accord with the public Blockchain while conserving their privacy. This technique may drive the adoption of open supply chain platforms in the future. Any supply chain planning to move into Blockchain could pass through the above policy enforcement steps for the required validation to recognize the best-fit Blockchain type and techniques. After this, it can explore the techniques mentioned above that fit its requirements. Nevertheless, the data transparency topic still takes considerable effort. The aforementioned projects lack transparency standards to manage and organize the data transparency requirements within the new DLT technology. This paper aims not to prompt actors to choose between different projects (like Vechain, Ambrosus, OriginTrail, etc). Instead, it sheds light on the available techniques and drives stakeholders to integrate more techniques in different ways to mitigate the gap behind the transparency concerns of the new introducing DLT-based supply chain. Another goal is to highlight the transparency access control topic and its influence on the decentralized supply chain projects. The analyses highlight the open issue related to inventing more tools to improve transparency in general, and specifically to advance the progress in the transparency/opacity access control.

8. Conclusions

This work highlights essential questions related to the Blockchain-based supply chains' data transparency. It considers the transparency challenges, the DLT transparency techniques, and additional measures that can be employed. Accordingly, the existing projects are presented with their adopted techniques. It is noted that some of them implement standard Blockchain features, including transparency and traceability. However, some other projects exploit additional techniques to enhance transparency and satisfy their requirements. We highlight these techniques and analyze them to investigate their impacts on a Blockchain-based supply chain. IoT technology and an advanced smart contract are the most-used techniques to achieve more transparency, as well as what Blockchain provides. Few projects use alternative methods, such as involving cryptographic tools like Merkle tree and zero-knowledge. We conclude that further enhancements are needed to achieve the required data transparency in the supply chain and to control unlimited access to sensitive data according to the opacity requirements.

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How Useful Is a Distributed Ledger for Tracking and Tracing in Supply Chains? A Systems Thinking Approach

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Abstract: *Background*: The use of blockchain technology for tracking and tracing (T&T) in supply chains is the subject of lively debate in scientific literature. However, distributed ledger technology (DLT) does not have to have the characteristic blockchain structure and often performs better without such a structure. Generalized DLT for T&T in supply chains has rarely been discussed in the existing literature. *Methods*: This article presents an exploratory case study research of eight companies to identify the main goals, and problems that the companies have when they engage in T&T. This practical perspective is complemented by a theoretical systems thinking perspective. Based on these two foundations, we discuss the usefulness of blockchain technology and, more generally, DLT for T&T in supply chains. *Results*: Based on our analysis, DLT is only necessary in special cases, e.g., when the owners of the data have an interest in deleting the data, but the data stakeholders do not. In the other cases examined, DLT competes with other technologies, such as conventional, centralized databases in combination with digital signatures. Furthermore, it became evident that DLT can only be useful for supply chain tracing. The technological features of DLT do not provide any benefit for supply chain tracking, i.e., the timely communication of the status of a physical good. *Conclusions*: Distributed ledgers often have a disadvantage in that they are very complex and, therefore, expensive. DLT should preferably only be used when it is technologically necessary or the simplest/cheapest choice, which is probably not all that often. Finally, the usefulness of distributed ledger technology and its integrated smart contract technology is highly dependent on how easy it is to link the real physical world to a digital record/contract in an error-free and tamper-proof way. Currently, such a definite link exists only in very few cases and is often impossible.

Keywords: logistics; supply chain; blockchain; distributed ledger; tracking; tracing

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1. Introduction

1.1. Research Context

A popular topic in the context of blockchain and distributed ledger technology (DLT) is tracking and tracing (T&T) in supply chains (SCs) [1].

Supply chains are product-related, cross-company value networks. Figure 1 provides an overview of some supply chain characteristics that are important in the context of this paper. A typical supply chain consists of many different bilateral or trilateral business relationships. The number of companies involved in a single transaction is usually small. However, even a small supply chain is often extremely complex. It is not uncommon for several hundred to several thousand companies to be involved in a single end-to-end product supply chain.

The term supply chain management (SCM) describes the cooperative planning and control of these value networks with the goal of increasing the competitiveness of individual supply chain actors and the entire supply chain [2]. Tracking and tracing plays a vital role in this context. The hardware used for T&T is an important primary source of information, and the software utilized for this purpose merges many different T&T information streams so that companies can use them for planning and control.

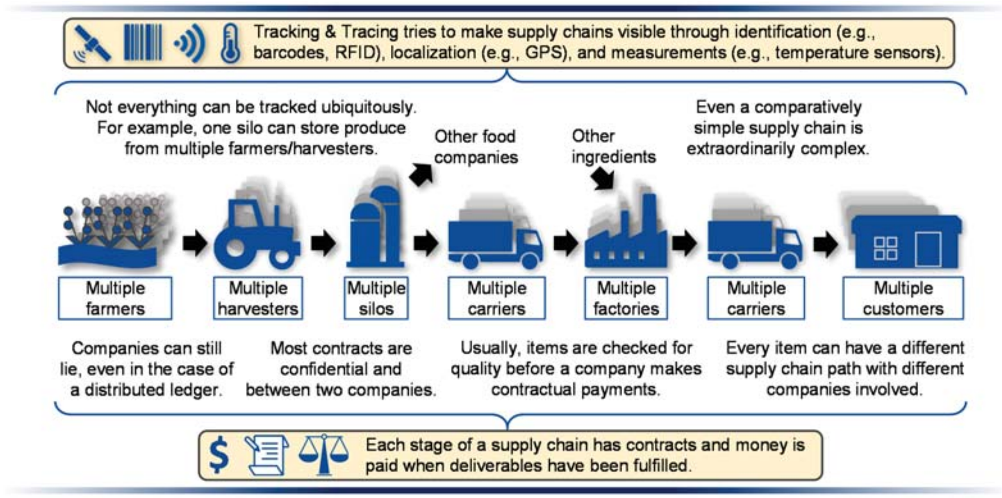

Figure 1. The structure of a supply chain system; illustrated by a simple food SC example.

In a narrow sense, "tracking" in supply chains refers to tracking the state (e.g., location or temperature) of an object (e.g., item, pallet, truck, or person) in real time or based on milestones. In a broader sense, tracking is not restricted to physical objects. Instead, one can also track metrics, statistics, property claims, and so on, which can be derived from tracking data (e.g., the quantity of inventory that is available) [3]. Based on this up-to-date information, operational decisions can be determined to efficiently manage supply chain operations (e.g., coordinate inbound logistics).

"Tracing" refers to storing tracking information for a specified time in such a way that it can be retrieved, for example, as part of an audit or a performance report [3]. Thus, tracing forms an information basis for medium- to long-term management decisions, such as process optimization projects. Furthermore, tracing can be used to resolve disputes regarding transactions within a supply chain. In addition, some laws even mandate tracing in supply chains (e.g., temperature measurements for pharmaceutical drugs).

Thus, depending on a company's goals regarding T&T, some technologies are more important than others. For some goals, T&T hardware is more important than software; sometimes database technology might be critical, but sometimes it might be of secondary importance. In addition, it is essential to note that if a company can choose among several technologies, then a decision for or against a specific technology is an economic decision. Depending on the situation, a company may opt for a T&T solution with a centralized database or for DLT; however, this does not necessarily have to be a blockchain [4] (p. 950).

1.2. Research Gaps

Many research articles regarding blockchain and distributed ledger technology have the following structure [5]: First, the properties of the studied technology (typically a blockchain) are explained. Building on these technological properties, a subsequent discussion is presented concerning how these properties might be useful in a supply chain context. While this approach has its merits, it also has its pitfalls. For example, *Verhoeven et al.* researched pilot projects and they found that many blockchain use cases that are contemplated in logistics and supply chain management lack mindful use principles [6]. *Van Hoek* calls this "(. . .) a degree of 'a solution looking for a problem' surrounding blockchain use cases" [7] (p. 115). *Verhoeven et al.* conclude: "The data associated with each case showed shortcomings in addressing specific challenges and only vaguely referred to the blockchain's role in solving these problems. However, more than once it looked such as the source of the problem was not on a technological level and, therefore, could not be addressed by blockchain technology (. . .)" [6] (p. 17). Other researchers have expressed the same sentiment [4] (p. 949). It could, therefore, be argued that the typical approach (i.e., to brainstorm problems for the solution "blockchain") is not ideal. As pointed out by the cited authors, there is a risk that the supply chain (process) context is lost.

We, therefore, take a different angle, which we believe is currently underrepresented in the literature. In the first step, we focus on the goals and problems relevant today in the practice of T&T in supply chains. We perform this explicitly in a general way, independent of the specific characteristics of blockchain and DLT. This allows us to avoid falling into the trap of treating blockchains and DLT as 'a solution looking for a problem'. Instead, we aim to produce a systematic problem description, which can then be used to analyze in which areas the Blockchain and DLT can actually help. Interestingly, there is little existing literature describing T&T requirements in business practice. The authors of [8] and [3] develop a holistic T&T definition based on a literature review and case studies, respectively. The authors of [9] give an overview of T&T technologies (e.g., GPS trackers) and [10] discusses the information systems perspective. However, these studies are descriptive in nature and aim to describe/define T&T. They do not focus on an analysis of the goals and problems companies have when they use tracking and tracing in supply chains.

Building on our systematic problem description, we compare blockchain and distributed ledger technology with other database technologies with which they compete. The evaluation of alternative technologies is important, especially in an economic context. On one end of the extreme, there is a simple centralized database and, on the other end of the extreme, there is a public permissionless blockchain. In between, there are several different database technologies (e.g., digital signature technology, non-blockchain DLTs, permissioned blockchains) with gradually different characteristics. Some of these 'in-between' technologies have often been neglected in the existing literature, despite them being potentially highly relevant in practice [11].

The terms *blockchain* and *distributed ledger* are sometimes used interchangeably. In this article, however, we want to draw a clear distinction between the larger set of distributed ledger technologies and the subset of blockchain technologies (please note that for this article, when we speak of blockchain(s) technology, we always mean blockchain-based ledgers). Blockchains have a very specific data structure that is necessary for the functioning of certain consensus mechanisms such as "proof of work". Distributed ledgers, on the other hand, can use completely different data structures and consensus mechanisms. A distributed ledger can be generally equated to a fully replicating database network with multiple parties [12]. However, the name "ledger" additionally implies the crucial property that existing data may not be changed or may only be changed under strict conditions.

There is already a fair amount of literature on T&T and blockchain technology, but explicit attention has rarely been given to the larger set of DLT. A *Web of Science* search using the search query TI = (* blockchain * AND (* track * OR * trace * OR * provenance * OR * visibil * OR * authen *)) produces 376 results. The same query with the term "* distribut * AND * ledger *" instead of "* blockchain *" yields only seven results (20 May 2021). Blockchain technology has received a considerable amount of attention during recent years, but, thus far, despite high hopes, it has not established itself in the context of supply chain management practice. Blockchain technology competes not only with centralized database technology, but also with other DLTs, which may be less complex than blockchains, while meeting the applicable requirements. Some of the conceptual literature on blockchain technology and T&T references DLT (e.g., [4] p. 936, [13]). However, it is seldom explained and, if so, only in a rudimentary form, whose properties are only possible with blockchain technology and whose properties could also be achieved with another distributed ledger technology.

We are not aware of any other publication that focuses on a conceptual discussion of distributed ledger technology for tracking and tracing in supply chains. The publications that are the most similar to our article consist of a couple of articles that discuss DLT for supply chain management in general ([14,15]) and a couple of publications that are focused on particular industries (e.g., food [16,17] and pharmaceuticals [18]). It is understood that DLT offers more functionalities than simple centralized databases. However, it is not always clear whether these additional functionalities are useful in T&T practice, whether blockchain technology is required in this context, or whether a simpler, alternative DLT is sufficient to meet the applicable requirements, especially since a decision for or against a database technology is often an economic decision. These issues have not been discussed in detail in the existing literature, and this article seeks to fill this research gap.

1.3. Research Questions and Structure of the Article

The two guiding research questions of this article are: **For which problems related to T&T in supply chains is DLT necessary (RQ1) and/or sensible (RQ2) and why?**

As argued above, to answer these questions we must first systematically understand the goals and problems found in practice: **What are the main goals and problems companies have when they (consider to) use T&T in supply chains? (RQ0)**

However, it is of course difficult, if not impossible, to answer these research questions in their entirety in absolute terms. As is so often the case in qualitative research that deals with the relationships between technology, people, organizations, and economics, a way must be found, if possible, to reduce the complexity of reality to a few critical aspects. Therefore, methodologically, this article is based on systems thinking and a case studies research approach for which we surveyed T&T experts from eight companies. In its structure, the article follows the approach suggested by *Eisenhardt* for theory building from case study research [19]. The goal is to develop a "good theory" in the sense that the theory is not unnecessarily complex (parsimony), is testable and logically coherent, and in the sense that "why questions" are answered; for example: Why is DLT useful or not useful for T&T in supply chains?

These types of "why questions" can usually only be answered by uncovering the complex relationships between the various systems involved (i.e., actors, institutions, technologies, ...). Case studies in combination with systems thinking is a natural way to perform this, as this approach allows us to understand and structure the complex issues found in practice. Systems thinking is an established approach used to identify the structures and relationships in a problem. Indeed, systems thinking/engineering is also popular in the context of selecting or developing IT systems [20]. While the technical side of IT systems is often analyzed with the help of systems thinking/engineering methods, efforts to embed IT tools in economic and organizational contexts often fall short. This is why there have already been calls for a more thorough consideration of the context of IT systems from the perspective of systems thinking (e.g., [21]). Considerations of economic and organizational contexts are particularly important for this article because, in a supply chain, many companies not only cooperate with each other, but also compete with each other.

The rest of the article is organized as follows: First, various database technologies are defined and their technical properties are discussed. Then, the method and results of the case studies are presented (RQ0). Finally, based on these two pillars, a systematic discussion of DLT in the context of T&T in supply chains is presented (RQ1 and RQ2).

2. Database Technologies and Their Characteristics

In the following section, we briefly explained various database technologies and their characteristics to clarify how blockchain technology is integrated into the concept of DLT and to differentiate between distributed ledgers and typical centralized databases.

2.1. Different Database Technologies

Centralized database with backups: A typical T&T database is centralized with (ir)regular backups.

Fully replicating centralized database: If a database, instead, immediately applies all changes to the data to other database nodes, it is called a fully replicating database.

Digital Signatures: The two database types presented, thus far, are centralized (in an institutional sense). This has the advantage or disadvantage that database owners can easily change data, even if these data have multiple stakeholders. However, this can be mitigated relatively easily with so-called digital signatures. Every involved company would digitally sign data packages (e.g., documents), and these digital signatures would ensure that any changes to the content of the data packages are noticed. The content of a data package is very securely linked to the digital signatures of the corresponding companies. If a company changes data, the digital signatures of the other signatories no longer match the data.

In a business context, such a digital signature mechanism requires one-time registration with a so-called certificate authority (trusted third party), which issues a private key and a public key; these keys are linked to the respective corporate identity.

Fully replicating database with known parties: A fully replicating database does not have to be centralized. Instead, several different companies can share a fully replicating database. In general, each node (e.g., company) of a fully replicating database stores all the data and is kept up to date. Therefore, in any case, a coordination mechanism is needed because nodes may fail (e.g., temporarily have no internet access). In addition, if several companies share a database, a company may deliberately object to a data change. Therefore, a mechanism is needed that reliably facilitates, for example, a majority decision.

The most famous such mechanism is called the *Paxos protocol*. The way that the Paxos protocol works is that company A requests authorization to change specific data. The other companies confirm that company A has received and possesses this authorization. Only then do the other companies accept the changes made by company A to the specified data. The Paxos protocol can easily be changed so that it works even if up to one-third of the companies involved collude. This type of enhanced Paxos protocol is called a *Byzantine Paxos* or a *practical byzantine fault-tolerant* (PBFT) algorithm [22] (p. 5585) and has several derivatives. The Byzantine Paxos, of course, requires that the number of database nodes be temporarily fixed. That is, new database nodes must be authorized before they can participate. In addition, it is possible that more than one-third of the companies involved collude, in which case the mechanism would fail.

Fully replicating database with unknown parties (public permissionless blockchain): However, if the participants of a database network are unknown and not fixed (i.e., a company can create as many pseudonymous nodes as it wants), then a Byzantine Paxos cannot be used. This exacerbated consensus problem can be solved more or less effectively in different ways. The most famous such consensus mechanism is called *proof of work and* was introduced in the context of the cryptocurrency *Bitcoin*. This type of database is usually called a public permissionless blockchain. To solve the consensus problem, one node is not set equal to one vote. Instead, the proof of work mechanism, for example, makes one unit of CPU power equal to one vote. However, this is relatively inefficient, and every consensus mechanism still has weak points. The proof of work mechanism, for example, can be defeated with enough computing power. Therefore, it does not make sense to use a public permissionless blockchain if it is not necessary [23] (p. 1956).

Private/public permissioned blockchain: In the context of a public permissioned blockchain, everyone can read and submit data, but only authorized parties can write data to the database. In the case of a private permissioned blockchain, additionally, both the read and write access are restricted to authorized parties.

Permissioned blockchains hardly differ from nonblockchain DLT. Permissioned blockchains can have different consensus mechanisms, and they may even have a PBFT [22] (p. 5585). Only the data structure of a permissioned blockchain is unique. As the name blockchain implies, data are stored in a chain, which is similar to a linked list. Traditional databases typically do not use this data structure for most data storage, as linked lists are unnecessarily inefficient in most cases. In a permissionless blockchain, the specific data structure of a blockchain is necessary for the functioning of special consensus mechanisms such as proof of work. In a permissioned environment, however, other faster consensus mechanisms such as PBFT can be used; thus, the data structure of a blockchain may be unnecessary in such cases.

Distributed ledger: A distributed ledger is neither a centralized (fully replicating) database nor a multiparty fully replicating database with a simple Paxos protocol. A distributed ledger is a multiparty fully replicating database with a mechanism that can ensure the immutability of the data that it contains. This includes a public permissionless blockchain, a permissioned blockchain, and a conventional multiparty fully replicating database with, for example, a Byzantine Paxos algorithm or digital signatures [12] (p. 8).

The Hyperledger framework is a famous example of a distributed ledger that uses a Byzantine Paxos algorithm as its default consensus mechanism [22] (p. 5585). The Hyperledger framework has many variants, and many of the most popular ones bear little resemblance to a conventional blockchain architecture.

2.2. Characteristics of the Different Database Technologies

Table 1 contains selected characteristics of the explained database technologies. This selection of characteristics is based on the results of the expert interviews (see next Section) and the general focus of the related scientific literature.

Table 1. Different database technologies and their characteristics.

Technology	Data Correctness	Data Availability	Data Im-mutability	Data Privacy	Complexity
Centralized database with backups	Depends on input	Safe but with delays	None	Very good	Low
with digital signatures	and consensus	−//−	Very strong	−//−	More complex
Fully replicating centralized database	Depends on input	Good	None	Very good	Medium
with digital signatures	and consensus	−//−	Very strong	−//−	More complex
Fully replicating database with known parties	Depends on input	Very good	None	Bad/good with encryption	Very high
with digital signatures	and consensus	−//−	Very strong	−//−	More complex
Byzantine Paxos (PBFT)	−//−	−//−	−//−	−//−	−//−
Private permissioned blockchain	−//−	−//−	−//−	−//−	−//−
Fully replicating database with unknown parties (public permissionless blockchain)	Depends on input and consensus	Exceptionally good	Exceptionally strong	Very bad/ good with encryption	Exceptionally high

Data correctness: In the case of a centralized database without digital signatures, the quality of the stored data is primarily dependent on the company operating the centralized database. However, in the case of the use of digital signatures or in the case of a distributed ledger with a suitable consensus mechanism, the accuracy of data depends on at least two companies. Usually, this should result in relatively more correct data in such a database. However, data can also be incorrect when all involved companies agree, for example, when the utilized measurements are incorrect [15]. In addition, usually, a maximum of only two or three companies will have observed a process step in a supply chain.

Data availability: In the case of a centralized database with backups, data must first be loaded from a backup medium in the event of a disruption, which creates delays. With a fully replicating database network, data are available simultaneously from several databases, and it is easy to switch to another server. If other companies are integrated into such a database network, its data availability increases even more since a failure at one company does not necessarily mean that a failure will occur at another company. A public permissionless blockchain has the potential to increase data availability even more, as significantly more active database nodes could exist.

Data immutability: With a centralized database, the company operating the database can easily delete or modify data. With the addition of digital signatures, however, as mentioned above, it is not possible to perform this without it being noticed. Nevertheless, the companies that have signed a data record could decide together to delete or modify that record in the future. In the case of a distributed ledger with many participating companies, this is not so easy since the companies involved have to decide together to allow a change or deletion. However, the strength (or weakness) of the immutability of the data in a distributed ledger is dependent on the number of actively participating companies. Moreover, it is also possible that companies collude against each other.

Data privacy: Conversely, a centralized database provides maximum data privacy. In a simple replicating database network with multiple involved companies on the other hand, all companies can see everything. Thus, in their basic form, these systems have poor data privacy. However, this problem can be mitigated if sensitive data are encrypted. Only the companies that are allowed to see the data have the decryption key. Nevertheless, this increases the already high complexity of these systems [13].

Complexity: There is no free lunch. If a consensus mechanism has additional functionality compared to another consensus mechanism, then it is more complicated and slower. A centralized, fully replicating database is already very costly in terms of both software and hardware. The constant replication puts a strain on the servers and their network connections. If other companies are involved, this problem becomes even worse, and maintaining the software that coordinates the database network can become very labor intensive. In addition, there is also the question of what data should be stored in a shared replicating database. If every T&T record was stored in a shared database, the volume of this data would explode quickly [16] (p. 148). Even if only information such as 'a record with a specific hash value must exist at company A' was stored in the shared database, the data volume would probably quickly become very large. Moreover, there would be both separate centralized databases and a shared replicating database [24].

3. Case Studies

For topics that are closely linked to business administration, i.e., closely linked to the actions of organizations and people, qualitative research based on case studies and expert opinions is particularly well suited. Accordingly, it makes sense that case studies and expert surveys/interviews are often used in research regarding the use of blockchain and DLT in the context of supply chain management. Among the more recent studies in this field are those of [6,7,23–28]. The methodology used to analyze the results is quite different depending on the respective study. The authors of ref. [25], for example, used a sensemaking approach with cognitive mapping. The authors of ref. [23] and ref. [24] used a grounded theory approach, ref. [26] used a design science approach, ref. [27] employed the Delphi study method, ref. [28] used an explorative case study research approach, and ref. [6], as well as ref. [7], used a mindfulness framework to evaluate the selected use cases. Our study differs from the existing literature in mainly three ways. First, we placed an explicit focus on T&T in supply chains. The existing studies that we are aware of all adopt a broader perspective (SCM in general) and, therefore, do not explore specific topics, such as T&T, in depth. Secondly, we explicitly decoupled the problem description from the studied technology. This allowed us to take a more holistic viewpoint, whereas the existing literature we are aware of tends to focus directly on problems tailored to blockchain technology. Thirdly, we applied a systems thinking approach, which was particularly appropriate in our case, since T&T in SCs combines a technical system, an information system, as well as an organizational and economic system. The approach of [25] is closest to our approach, as we also used cognitive mapping.

The remainder of the article follows the structure suggested by *Eisenhardt* for theory building from case study research [19]:

1. Getting started.
2. Selecting cases.

3. Crafting instruments and protocols.
4. Entering the field.
5. Analyzing data (within-case analysis and cross-case patterns).
6. Shaping hypotheses.
7. Enfolding literature.
8. Reaching closure.

The first point "**Getting started**" has already been covered in the introduction (research questions) and the description of the technological basics.

Selecting cases: We were able to survey eight companies/experts. While this sample was too small to make broad, generalized statements about all businesses, it was sufficient for the intended purpose of the case studies, namely, to give a rough, explorative indication of the problems that are relevant in the context of business practice. Indeed, *Eisenhardt* argues that a case count between 4 and 10 often works well because this number of cases usually provides sufficient empirical foundation without adding too much complexity [19] (p. 545). Table 2 contains anonymized information about the companies/experts.

Since the number of cases in case study research is typically small, it is usually not sensible to perform a random sampling or to attempt to statistically reconstruct a population (of companies). Instead, a so-called "theoretical sampling" is often sensible [19] (p. 537). The idea behind theoretical sampling is to create a sample that is valuable for looking at a topic from different angles. Our goal was to survey experts from companies that operate in different parts of supply chains and perform different functions. We were able to include companies from raw material processing (company A) to B2C (e-)retailing (company H). Furthermore, the sample included companies from different industries and of different sizes. This diverse sample should have led to the emergence of a fairly broad and rich picture from the experts. Furthermore, it was important that the companies used at least some form of tracking and tracing in their supply chains. Please note that it was our goal to understand the main goals and problems companies have when they (consider to) use T&T in a supply chain. Therefore, our theoretical sampling did not put much emphasis on whether or not a company/expert has had much experience with distributed ledger technology. We believe that such an approach, which focuses directly on blockchain and distributed ledger technology, could also be valuable. However, there would be a risk that a sample from what is currently a very small population of companies that have extensive experience with DLT, would lead to theories that may not be generally applicable. Instead, we exploited the fact that DLT, as a database technology, is deterministic in its properties. Expert opinions about a technology are, therefore, arguably less interesting than the problems that the experts are trying to fix. Whether a technology is suitable for fixing these problems can be analyzed in a logically closed manner based on its technical properties.

Table 2. Surveyed companies/experts.

Company	A	B	C	D	E	F	G	H
Industry	Food	Carrier	Automotive supplier	Automotive supplier	Industrials	Industrials	IT Consulting	B2C Retailer
Region	Worldwide	Europe	Worldwide	Worldwide	Worldwide	Worldwide	Worldwide	Europe
# of employees	100–499	100–499	25,000–49,999	50,000–99,999	50,000–99,999	4999–9999	500–999	1000–4999
Surveyed expert	Director of logistics	CEO	SC expert	IT/SC expert	SC division manager	VP of global logistics	Senior consultant	Director of SCM

Crafting instruments and protocols and entering the field: The three steps of "crafting instruments and protocols," "entering the field," and "analyzing data" are often overlapping with an iterative back and forth between the steps [19] (p. 538). We opted for a data collection that was conducted in written form via e-mail with open-ended questions that allowed for the possibility of additional questions or answers from the interviewed experts and the interviewer. This approach is referred to as a *hybrid* survey [29] (p. 239). Personal, individual in-depth interviews carry the risk that the interviewer may, subconsciously, influence the experts' answers [29] (pp. 152, 238). In our case, we wanted to minimize this bias. Reducing personal biases is particularly important in the context of the topic at hand, as positive and negative opinions on distributed ledger technology and blockchain technology in particular are often strong, both in practice and in academia. On the other hand, we did not want to eliminate the possibility of subsequent questions from both sides; thus, the chosen hybrid approach seemed to be the most fitting one.

Reflecting the iterative nature of the process, the questions were initially discussed with two experts from two companies, and this resulted in a few minor adjustments that made the questions easier to understand. The data collection was conducted during the months of March, April, and May 2021. During our contact with the experts at companies A and H, there were several e-mails with follow-up questions on our part. With the expert at Company C, we had, in addition to the e-mail responses, a longer video call about the content of the questions; however, only the e-mail responses were included in the coding. Overall, our approach worked well and produced valuable and interesting data. Only the expert from company B answered our questions in a short-winded manner, but this was probably due to his position (CEO) and corresponding lack of time.

Our goal was to obtain an unbiased view from the examined experts; thus, we mainly asked broad, open-ended questions. We started with an explanation about what we meant when we spoke of T&T in supply chains, asked for metadata and then focused on the following questions:

- What are the company's goals with its T&T IT system?
- What are the biggest problems related to successfully implementing a T&T IT system, and what are the biggest problems with T&T in general?

We also asked questions about T&T technology and IT systems currently employed or planned and their scope within the supply chains of the companies, what tracking and tracing data are collected and by whom, and what data are made available to the company and, if so, when. Furthermore, we asked which employees have access to which data and how the data are stored (database), transmitted, and accessed (e.g., automated IT interfaces). Finally, we briefly asked about DLT and blockchain technology.

Analyzing data (within-case analysis and cross-case patterns): When analyzing the collected data, one can distinguish between the within-case analysis and the discovery of cross-case patterns [19] (p. 540). The first step in the within-case analysis is to clean, prepare, and structure the data. This step was easy in our case as we received written answers from the experts. This is followed by a step that is already strongly connected to the discovery of cross-case patterns. One has to code the metadata of the companies and the answers from the experts into predefined categories. Coding categories can result from the research questions or the underlying theory and technology, but can also be derived exploratively from the experts' answers. Roughly speaking, this involves checking whether a statement made by one expert was also made exactly or in a similar form by other experts. The result are abstract categories or answers that summarize the responses of the various experts.

To create the coding in our case, two individuals independently coded all the answers. This did not only increase the reliability of the coding, but also the validity of the findings because multiple investigators often had complementary insights [19] (p. 538). These individuals created a codebook together with the goal of making the categories exhaustive and mutually exclusive [30] (p. 132). The derivation of the coding categories was mainly exploratory (e.g., goals and problems with T&T), but also based on the technological characteristics of DLT (e.g., immutability). For seven companies, 110 categories each were coded. For Company G (IT Consulting), only 63 categories were coded because the company did not perform T&T for itself. After the first round of coding, the intercoder reliability was acceptable but not very good (average Krippendorff's alpha ≈ 0.723). Therefore, the two coders discussed the codebook, improved it, and independently recoded the categories that had unacceptable intercoder reliability scores in the first round. After the second round, the intercoder reliability was good or very good for each company and for almost all the questions (average Krippendorff's alpha ≈ 0.921). The two coders discussed all the remaining discrepancies, and a consensus decision was reached.

Results: Figure 2 provides a cognitive map of the survey results. A cognitive map is a systems thinking method, which was used in our case for the cross-case pattern analysis. The cognitive map summarizes the relationships between T&T goals and the different problems encountered by the studied companies.

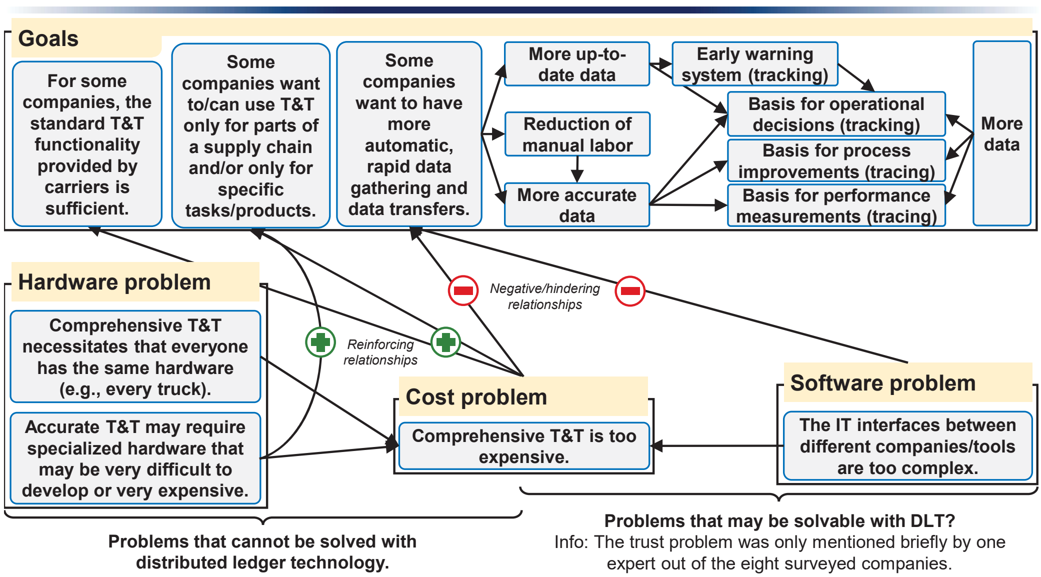

Figure 2. Cognitive map of the survey results and partial answer to RQ0.

None of the companies surveyed were engaged in comprehensive T&T along whole supply chains at the time of the study. Only company E had generally covered some parts of a supply chain and had the ambition to implement comprehensive T&T. In principle, there was a broad demand for more automated and efficient data gathering and data transfers. Software automation could reduce manual labor (A, E, F, and H), and make data handling less prone to errors (D, E, and H). More up-to-date data would also enable the use of early warning systems (D, E, F, G, and H) and could be used as a basis for operational decisions (A, B, C, D, and G, e.g., the short-term rescheduling of truck ramps (A) or early reorders of products (D)). These goals were enabled by the "tracking" component of T&T. Moreover, the additional data collected by the T&T systems could be used for performance measurements and reports and to identify potential process improvements (B, C, E, G, and H), which reflects the "tracing" component of T&T. Some representative answers were as follows:

What are your/typical goals with tracking and tracing IT systems?

(Interviewer)

"Transparency, competitive advantages, relevant for measurements (order lead time and delivery time measurement and performance), (. . .), identification of process weaknesses (gap analysis)"

(Expert E)

"In the case of real-time monitoring after the condition of the goods has been transmitted as presumably bad [g-forces], check for immediate resupply to avoid a production stop."

(Expert D)

> *"(. . .) With better data and more reliable delivery performance, we can reduce safety stock and increase inventory turnover."*
>
> *(Expert C)*
>
> *"(. . .) [Better] customer service through improved information basis. (. . .)"*
>
> *(Expert F)*
>
> *"Supervision of employees."*
>
> *(Expert G)*
>
> *"[Regarding GPS tracking:] Basically, it is "just" a communicative shortcut so you do not have to keep contacting truck drivers directly via phone. (. . .) Example: A supplier arrives at our plant ahead of schedule (. . .). The ramp is free, but an unloading appointment for our truck is scheduled in 15 minutes. Now, the fleet team leader can check where our truck is and if it will make it to the appointment on time. If it is late, the other supplier can be pulled forward, for example."*
>
> *(Expert A)*

Many of the surveyed companies wished for more automation. However, this desire did not necessarily lead to a more automated T&T. Some companies were satisfied with standard carrier T&T capabilities and functionalities. Carriers usually make their T&T data available via a web portal. The experts gave two main reasons why companies were satisfied with this basic T&T: the excessive technical complexity of hardware and software (B, D, E, F, G, and H) and the high costs associated with them (A, C, D, G, and H).

Decisions for or against (automated) T&T are usually economic decisions (please note that none of the surveyed companies had a legal obligation to implement specific types of T&T). T&T not only has benefits, but also costs, and often the benefits are simply not worth the costs. Some representative answers were as follows:

> *"With the current form of shipment tracking (via carrier IT systems/websites), [company C] does not incur any costs since carriers generally make the data available. With the planned expansion already described (SupplyOn), the costs will certainly play a major role or could become a hurdle, and the costs and benefits will have to be weighed against each other. Moreover, in general, the more parties that are involved in a tracking and tracing chain, the more difficult the implementation will be."*
>
> *(Expert C)*
>
> *"[Regarding the biggest/typical problems:] The desire to track every event vs. having the IT capacity to process all the data. Documenting every event, but not being able to perform any analyses with the data afterward, or not being able to draw any conclusions. (. . .) Infrastructure and costs in the companies:*
>
> - *Processes must be set up.*
> - *Hardware and software must be procured.*
> - *Employees must be trained.*
>
> *There must be a very concrete benefit/added value for the investment to be made."*
>
> *(Expert G)*
>
> *"The T&T offerings of the carriers are sufficient. The integration and consolidation of information –especially from different carriers– is currently not trivial due to differences in data and systems. Intermediary stages (carriers ↔ own IT solution) would be required to be able to make the data available to customers through our own systems in a meaningful way."*
>
> *(Expert H)*

T&T hardware and software are expensive (e.g., for comprehensive real-time transport tracking, individual trucks each have to have similar hardware installed (A, C, and D)) and very complex [17] (p. 13). For example, Expert D stated that special sensors/adapters to accurately measure g-forces must be developed. Thus, a complete and accurate T&T is sometimes simply not possible due to hardware restrictions. Additionally, T&T software interfaces are very complex. Problems usually do not arise from a single interface, but rather from maintaining many different interfaces ([24]). The complexity of maintaining many different IT interfaces is expensive and presents a problem for small companies with little IT knowledge. All of these issues lead to a situation where companies consider carefully in which SC segments and for which (expensive/sensitive (D)) products they want to selectively apply specific T&T technologies (e.g., inbound for increased operational efficiency (A and D) or outbound for increased customer benefit (F and G)). Implementing T&T across a whole supply chain is usually not a goal.

In addition to these hardware and software problems, the experts mentioned only a few other problems infrequently. A notable exception was the "employee problem". Employees do not like to be monitored (A and G); moreover, they may lack the skills to use and maintain T&T IT systems (B, F). Trust issues, which are often mentioned in connection with DLT or blockchain technology, were only addressed by expert D (representative answers):

> *"As we understand it, with blockchain technology, data are verified and stored at/in all databases involved. (. . .) This (. . .) enables (. . .) better data availability and contestability in liability cases."*
>
> *(Expert D)*

> *"Blockchain increases complexity. No use case or benefits identifiable. Exclusively trusted partners in the supply chain and plant network."*
>
> *(Expert E)*

> *"Blockchains are difficult to set up. (. . .) The costs of a blockchain are usually greater than the benefits of the data collected. Only a few companies have goods that are high-priced enough for economic considerations to make sense. (. . .) Digitization in supply chains has not progressed far enough for blockchain. All supply chain partners need to participate for it to work."*
>
> *(Expert G)*

> *"The requirements of mid-sized retailers can certainly be implemented without blockchain technology."*
>
> *(Expert H)*

4. Discussion and Shaping Hypotheses

The two previous sections (Section 2. Database Technologies and Their Characteristics and Section 3. Case Studies) now served as the basis for a discussion of the research questions one and two: **For which problems related to T&T in supply chains is DLT necessary (RQ1) and/or sensible (RQ2) and why?**

4.1. The Difference between Tracking and Tracing

One key finding of the case studies was that, for the following discussion, T&T should be divided into hardware and software components and that the individual components, namely, 'tracking' and 'tracing', should be considered separately.

Therefore, when we asked in the title of this article how useful DLT is for T&T in supply chains, it is important to note that there are many areas where DLT cannot be useful, because it is merely a software technology and merely a database technology.

Furthermore, some of the companies in our survey primarily used tracking and rarely or never used tracing. Tracking is the timely collection, provisioning, and use of T&T data. For this purpose, T&T data do not need to be stored long-term. Therefore, a complicated distributed ledger tailored to data immutability is not useful for tracking. Moreover, DLT does not make sense for purely intracompany use cases. Hence, the primary remaining question must be:

How useful or necessary is DLT for tracing cross-company T&T data?

4.2. The Supply Chain Context

To answer this question, it was important to consider the context of supply chains. A supply chain is a complex system with different levels and many relationships. In any given supply chain, there is (1) the institutional level, i.e., the companies operating in the supply chain, (2) the physical level, which entails the material flow from raw material suppliers to consumers, and (3) the informational level, which refers to the information flows and IT infrastructure in the supply chain. T&T can be viewed as part of the information flow and IT infrastructure of a supply chain, and it is accordingly embedded in this system and influenced by the physical and institutional levels. To a large extent, these system components were also reflected by our case studies. In the context of distributed ledger technology, three circumstances stood out in particular:

1. The volume of data generated in an SC is enormous. A distributed ledger is a shared replicating database that multiplies the necessary amount of storage; therefore, it would be wasteful and expensive (if not impossible) to store all the T&T data generated in an SC in a distributed ledger [16] (p. 148). Instead, only selected T&T data or meta-data (e.g., hashes of data) can be sensibly stored in a distributed ledger.

2. In a supply chain, companies compete with each other. Suppliers or customers compete against each other, and the relationships between suppliers and buyers are delicate. A supplier or buyer must fear being replaced by a competitor.

Supply chain participants, therefore, generally want to keep much of their data secret; if they make their data available at all, they often want to do so only for direct business partners [10] (p. 350). Cross-company T&T in supply chains, therefore, usually consists of many different private information-sharing relationships.

This context (extreme data volume and a need for data privacy/access controls) leads to a situation in which distributed ledgers cannot exist alone. Instead, accompanying central databases and IT interfaces are needed [13]. Therefore, it is rather unlikely that DLT can reduce the number of IT interfaces used in an SC. Some of the experts who participated in our survey explicitly complained about the complexity of using many different IT interfaces.

3. Supply chain participants are interested in long-term business relationships and do not lightly damage or destroy their business relationships by lying about data. Risk mitigation costs money, and a company will employ specialized technology to protect itself against the risk that a supply chain partner may lie only if the expected cost of that risk is high. Indeed, Expert G gave this argument in our survey as a reason why blockchain technology is often not worth the effort. Furthermore, this result was also supported by other scientific studies (e.g., [31]).

4.3. The Physical Level vs. the Informational Level

Nevertheless, one may still ask if DLT is useful when the stakes are high and companies want to protect themselves from lying. One might think that DLT could help in this case; however, database technology cannot prevent companies from lying about new data [4] (p. 947). DLT only ensures that existing data are not changed or deleted.

However, a consensus mechanism has additional advantages. Through a consensus mechanism, data can be automatically and forcibly written to a database. This is called a smart contract. A smart contract is stored in a shared database and is triggered as soon as specified data are present in the database. For example, automatic payments linked to goods receipt confirmations are conceivable [1] (p. 6889). Nevertheless, smart contracts encounter a problem whenever there is no automatic, accurate interface with physical reality. Companies can lie to force or prevent the execution of a smart contract (e.g., incorrectly stating that ordered items never arrived). Normally, only a package is tracked, and the contents of the package are not tracked. T&T data could help in this situation (e.g., by including weight and dimension measurements), but, in the end, a receiving company may still choose to manually verify the quality of received goods, especially in the case of expensive items. Moreover, goods receipt confirmations are also recorded in companies' internal ERP systems. Thus, if a receiving company has complete control over when a goods receipt confirmation takes place (and, thus, when the related smart contract is triggered) and this confirmation is stored in the company's ERP system anyway, the critical question arises of why a smart contract should be used when the company could instead simply arrange for the applicable payment to be performed automatically through its ERP system.

4.4. The Technological Alternatives

The question of whether DLT is useful or necessary for T&T in supply chains, therefore, ultimately revolves around how useful/necessary data immutability is and whether a sufficient level of data immutability can be achieved with other, less complex technologies. The importance of data immutability varies by use case, but can be very important (e.g., for anything directly related to contracts). Sometimes, data immutability is even required by law (e.g., in the pharmaceutical industry [18]). Therefore, there is, undoubtedly, a place for and value in technologies that enable data immutability [27]. However, technologically, DLTs with consensus mechanisms compete with simple centralized databases in combination with digital signatures.

Both of these technologies have security vulnerabilities. The strength of a consensus mechanism in a distributed ledger depends on the behavior of the database nodes (companies). Digital signatures, in contrast, initially rely on a trusted third party and later on the related company's own security. This becomes problematic if a company's private key is stolen and the company does not notice the theft. Public keys are less problematic. If a reputable certificate authority creates correct keys, the connection between a company and a public key cannot be changed easily without it being noticed. Since the corporate identity connected to a public key is publicly available information, strong public governance is possible. Data digitally signed with a private/public key combination are immutable as long as accurate backups of the public key servers exist and as long as all the database owners do not collectively delete the data. Thus, in some respects, digital signatures offer stronger data immutability than DLTs without digital signatures; however, they have a weakness in that companies could collectively decide to simply delete data. Nevertheless, in regard to contractually relevant T&T data, at least one of the companies involved in a contract is always interested in keeping the relevant data. Thus, in these situations, digital signatures are a viable choice and the question of which alternative is better ultimately comes down to what a company prefers in terms of security: relying on its own security or relying on the behavior of other companies in a distributed ledger?

Nevertheless, situations could exist where, for example, a law mandates data immutability and all the companies involved have an interest in illegally deleting data. In such cases, indeed, only a suitable DLT or a trusted third party (data trustee [10] (p. 350)) can be used. However, a distributed ledger would have to be public or include companies that have no interest in deleting data.

4.5. Enfolding Literature

The majority of the literature on blockchains and DLT in supply chains seems to be rather positive towards the technology. While it is often pointed out that the technology is still young and needs to prove itself, it is also claimed that the technology has the potential to disrupt entire structures and relationships [32] (p. 62) and that its future looks promising [5] (p. 2063). Based on our study, however, we painted a more cautious picture. Our results indicated that blockchain technology and DLT in general seem to be useful only in rare cases. While we were not the only ones to come to such a cautious conclusion (e.g., [4] (p. 950), it is, nevertheless, worth asking what causes such a wide range of, possibly contradictory, conclusions.

We believe that one important factor in answering this question is that some authors are more focused on the future and other authors (similar to us) are more focused on the current problems and goals found in practice. For example, it is an important prerequisite for the usefulness of DLT, that the data, which are stored immutably in the distributed ledger, are also correct. If this is not the case, the content of the data cannot be trusted and the technical complexity of a DLT would be unnecessary [4] (p. 949). However, companies/people can lie and, currently, there is often no way to accurately track the physical world without the possibility of manipulation. Only if one looks into the distant future and simply assumes that at some point it will be possible to accurately track the physical (real) world, will there be an increased number of beneficial use cases for DLT and its ability to immutably store the data (e.g., for audits or smart contracts).

Another important factor is probably that the economic reality of businesses and the supply chain context is often neglected in current blockchain and DLT research. Distributed ledger technology is, foremost, a technology with deterministic properties. It is tempting to take these technical properties and look for problems that can be 'technically' solved with DLT. However, this type of approach can be deceptive. Sometimes, use cases are identified that could be solved with other simpler technology. In this case, DLT would be similar to 'using a sledgehammer to crack a nut'. In other cases, it may be that DLT is the only feasible technology, but for economic reasons (including game theoretic reasons), it is simply not worth solving the problem. Both future-oriented research, and research that specifically investigates which problems can be technically solved by DLT, are valuable. This study and some other studies as well, have, however, taken a somewhat different approach, in the sense that a spotlight was put on the sobering reality of business administration.

5. Summary, Limitations, and Conclusions

The primary research questions of this article were: **For which problems related to T&T in supply chains is DLT necessary (RQ1) and/or sensible (RQ2) and why?**

Table 3 provides a concise overview of the discussions from the previous sections and may serve as a partial answer to RQ1 and RQ2. The preceding RQ0 ("What are the main goals and problems companies have when they (consider to) use T&T in supply chains?") was already answered in the form of Section 3 ("Case studies"), especially Figure 2.

We found that DLT was only necessary in very special cases, such as when data immutability was mandated and all the companies that were directly associated with a set of data had an interest in deleting it. In some cases (e.g., tracing for external needs), a distributed ledger provides value; however, depending on the situation, it may not be sensible, as an alternative exists in the form of digital signatures. In many cases, DLT does not help at all (e.g., T&T hardware, tracking, tracing for purely internal needs). Nevertheless, this does not mean that DLT is useless. DLT offers additional features that other types of databases do not. This fact alone is positive in itself, even if these functions are not needed very often. Furthermore, DLT is simply useful as an alternative technology. Competition between technologies is generally a good thing. For example, digital signatures, as an alternative technology, rely on so-called certificate authorities (which typically do not offer their services for free). Even if competition between certificate authorities did not work (imperfect market), certificate authorities would have to keep in mind that customers could also use distributed ledgers as an alternative. This means that, even if using DLT would be significantly more complex than using digital signatures, the technology provides an upper-cost limit, which is useful to have.

Table 3. Is distributed ledger technology useful for tracking and tracing in logistics?

Problem	Comment
A company has a problem with T&T hardware.	DLT cannot help.
Companies/people do not want to share their T&T data.	DLT cannot help.
A company wants to use tracking (e.g., for operational decisions).	DLT does not provide an advantage.
A company wants to use tracing for purely internal needs.	DLT does not provide an advantage.
Database technology is complex and expensive to maintain.	DLT cannot help because it is a complex/expensive technology.
The IT interfaces between companies are very complex and expensive to maintain.	DLT cannot help because not all T&T data are stored in a distributed ledger.
A company wants to use tracing with data immutability for external needs involving other companies (e.g., contractual penalty payments).	DLT can help, but digital signatures are an alternative because at least one party would be interested in keeping the records.
A company must perform tracing with data immutability because the law mandates it.	Depending on the law, either a trusted third party or a DLT could be used.
A company wants to use tracing with data immutability to create a single point of truth.	DLT cannot help. The data may be inaccurate, e.g., because measurements were inaccurate.

We hope that the reader, both from practice and science, was able to draw valuable insights from our article. Table 3 may be particularly helpful for a practitioner, as it allows the reader to easily check whether it makes sense to use DLT or not for many typical problems/objectives encountered in practice. There is of course a gray area in which several different technologies (including DLT) are viable alternatives. In this gray area, the decision for or against a technology is always a case-by-case decision that depends on the specific context. Unfortunately, it is not possible to provide practitioners with simple guidance for these cases. However, our results do narrow down this gray area.

The scientific reader may benefit from our article as we presented a theory that is parsimonious, logically coherent, and testable. The theory is parsimonious in the sense that the gray area mentioned above could be narrowed down relatively easily by asking a few control questions. The theory is logically coherent in the sense that the technical properties of DLT were deterministic and the T&T problems/goals found in practice were systematically analyzed and interconnected using systems thinking. The theory is testable in the sense that any researcher is free to ask other companies about their T&T goals and problems and also to verify whether DLT is useful for these problems/goals or not. In addition, we hope that this article will serve as an impetus for future research to give digital signatures in combination with conventional central databases more thought, as an alternative to DLT. The comparison of these two technologies, especially in terms of business and IT management, is probably too often overlooked.

However, this article also has some limitations, which may serve as a motivation for future research. In this paper, we presented the results of an exploratory case study research of eight companies. The case studies served as a basis to identify the major T&T requirements and problems that exist in practice. It is possible that these eight companies did not adequately represent all typical T&T problems and goals found in practice. In addition to conducting the case studies, we derived the components and used cases of T&T using a systems thinking approach. It is, therefore, possible that we overlooked important problems for which DLT would be very useful.

In addition, our article had a B2B focus. While the results should also be valid in a B2C context, it might be worthwhile to explore the B2C perspective in more detail.

Moreover, as already discussed, we did not take an explicit look into the future. It is exciting that it may someday be possible to use T&T technology to make entire supply chains visible in an error-free and tamper-proof way, but this is certainly very far in the future. However, an analysis of whether DLT makes sense in such a future, which entails the possibility of smart contracts, on the one hand, but an enormous amount of generated data, on the other hand, would undoubtedly be an important and sufficiently extensive topic for a separate article.

It is undisputed that logistics and supply chain management can benefit from more transparency. Wherever uncertainty and risk exist, economic inefficiencies arise (e.g., [33]). In addition, production and logistics also have a strong social responsibility. Environmental pollution, welfare, and social justice are crucial issues worldwide (i.e., trend towards more sustainability) and production and logistics play a pivotal role in many aspects of these topics. Therefore, it is important that the role of production and logistics in relation to sustainability is made more transparent [34]. However, merely for transparency on its own, DLT is not necessarily needed. Transparency can often also be achieved with conventional databases and information sharing. The most prominent feature of distributed ledgers is that they can combine high data availability for all participants with data immutability. Use cases that can benefit from both these properties are, therefore, particularly interesting for future-oriented discussions about DLT applications. However, it is often the case that companies do not (want) to record and share their information. This may simply be because transparency costs a lot of money, but it may also have competitive reasons, as transparency can create disadvantages when competing with rival companies. This means that, as other authors also have pointed out [4] (p. 949), database technology is often not the problem at all. Instead, the attitude toward transparency and the connected processes within companies must first change. On game-theoretic grounds, it can be argued that, in many situations, such a change is unlikely to occur by itself. Therefore, it may sometimes make sense to mandate transparency and information sharing by law [35], and perhaps these are the kind of situations where DLT is most valuable.

In any case, we thank the reader for their attention and hope that this article proved a valuable read.

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Article

Intra- and Interorganizational Barriers to Blockchain Adoption: A General Assessment and Coping Strategies in the Agrifood Industry

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Abstract: *Background*: Companies partaking in modern supply chains face numerous intra- and interorganizational barriers when it comes to the adoption of blockchain technology. Empirical research is missing that explores how exactly these barriers can be overcome. In this paper we first explore barriers that organizations need to overcome to successfully deploy blockchain technology. In a second step, we investigate the agrifood industry and highlight differences in coping strategies between incumbents and start-ups. *Methods*: We conducted a quantitative survey with 190 supply chain experts to identify barriers and an in-depth qualitative study that included 10 expert interviews to better understand the current situation in agrifood organizations. *Results*: The findings from the quantitative study show that the most relevant organizational barrier to blockchain adoption is the widespread lack of understanding of the technology and its potential benefits. In the qualitative study we illustrate how various intra- and interorganizational barriers can be overcome and how the resources and capabilities differ between incumbents and start-ups. *Conclusions*: Our results provide academics with a better understanding of the relevant barriers and bridges of blockchain adoption. Practitioners benefit from learning about the resources and capabilities they need to deploy in order to benefit from blockchain technology.

Keywords: blockchain; distributed ledger technology; agrifood supply chain; adoption barriers; survey; qualitative interviews

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1. Introduction

The effective and efficient management of supply chains is a complex task whose practical implications extend far beyond increasing companies' operational performance or profits. Many of these problems are exacerbated in the supply chains of perishable goods. Opacity and inefficiencies in supply chains cause the perishing of agrifood products, which leads to substantial waste and even poisoning with potentially fatal consequences for human beings. Recent examples of the latter are listed on dedicated websites that showcase outbreaks of E.coli, salmonella, or campylobacter, all of which were caused by tainted food [1]. Additionally, the amount of global waste in this area is alarming. Thyberg et al. [2] estimate the aggregate disposal rate in the United States to be 0.28 kg per person per day, equating to 32.2 million tons of waste disposed of annually. Caldeira et al. [3] present a detailed analysis for the European Union and assess the yearly total amount of food waste to lie between 119 and 145 million tons. Not surprisingly, the highest proportions of waste were found among highly perishable food categories such as fruit (41%), vegetables (46%), and fish (51%).

Academia and industry generally agree that blockchain technologies are an appropriate means to tackle some of the most pressing problems in this sector. Rana et al. [4], for example, review existing academic literature and conclude that the application of blockchain can help to create sustainable agrifood supply chains. However, they also point out that new challenges related to scalability, privacy, cost, and connectivity might arise (see also Lacity [5], van Hoek et al. [6], Rejeb et al. [7], Treiblmaier [8]). In their systematic review, Rocha et al. [9] identify several supporting activities that blockchain can offer to agribusiness, including financial and environmental management. Rogerson and Parry [10] identify visibility as the main adoption driver in agrifood supply chains but also mention unsolved challenges such as lack of trust, human error, fraud, and governance issues. Based on a comprehensive literature review, Rejeb et al. [11] identify various technical, organizational, and regulatory challenges in blockchain adoption. Finally, Garaus and Treiblmaier [12] take a consumer perspective and illustrate that the traceability of agrifood products helps to strengthen consumers' trust in retailers, which is especially pronounced for unfamiliar retailers.

Given the huge potential of the technology, it is not surprising that the industry has already launched several high-profile projects. The IBM Food Trust, for example, was established with the mission to improve transparency, standardization, and efficiency throughout the food supply chain [13,14]. Another example is OriginTrail, a supply chain ecosystem that fosters universal data exchange, connecting legacy IT systems and enabling data integrity. OriginTrail established several technology and research partnerships, with companies such as SAP, BSI, GS1, and Oracle, among others [15]. In addition to well-established players, numerous start-ups such as AgriChain, AgriDigital, Agrolot, Greenfence, Mixing Bowl, Ripe, and TE-FOOD harness blockchain technologies to improve communication between supply chain participants, enable the traceability of the produce, establish cryptomarkets of agricultural crops, and facilitate the trading of agrifood products [16,17].

As opposed to their incumbent counterparts, newly founded ventures usually do not face the same intra- and interorganizational barriers and also differ in their practices, methods, and knowledge management tools [18]. They cannot capitalize on their existing network of ecosystem partners such as incumbents do and often have limited access to resources [19]. Previous research has also postulated that a firm's prior experience is a key driver for success and found, for example, that incumbents establish significantly more productive new plants than entrepreneurial entrants [20].

Given these differences between established and new enterprises, it makes sense for any study investigating the potentials of blockchain technology adoption to scrutinize the differing importance of intra- and interorganizational barriers depending on industry experience and the resources that companies have at their disposal to overcome such barriers. In the context of this study, a company's resources include all assets, processes, capabilities, attributes, information, and knowledge that enable it to improve its effectiveness and efficiency [21,22].

Given the amount of literature that has recently been published on the potentials of blockchain in supply chain management [23,24], a solid understanding regarding the importance of adoption barriers exists. However, there still is a dearth of research that explores how to overcome those barriers. Additionally, prior research has not quantified the potential positive impact of blockchain, nor has research identified the resources companies could deploy to capitalize on the use of blockchain. To fill these research gaps, we therefore strive to answer the following four research questions:

> Research Question 1 (RQ1a): Which intra- and interorganizational barriers to organizational blockchain adoption identified in prior literature are still rated most important by supply chain professionals?
>
> (RQ1b): To what degree are organizations ready to adopt blockchain technologies?
>
> Research Question 2 (RQ2): What resources can organizations in the agrifood industry use to overcome intra- and interorganizational barriers to blockchain adoption?

Research Question 3 (RQ3): What are the differences in coping strategies between incumbents and start-ups in the agrifood industry?

RQ1a and RQ1b are assessed using quantitative data from a survey with 190 respondents conducted at a major supply chain conference. RQ2 and RQ3 are answered with the help of case studies, including qualitative interviews, panel discussions, and the analysis of publicly available material from blockchain incumbents and start-ups.

This paper is organized as follows: We summarize the literature on barriers to effective blockchain adoption in SCM in the literature review section. We describe the quantitative and qualitative research approaches in the methodology section. We then discuss the results of our quantitative and qualitative analyses, and focus on identifying the key resources that can support organizational blockchain adoption. We end this paper with the discussion and conclusion sections, as well as an outlook on future research.

2. Literature Review: Barriers to Effective SCM and Blockchain Adoption

On a general level, numerous important barriers to strategic supply chain management (SCM) have been identified, the impact of which Fawcett, Magnan, and McCarter [25] label as "intimidating". They analyzed organizational and individual implementation barriers to effective SCM. Their list includes lack of top management support, non-aligned strategic and operating philosophies, inability or unwillingness to share information, lack of trust among supply chain members, unwillingness to share risks and rewards, inflexible organizational systems and processes, cross-functional conflicts and "turf" protection, inconsistent/inadequate performance measures, resistance to change, and lack of training for new mindsets on skills. More specifically concerning blockchain in supply chains, Saberi et al. [26] identify and group the major barriers to blockchain into four categories, namely intra- and interorganizational barriers, systems-related barriers, and external barriers. In this study, we build on this existing framework and especially focus on the former two since those are the ones that organizations can influence themselves (see Figure 1). In the following sections, we provide an overview of how current literature perceives these barriers and which solutions have been suggested so far, with a special focus on the agrifood industry.

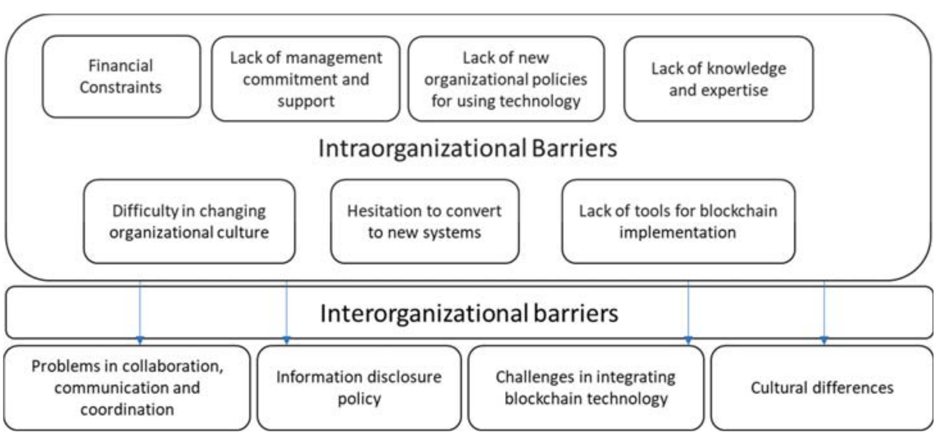

Figure 1. Intra- and interorganizational barriers to blockchain adoption based on [26].

2.1. Intra-Organizational Barriers

2.1.1. Financial Constraints

Financial resources are typically considered to be critical for the ability of organizations to acquire blockchain technology [27,28]. The digitalization of agrifood supply chain processes using blockchain technology requires investment in hardware, software, and knowledge [29,30]. Even though this investment may not be as substantial as that required for other supply chain technologies [6], the exact nature of the investment and operating costs are currently not widely and well-understood by managers considering blockchain [31]. In this respect, Dutta et al. [28] point out that blockchain's non-trivial operational and implementation costs must not be underestimated. Additionally, the maintenance costs of blockchain systems need to be adequately monitored [32] to gain a competitive advantage [33]. In the long run, blockchain-enabled agrifood traceability systems need to yield a positive return on investment to justify the deployed resources [34]. Similarly, the use of blockchain for agrifood traceability might be too costly for small organizations with insufficient resources since system operation and maintenance routinely require significant financial resources [35]. Therefore, in ensuring the smooth implementation of blockchain, sufficient financial resources are a key intraorganizational barrier to the innovation and adoption of the technology.

2.1.2. Management Commitment and Support

The potential value of blockchain adoption in the agrifood organization can be undermined by a lack of management commitment and support as well as a lack of management engagement in the technology across the organization [27,31]. As per Rogerson and Parry [10], the absence of management support can stifle new technology adoption. As such, when orientating their agrifood business processes toward blockchain integration, agrifood organizations need a clear strategic perspective that emphasizes top management involvement and organizational support to facilitate the implementation within their business operations [28]. With sufficient managerial support, blockchain adoption can be significantly enhanced since this ensures the mobilization of sufficient resources. Nevertheless, the immaturity of the technology is still an important concern for managers that negatively affects their commitment and support [27]. As a result, given that (mostly upper level) managers oversee critical activities and budgets, their support is an important prerequisite for providing crucial resources.

2.1.3. Organizational Policies

Adopting blockchain requires new organizational policies, mechanisms, and procedures to be implemented as part of an organization's overarching corporate strategy. According to Kouhizadeh et al. [27], a lack of organizational policies represents a prominent barrier to blockchain adoption. The potentials of leveraging blockchain in agrifood operations can therefore only be fully realized if the enablers of its adoption are reinforced with favorable organizational strategies and policies [36]. For example, Chanson et al. [37] point out how organizational policies are necessary to define how the users of blockchain systems can prevent, identity, and overcome security incidents. Moreover, there is a need to employ changes in current organizational structures (e.g., changes in responsibilities, goals, routines, decision-making activities, systems) and policies so that blockchain can confer substantial benefits on the agrifood organization. Therefore, the compatibility of blockchain with an agrifood organization's existing policies and practices is essential to its successful deployment [38–40]. In this respect, agrifood organizations need to support a wide range of activities (e.g., product control, monitoring, data capture and documentation, traceability) that should be governed by organizational policies and mechanisms to achieve more efficient processes operational excellence.

2.1.4. Knowledge and Expertise

Organizations perceive blockchain adoption as a demanding task requiring a sufficient understanding of the technology and its integration in the agrifood supply chain [41]. Klerkx and Rose [39] argue that digital technologies strongly impact supply chain operations and demand new knowledge, skills, and labor management across various actors. Given its immaturity, Zhao et al. [42] posit that a limited number of people possess in-depth knowledge and skills on how blockchain can be successfully adopted in the agrifood supply chain. Since the users' level of knowledge and skills ultimately determines the effectiveness of system use in various contexts [43], a lack of knowledge and engagement with blockchain technology can significantly slow down its adoption in the agrifood industry [35]. Antonucci et al. [44] therefore suggest that agrifood organizations upgrade their base knowledge and technical assistance to support and help other stakeholders, and that governments assume an active role in supporting blockchain-enabled agrifood supply chains. However, Lin et al. [45] note that if the current organizational systems adequately satisfy their business needs, adopting blockchain is not likely to happen because successful implementation requires knowledge on both agriculture and blockchain and a certain amount of external pressure to do so.

2.1.5. Organizational Culture

Organizational culture plays an important role as an enabling factor when it comes to the adoption of blockchain within an agrifood organization. According to Kouhizadeh et al. [27], the integration of blockchain in the supply chain can be impeded by difficulties in changing organizational culture. In the context of the agrifood industry, Yadav et al. [46] state that stakeholders such as farmers and middlemen may resist blockchain adoption because this would require a substantial cultural change. The management culture induced by blockchain-enabled agrifood supply chains can significantly impact the quality of agrifood products and the vitality of the organizations involved [47]. Blockchain has the potential to alter the organizational culture of farming businesses, transforming it from a "hands-on" and experience-driven management style to a more data-driven approach and algorithmic rationality [39]. Although the technology can support a culture of trust through its tamper-proof recording capability [48], blockchain adoption faces several issues on a more human level. In this regard, Kurpjuweit et al. [49] argue that the successful implementation of blockchain is preceded by a supportive organizational culture that encourages employees and managers to take risks and deliberately push the implementation process.

2.1.6. Conversion to New Systems

A challenging issue facing agrifood organizations is the involvement of employees in new systems and organizational mechanisms that may include the use of new technology. As an emerging technology, blockchain integration in the organization may require modifying legacy systems [27]. In a recent study, Abreu and Coutinho [50] assert that numerous legacy systems lack direct interfaces to blockchains and require a substantial redesign when integrating data or blockchain-based functionalities with legacy systems. The immaturity of blockchain and its ongoing development raises further problems for system development and the integration of existing legacy systems [51,52]. For some early adopters of the technology, caution has been exercised to weigh the potential benefits of blockchain against the barriers to its implementation [53]. In addition, the intrinsic complexity of blockchain systems makes traditional ways for managing business processes inapplicable, thereby resulting in issues pertaining to ease of use, process delays, and resistance to adapt to the blockchain environment [35,46,48]. Therefore, managing the resistance to blockchain adoption within an organization is a complicated issue that needs to be tackled sensibly to motivate the active participation of employees, increase awareness, and avoid the failure of the adoption process.

2.1.7. Implementation Tools

Despite the predicted potential of blockchain, there also exists a substantial likelihood of failure. One of the explanations for this is the lack of tools necessary for the effective integration of the technology [27]. As such, blockchain is not a standalone technology, but rather depends on its integration into sensing technologies such as the Internet of Things (IoT) and Radio-Frequency Identification (RFID) [14,54,55]. Agrifood organizations are thus compelled to invest in these digital technologies, with a special focus on integrating real-time information and data processing tools to optimize production, facilitating traceability and increasing responsiveness to changing conditions in their supply chain [56–58]. Agrifood organizations also need accurate, robust, and efficient tools to ensure the transparent and efficient control of safety in raw materials in accordance with compliance standards [59]. Moreover, blockchain needs to be sustained by IoT capabilities to unleash its full potential and to provide process visibility, transparency, and data access [60]. However, Tsolakis et al. [48] believe that the supply, implementation, and maintenance of digital tools (e.g., IoT, sensors, RFID equipment) can be challenging due to infrastructural configuration requirements.

2.2. Interorganizational Barriers

2.2.1. Collaboration, Communication, and Coordination

Collaboration represents a vital prerequisite for improving supply chain effectiveness, particularly for farmers and their customers [61,62]. Collaboration, communication, and coordination are critical in reducing logistics costs and increasing partners' involvement in identifying and reducing waste across the supply chain. A lack of coordinated approaches can impede blockchain adoption [27]. Conflicting objectives, priorities, and incentives among the various entities may lead to several consistency problems, inefficiencies, and increased costs (e.g., production costs, inventory costs, long lead times) [28,33,63]. Despite the manifold advantages, Yadav et al. [46] argue that organizations may be reluctant to actually collaborate and engage in consortia creation. Potential reasons for this behavior are the urge to obtain individual advantages from technology adoption and a reluctance to work with competitors. It is crucial to overcome these barriers since collaboration must no longer be seen as an option, but rather as a necessity [64] that enables organizations to intelligently exploit blockchain technology and leverage its collaborative capabilities in the industry.

2.2.2. Information Disclosure Policy

Information disclosure is beneficial to partners in agrifood supply chains as it helps to reduce potential hazards in critical processes and ensure agrifood safety [65]. Although information disclosure represents a key variable in developing and maintaining mutual relationships between the stakeholders, it is a risky practice that can result in the loss of control, power, tactical flexibility, and image [66]. In this regard, the adoption of blockchain in the agrifood supply chain can be hampered by the challenges associated with the information disclosure policy between partners [27]. For example, Lin et al. [32] highlight that sensitive information disclosure is a major issue slowing the use of blockchain for agrifood traceability. The loss of information, inaccurate information dissemination, and inadvertently allowing access to confidential information to unauthorized parties are additional information disclosure risks in the agrifood supply chain [27]. Distrust among agrifood organizations through the data captured and disclosed by blockchain constitutes another emerging threat in agrifood supply chains that can lead to adverse consequences for collaborative relationships. This can be attributed to a perception of insecurity regarding blockchain and general suspicion toward its capabilities [54].

2.2.3. Integrating Blockchain Technology

Achieving sustainable development in an agrifood supply chain requires organizations to focus on a clear strategy for delivering healthy and high-quality agrifood products, thereby ensuring better economic, environmental, and social performance [67]. A clear path toward fostering agrifood supply chain sustainability is to benefit from blockchain's capabilities of reducing agrifood fraud, increasing product originality and quality, enforcing fair competition, and promoting sustainable practices among organizations [47]. Despite the fact that blockchain can be a potential contributor and a transition pathway toward sustainable agrifood supply chains, the integration of sustainable practices and blockchain is a complex task for many organizations and needs to be coordinated with numerous business partners. In this regard, Kouhizadeh et al. [27] state that some managers fail to establish long-term commitment and support for sustainability practices through supply chain processes, particularly after adopting new technology. Similarly, the transition toward sustainability is a challenging task that permeates an entire organization and necessitates that all industry stakeholders are committed to the realization of core sustainability objectives. This implies that a lack of reward systems to guarantee data integrity and incentivize sustainability initiatives by government and agrifood organizations can hinder the promotion of sustainable practices and blockchain technology within and across organizations [27]. Thus, agrifood organizations' overall orientation toward the combination of sustainability and blockchain represents a multi-phase and dynamic process that occurs over a long time and requires strenuous efforts to ensure sustainability in their supply chains.

2.2.4. Cultural Differences

Previous research has established that cultural differences can cause increased transaction costs and reduced cooperation [68]. Cultural gaps have the potential to heavily influence the operations of agrifood organizations, which in turn impacts their decisions pertaining to production planning, demand forecasting, and quality management. In the context of blockchain adoption, Kouhizadeh et al. [27] find that the cultural differences of supply chain partners regarding technology and sustainability yield diverse mindsets that can hamper blockchain implementation and transparency in the supply chain. Hew et al. [40] illustrate the case of Malaysia as a country with a conservative culture that prohibits the adoption of emerging technologies such as blockchain. Qian et al. [69] emphasize the need to create a culture of collaboration to accelerate the transition from traditional to blockchain-based agrifood supply chains.

Table 1 summarizes the main problems that we identified in previous research building on the categories from Saberi [26]. Additionally, we include related literature that goes further into detail as well as the measures that we used for their operationalization. We discuss the measures in some detail in the following sections, and the exact wordings can be found in Appendix A (Tables A1 and A2).

Table 1. Previous research findings and operationalization.

Barriers from Saberi et al. [26]	**Problems**	**Literature**	**Measures (See Tables A1 and A2 in the Appendix A)**
Intraorganizational			
Financial constraints	Lack of financial resources; lack of funding; unclear ROIs, unpredictable costs of blockchain implementation	[27–30,32–35]	B1, B2, B3, B4, OR4
Lack of management commitment and support	Missing blockchain strategy; poor understanding of technological advantages; immaturity of the technology	[10,27–33]	OR1, OR2, OR3
Lack of new organizational policies for using technology	Unclear use cases; lack of integration with operations and strategy	[27,36–40]	B8, B10, B11, B14, B16, B17, OR4, OR5, OR6, OR7
Lack of knowledge and expertise	Lack of qualified individuals; lack of awareness; unclear benefits	[35,39,41–45,70,71]	B5, B6, B7, B8, OR7
Difficulty in changing organizational culture	Gaining employees’ commitment; fostering understanding regarding blockchain	[27,39,46–49]	B17, OR1, OR3, OR5, OR7
Hesitation to convert to new systems	Necessary replacement of legacy systems; lack of compatibility between blockchain technologies and legacy systems; unclear benefits, redesign of business processes; resistance to change	[27,35,46,48,50–53]	B4, B12, B14, B15, B16, B17, OR1, OR2, OR3, OR4, OR5
Lack of tools for blockchain technology implementation	Lack of experience with tools; integration problems	[27,48,54–56,59,60]	B12, B13, B14, B15, B16
Interorganizational			
Problems in collaboration, communication, and coordination	Conflicting objectives; differing priorities and incentives among supply chain partners; competitive mindsets	[27,28,33,46,62–64]	B10, B11, B12, B13, B14, B16, B17, B18, B19, B20, B21, B22, OR5, OR6
Challenge of information disclosure policy	Potential loss of control, power, tactical flexibility, image; reluctance to share sensitive information; distrust	[27,32,54]	B10, B11, B12, B14, B15, B17, B20, B21, B22
Challenges in integrating blockchain technology	Lack of long-term commitment; difficult transition periods; lack of interorganizational reward systems	[27,47]	B10, B11, B12, B14, B16, B17, B20, B22
Cultural differences	Increased transaction costs; reduced cooperation; negative impact on operations; goal conflicts; legal issues; different privacy policies	[27,40,70]	B10, B11, B17, B18, B20, B21, B22

3. Methodology

The initial exploration of barriers to and drivers for blockchain adoption in supply chain was enabled by the early work of Saberi et al. [26] and van Hoek [72]. The conceptual study of Saberi et al. [26] established the main categories of blockchain adoption barriers, and the study of van Hoek [72] built upon this by conducting an initial measurement of the applicability of those barriers in a focus group setting. In an earlier paper, we reported on focus group findings that helped to operationalize the categories of barriers and drivers from literature into concrete items [73]. To further our understanding at the start of this research project, we extended this effort by conducting a larger study with two audiences at a US-based conference and at a Polish supply chain conference. Across the estimated 400 total attendees during the two conference sessions, we captured 190 responses. While the dataset represents a convenience sample, it served to further the exploration of blockchain adoption barriers as perceived by supply chain experts. The aim was not to achieve statistical generalization, but rather to explore possible patterns in a larger dataset. This in turn was used to focus our qualitative research stage, which included the analysis of various artifacts and the conducting of 10 interviews with supply chain managers. In these interviews, we specifically focused on intra- and interorganizational barriers in the agrifood industry to eliminate the confounding influence of the type of industry. The questions for the interviews can be found in Appendix B.

4. Results

In the following sections, we first present the results from our quantitative survey among 190 supply chain experts to answer RQ1a and RQ1b regarding the nature of intra- and interorganizational barriers related to general blockchain adoption and organizational readiness. Next, we present the findings from a qualitative survey among agrifood industry professionals to identify the resources companies in the agrifood industry can use to overcome the respective barriers (RQ2). Finally, we differentiate between coping strategies between incumbents and start-ups in the agrifood industry (RQ3).

4.1. Quantitative Results

Figure 2 illustrates the respondents' assessments of the respective organizational barriers as measured with several Likert-type items with a 7-point range, from 1 ("not at all") to 7 ("to a very large degree").

On average, the respondents' assessment hovered between 3 ("to a small degree") and 5 ("to a sizeable degree"), with many answers being close to 4, the midpoint of our scale ("to a modest degree"). It has to be noted, however, that there was substantial variation among the answers, and we received the full range of answers from 1–7 for each respective item. In a nutshell, items B1–B4 were related to the costs and uncertainties of blockchain implementation, B5–B9 measured the lack of understanding on the side of the companies, B10 and B11 were about data security and privacy concerns, and B12–B22 operationalized several technical, regulatory, collaborative, and cultural issues. Further details can be found in Table A1 in the Appendix A.

The most relevant organizational barriers to blockchain adoption turned out to be the widespread lack of understanding pertaining to the technology itself and its potential benefits. Furthermore, the experts also highlighted that it is uncertain how blockchain can be integrated with legacy systems, how high the resulting costs as opposed to the expected ROI will be, and what the current technical limitations of blockchain technology are. The three least relevant items turned out to be the actual implementation and deployment costs as well as the costs of having a blockchain pilot. Again, it has to be pointed out that the range of answers was relatively small, ranging from 4.39 (LOU about blockchain technology) to 3.11 (cost of blockchain pilot). This indicates that, on average, the experts agree that numerous relevant organizational barriers exist but none of them constitutes an insurmountable obstacle.

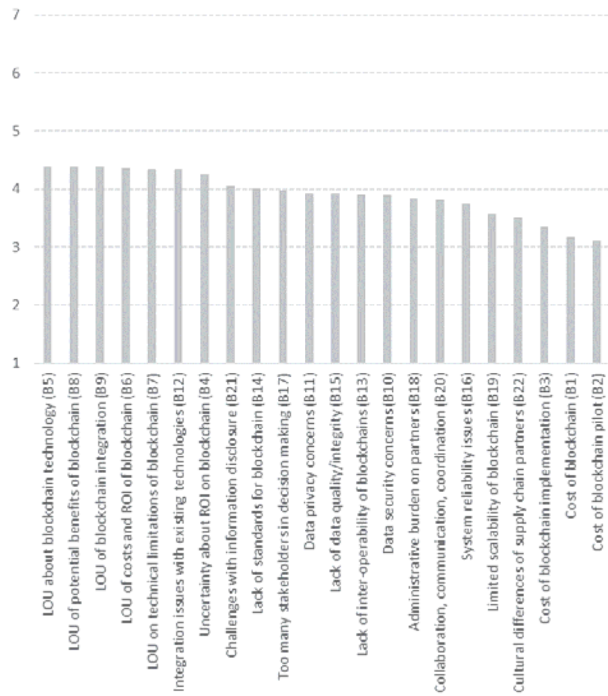

Figure 2. Average assessment of organizational barriers to blockchain adoption (n = 190; 1 = "not at all"; 7 = "to a very large degree"; LOU: Lack of Understanding).

In spite of the average assessment pertaining to the importance of existing barriers to blockchain adoption, organizations do not consider themselves to be ready yet, as can be seen in Figure 3.

The average assessment regarding the various readiness dimensions hovers around values between 2 ("to a very small degree") and values slightly higher than 3 ("to a small degree"). It has to be noted, again, that the full range of answers showed a high level of dispersion, ranging from 1 to 7 for all questions. OR1–OR3 measure the internal recognition of the importance of blockchain as well as the management's engagement. OR4–OR7 refer to an existing business case, strategy, roadmap, and dedicated team, respectively. Again, more descriptive statistics can be found in Appendix A.

When it comes to the respective criteria of organizational readiness, executive engagement and the general recognition of blockchain's potential came first, followed by the engagement of operational management. Conversely, an existing roadmap and a dedicated team were the two drivers of organizational readiness that came in last. On average, the experts perceive a fairly low level of organizational readiness when adopting blockchain.

In a next step, we explored the underlying factor structure for our measurement items that were not based on previous research but rather gained from operationalizing the barriers suggested in the literature. Following the recommendation from Treiblmaier and Filzmoser [74], we conducted an exploratory factor analysis (EFA) using the scree plot and Eigenvalues > 1 as criteria for selecting the number of factors and an orthogonal Varimax rotation to facilitate the interpretation of the factors. Since the factor structure was not known ex-ante, our research aimed to investigate the preliminary construct validity. As can be seen in Table A3 in Appendix A, the four emerging factors mimic the aforementioned structure of (1) cost and uncertainty, (2) lack of understanding, (3) security and privacy, and (4) technical, regulatory, collaborative, and cultural issues, with only one single item (B4:

Uncertainty about ROI on blockchain) exhibiting a cross-loading. In summary, these items can be used as a foundation for further scale development and future quantitative studies.

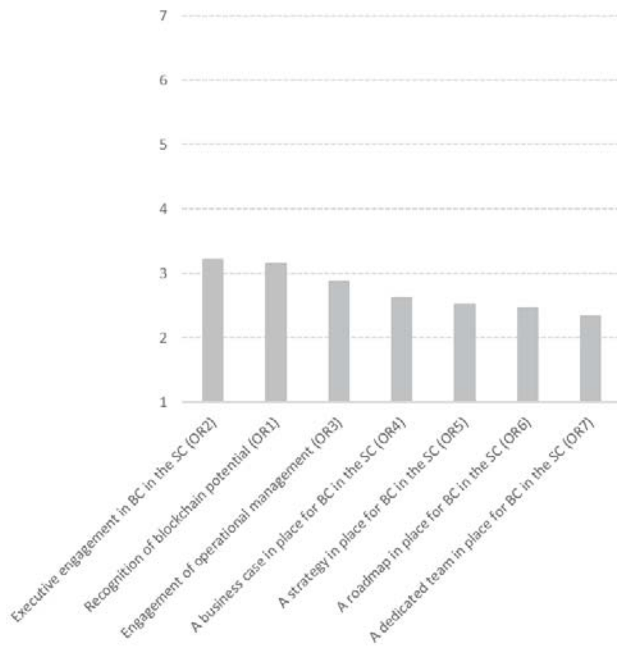

Figure 3. Average assessment of organizational readiness to blockchain adoption (n = 190; 1 = "not at all"; 7 = "to a very large degree").

4.2. Qualitative Results

After confirming the importance of the respective barriers as well as assessing organizations' insufficient level of preparedness to cope with them, we explored coping strategies and techniques, with a special focus on the agrifood industry. In order to do this, we used a number of evidentiary sources that include online material from companies (e.g., reports, video presentation), panel discussions, and in-depth qualitative interviews [75]. In total, 10 interviews were conducted with managers involved in blockchain-based IT projects from incumbents (6) and start-ups (4), respectively, until a level of theoretical saturation was reached, and no further resources and capabilities emerged. The companies operated in different agrifood supply chains, including meat, beverages, wool, and agrifood health products. We explicitly differentiated between incumbents and start-ups to consider the varying resources they possess and their respective level of specialization [18–20].

In Table 2, we summarize the main resources that companies in the agrifood supply chain use following the framework shown in Figure 1 and further illustrate whether there are any relevant differences in the coping strategies between incumbents and start-ups.

In order to successfully cope with the first major intraorganizational barrier, namely financial constraints, dedicated budgets for blockchain adoption are needed. Given the novelty of the technology, the total costs of implementation and operation are hard to calculate. Incumbents and start-ups deal with financial bottlenecks in different ways. While the former mostly depend on internal funding (including financial support from parent organizations and global budgets), the latter frequently need to find external support, which might come in the form of equity or loans. Additionally, public funding provides an alternative strategy for start-ups.

Table 2. Bridging techniques and capabilities to overcome barriers to blockchain adoption in the agrifood industry.

	General Resources and Capabilities	Specific Resources and Capabilities	
Barrier		**Incumbent**	**Start-Up**
Intraorganizational			
Financial constraints	Dedicated budget	Internal budget; internal sponsor; parent organization; global budgets	External investments; venture capital; seed funding; crowdsourcing; public funding; voluntary contributions
Lack of management commitment and support	-	Bottom-up information about benefits; external advisory; creating minimum viable products	Not applicable
Lack of new organizational policies for using technology	-	Restructuring and educating existing units; process redesign	External advice (e.g., for regulatory compliance)
Lack of knowledge and expertise	Education; specialist training; outsourcing	Technology consultants; in-house training	Business consultants; technology consultants; active networking; communities
Difficulty in changing organizational culture	-	Management support; external consulting; internal change management	Not applicable
Hesitation to convert to new systems	-	Management support; internal support; resource reallocation	Not applicable
Lack of tools for blockchain technology implementation	Outsourcing; consulting; development; staying updated	Integration with existing systems	Not applicable
Interorganizational			
Problems in collaboration, communication, and coordination in the supply chain	Standards; contracts; encouraging platform use; creating incentives; communicating value and benefits	Established partnerships and trust relations; joint ideation; main incumbent can fund the majority of the initial adoption	Brand building; trust building; creating markets need to articulate the business case to all parties and secure funding; who is going to pay for this?
Information disclosure policy	Regulatory compliance; transparency pertaining to information use	Governance structure development	Trust building
Problems with integrating blockchain technology	Internal competence; external consulting; talent scouting; interorganizational cooperation	Scope of adoption to part of the supply chain and consider scaling broader later	Partial supply chain scope simplifies initial adoption
Cultural differences	Communication; clear procedures and responsibilities	Established partnerships and trust relations	Brand building; trust building

Lack of management commitment may pose a major hurdle that incumbents try to overcome with an internal bottom-up informational strategy, external advice (e.g., from specialized consulting companies), and the creation of prototypes that should illustrate the viability of the technology. When it comes to missing organizational policies, incumbents need to change existing structures and processes and refer to internal restructuring and process redesign, whereas start-ups in the blockchain space usually design their business models from scratch to account for the idiosyncrasies of the technology. Occasionally, start-ups also refer to external support and mentoring, the latter of which is sometimes included in state-funded support campaigns. The current lack of knowledge and expertise is equally perceived by incumbents and start-ups, and the existing market supply is insufficient to fulfil the demand of the industry regarding developers in that area. Incumbents are regularly capable of paying higher wages and recruiting skills from existing labor markets, but they also foster in-house education. Start-ups also occasionally rely on external consultants, active networking (e.g., via social media), and existing communities. Most notably, several start-ups also indicated that they rely on external support for business matters, which is less frequently the case for incumbents. Cultural issues and the hesitation to convert to new systems only pose a problem for incumbents, which is not surprising since the start-ups were specifically founded for blockchain projects, and their internal procedures are aligned with the requirements of blockchain adoption. Consequently, several incumbents find it difficult to adapt their existing culture and processes to decentralized systems that often require a change in thinking, which is especially profound in cases where decentralization affects existing power structures [76]. In order to cope with this problem, they refer to internal change management but also frequently consult external advisors.

The final intraorganizational barrier pertains to a lack of tools, many of which are not fully developed and frequently require extended testing periods. Again, outsourcing and external consulting provide viable strategies for all companies, although this option is more frequently pursued by incumbents. As opposed to start-ups, incumbents also have to deal with the integration with legacy systems, which can be seen as another barrier but also as a resource, since they do not frequently need to develop a system completely from scratch but can rely on existing infrastructure.

As far as interorganizational barriers are concerned, collaboration, communication, and coordination along the whole supply chain turned out to be the most complex barrier to overcome for both incumbents and start-ups. They all stress the need to create common standards (which is frequently beyond the capability of a single company), but also to draw up contracts that are in line with the idiosyncrasies of blockchain (e.g., when it comes to the immutability of data) and actively communicate the value and benefits of blockchain-based platforms to their partners.

Quite obviously, established companies can rely on their existing networks and can include their business partners in the design and creation of blockchain-based networks. In contrast, start-ups first need to build their brand and create trust-based relationships with their business partners, which necessitates the alignment of numerous strategic and operational processes [77,78]. When it comes to the information disclosure policy, the interviewees highlighted the need to follow existing regulations and to communicate this within their respective business circles. Again, transparency in information use is a major resource and a prerequisite for sustainable supply chain relationships.

Concerning problems pertaining to the interorganizational integration of blockchain technology, both incumbents and start-ups either rely on their in-house competencies or interorganizational cooperation. Alternatively, both refer to external support, as was the case with the intraorganizational barrier labeled “lack of knowledge and expertise”. Finally, cultural differences pose a well-known barrier that is fairly pronounced in supply chain networks. Since the adoption of blockchain technologies regularly implies increased data sharing and transparency, close cooperation based on trust and clear procedures and responsibilities are seen as the main capabilities needed to overcome this barrier. In this regard, incumbents can rely on their established networks while start-ups still need to develop their brand and long-lasting relationships.

Generalizing our findings, Table 3 summarizes the major barriers and bridges of the 4 start-ups and 6 incumbents as well as differences and similarities when it comes to blockchain adoption.

Table 3. Overview of differences in blockchain barriers and adoption between start-ups and incumbents.

	Start-Up	Incumbent
Differences in barriers and bridges	Investment costs; "who will pay for it?" Less concern about existing infrastructure	Uncertainty of running costs
Similarities in barriers and bridges	Need to drive inter- and intra-organizational engagement and make the case for all parties Very targeted use cases of blockchain to focus on adoption	
Differences in blockchain adoption	Can go fairly quickly with less internal hurdles to clear	Can drive scaling across the supply chain more effectively with scale and leverage
Similarities in blockchain adoption	Part of the supply chain in scope; adoption is not (yet) end-to-end More learning about interoperability, costs, and change management needed	

5. Discussion and Implications

Previous research and evidence from the industry has indicated numerous potentials of blockchain technology for supply chain management [23,62]. However, the disruptive nature of the technology necessitates significant changes within and between organizations, which leads to the emergence of adoption barriers [79]. While these barriers have been identified and categorized in previous literature [31,72], a structured approach was missing to highlight the resources that companies can deploy to overcome them. In this paper, we close this research gap and build on a comprehensive literature review, a quantitative survey, and an in-depth qualitative study to identify and categorize the respective resources and capabilities. Furthermore, we exemplify our findings by focusing on the needs of the agrifood industry and differentiating between incumbents and start-ups. Specifically, we illustrate that different resources are needed for successful blockchain adoption depending on a company's experience and relations in the market.

5.1. Theoretical Contributions

From an academic perspective, our exploratory study postulates that numerous strategic resources exist, which a firm can exploit to achieve sustainable competitive advantage. The identification of these resources, which we accomplished in this paper, will support future academic research that strives to dive deeper and investigates how a specific resource in one of the established categories can actually impact a company's effectiveness or efficiency [80]. This research stream can build heavily on the resource-based view of the firm, with the goal of identifying those resources that can gain a competitive advantage for a company [23,55].

Our study extends previous conceptual and empirical research in the agrifood industry in that we highlight how substantial investments in hardware, software, and knowledge are needed if companies in the agrifood company want to adopt blockchain [29]. More specifically, we build on previous research and identify those operational barriers that specifically impede the adoption of blockchain technology [30]. Prior studies have also identified lack of government regulation and trust among stakeholders as major adoption barriers [46], which our study confirms and extends by highlighting additional and more refined impediments. We also detail specific measures related to some of the more generic challenges (e.g., organizational, social, technological) outlined in previous literature [56].

Previous research agrees on the importance of several key factors such as traceability in agrifood chains and the suitability of blockchain to foster transparency [57,58]. Our research contributes to this growing body of literature by pinpointing specific barriers and highlighting the differences between start-ups and incumbents, which has been largely ignored so far. We also contribute to existing literature, which stresses the importance of interorganizational cooperation as an antecedent of successful blockchain adoption and deployment [61,62]. The resources and capabilities that we identify in this paper provide some indications for tackling pending problems in interorganizational communication and collaboration.

This study therefore provides fertile ground for a plethora of novel research questions and allows for interesting comparisons between companies and industries when it comes to blockchain adoption [81]. Furthermore, measures need to be developed to operationalize the impact of specific resources [82], which can be achieved by building on the operationalizations that we introduce in this study (see Appendies A and B). All of these tasks are important prerequisites for further rigorous studies that help to build a theory-based academic research agenda [83].

5.2. Managerial Contributions

From an industry perspective, the presented resources and capabilities represent those pain points that companies need to tackle in order to successfully integrate blockchain technology into their agrifood supply chain. More specifically, the application of blockchain can help to streamline agrifood chains and tackle several important issues such as the need to reduce food waste [2,3], to increase food chain sustainability [4], and to ultimately improve the quality and healthiness of food products [67]. Furthermore, the bridging techniques and capabilities presented in this paper provide viable managerial policies and strategies which can help to realize the benefits of blockchain that previous research identified for the agroindustry [9]. Our results also provide some indications on how to overcome existing challenges pertaining to the lack of trust and governance, which is an important obstacle in the industry [10].

Further work in this area can include the development of checklists that help managers to better understand their current blockchain adoption status and which issues they need to tackle to overcome existing barriers. A systematic interorganizational analysis of blockchain adoption barriers and the resources needed to bridge them will also help industry associations and standardization bodies to detect problems that can only be solved from an overarching perspective.

6. Conclusions, Limitations, and Further Research

This study presents a snapshot of existing blockchain adoption barriers in supply chains and potential corresponding solutions, with a specific focus on the agrifood industry. The technology in this area is advancing fast, as is the surrounding environment, which includes legislation and regulation. Our findings are also limited by the size and the composition of the quantitative and qualitative samples that we used, and we recommend that replication studies be conducted, with a special focus on other sectors in the industry and different stakeholder groups. Several of the critical resources that we identify in this paper might be commonly available in the future and no longer be a pending issue, while new barriers that lead to the emergence of new critical resources might yet arise.

Furthermore, we have presented all intra- and interorganizational barriers as independent of each other, which might not be the case in the real world and yields numerous interesting research questions as to what extent these barriers can be addressed simultaneously. In summary, we believe that this paper provides the foundation for numerous research streams, be it the development of more refined frameworks, models, or theories in academia or the identification of important pain points in the industry as well as the resources and strategies that are necessary to overcome them.

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Appendix A. Quantitative Survey

Table A1. Barriers. To what degree is your company experiencing the following barriers to blockchain in the supply chain?

		Mean	SD	Var	Min	Max
B1	Cost of blockchain	3.17	1.84	3.39	1	7
B2	Cost of blockchain pilot	3.11	1.76	3.09	1	7
B3	Cost of blockchain implementation	3.34	1.85	3.43	1	7
B4	Uncertainty about ROI on blockchain	4.25	1.95	3.81	1	7
B5	Lack of understanding (LOU) about blockchain technology	4.39	1.9	3.61	1	7
B6	LOU of costs and ROI of blockchain	4.35	1.9	3.62	1	7
B7	LOU of technical limitations of blockchain	4.34	1.87	3.52	1	7
B8	LOU of potential benefits of blockchain	4.39	1.93	3.72	1	7
B9	LOU of how to integrate blockchain into existing supply chain processes	4.39	1.97	3.87	1	7
B10	Data security concerns	3.89	1.94	3.75	1	7
B11	Data privacy concerns	3.93	1.97	3.87	1	7
B12	Integration issues with existing technologies	4.34	1.91	3.64	1	7
B13	Lack of interoperability of blockchains	3.91	1.87	3.51	1	7
B14	Lack of standards for blockchain	4.01	1.84	3.39	1	7
B15	Lack of data quality/integrity	3.92	1.86	3.46	1	7
B16	System reliability issues	3.75	1.82	3.31	1	7
B17	Large number of stakeholders involved in decision making about blockchain	3.98	1.95	3.8	1	7
B18	Administrative burden of blockchain on supply chain partners	3.83	1.82	3.29	1	7
B19	Limited scalability of blockchain	3.57	1.83	3.36	1	7
B20	Collaborating, communicating, and coordinating in the supply chain	3.82	1.85	3.41	1	7
B21	Challenges in information disclosure policy between supply chain partners	4.06	1.92	3.68	1	7
B22	Cultural differences of supply chain partners	3.52	1.94	3.77	1	7

(1: not at all; 2: to a very small degree; 3: to a small degree; 4: to a modest degree; 5: to a sizeable degree; 6: to a large degree; 7: to a very large degree; $n = 190$).

Table A2. Organizational readiness. To what degree does your company have . . . .

Var	Text	Mean	SD	Var	Min	Max
OR1	Recognition throughout the company of the potential of blockchain in the supply chain (BC in the SC)	3.15	1.71	2.91	1	7
OR2	Executive engagement in BC in the SC	3.22	1.79	3.21	1	7
OR3	Engagement of operational management in BC in the SC	2.87	1.7	2.89	1	7
OR4	A business case in place for BC in the SC	2.62	1.69	2.86	1	7
OR5	A strategy in place for BC in the SC	2.52	1.71	2.94	1	7
OR6	A roadmap in place for BC in the SC	2.46	1.71	2.92	1	7
OR7	A dedicated team in place for BC in the SC	2.33	1.71	2.92	1	7

(1: not at all . . . 7: to a very large degree; $n = 190$).

Table A3. Factor analysis.

	Factor1	Factor2	Factor3	Factor4
B1			0.885	
B2			0.899	
B3			0.866	
B4		0.625	0.409	
B5		0.839		
B6		0.848		
B7		0.821		
B8		0.697		

Table A3. *Cont.*

	Factor1	Factor2	Factor3	Factor4
B9		0.741		
B10				0.807
B11				0.845
B12	0.657			
B13	0.671			
B14	0.661			
B15	0.653			
B16	0.718			
B17	0.690			
B18	0.819			
B19	0.751			
B20	0.720			
B21	0.673			
B22	0.612			
SS loadings	6.197	4.400	3.076	2.053
Proportion Var	0.282	0.200	0.140	0.093
Cumulative Var	0.282	0.482	0.621	0.715

(Four-factor solution based on scree plot and Eigenvalue > 1; varimax rotation; items with loadings below 0.4 were suppressed).

Appendix B. Interview Guideline for the Qualitative Survey

Intraorganizational barriers
Does your company face the following intraorganizational barriers?
If so, what kind of measures do you take or resources do you use to overcome them?

- Financial constraints;
- Lack of management commitment and support;
- Lack of new organizational policies for using blockchain technology;
- Lack of knowledge and expertise;
- Difficulties in changing organizational culture;
- Hesitation to convert to new systems;
- Lack of tools for blockchain technology implementation in sustainable supply chains.

Interorganizational barriers
Does your company face the following interorganizational barriers?
If so, what kind of measures do you take, or resources do you use to overcome them?

- Problems in collaboration, communication, and coordination in the supply chain;
- Challenges of information disclosure policy between partners in the supply chain;
- Challenges in integrating sustainable practices and blockchain technology through SCM;
- Cultural differences of supply chain partners.

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Article

Using Blockchain Technology to Foster Collaboration among Shippers and Carriers in the Trucking Industry: A Design Science Research Approach

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Abstract: In the global trucking industry, vertical collaboration between shippers and carriers is attained by intermediaries, called brokers. Brokers organize carriers for a shipper in accordance with its quality and price requirements, and support carriers to collaborate horizontally by sharing a large distribution order from a shipper. Brokers also act as trustees, preventing the passing of private information of any party to the others. Despite these benefits, intermediaries in the trucking industry are involved in several sustainability problems, including high costs, high levels of carbon emissions, high percentages of empty miles, low-capacity utilizations, and driver shortages. Several studies have acknowledged the importance of improving collaboration to address these problems. Obviously, the major concern of brokers is not collaboration, but rather to optimize their own gains. This paper investigates the potential of blockchain technology to improve collaboration in the trucking industry, by eliminating brokers while preserving their responsibilities as organizers and trustees. This paper extends the transportation control tower concept from the logistics literature, and presents a system architecture for its implementation through smart contracts on a blockchain network. In the proposed system, the scalability and privacy of trucking operations are ensured through integration with privacy-preserving off-chain computation and storage solutions (running outside of the blockchain). The potential of this design artifact for fostering collaboration in the trucking industry was evaluated by both blockchain technology experts and trucking industry professionals.

Keywords: blockchain; trucking; collaboration; trustee; transportation control towers

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1. Introduction

Despite its significant contributions to the economic growth and social welfare of all nations around the world, the global trucking industry suffers from many problems, mainly due to the heavily fragmented nature of the industry, as well as the poor level of collaboration among its involved parties.

Traditionally, trucking operations between shippers and carriers have been orchestrated by freight brokers acting as organizers and trustees in the industry. Brokers organize carriers for a shipper in accordance with its quality and price requirements, and support carriers to collaborate horizontally through sharing large distribution orders from shippers. Brokers also act as trustees, preventing the passing of private information of any party to the others. Considering the fragmented structure of the carrier market, with its high degree of competition, brokers currently play an important role in bringing shippers and carriers together in the industry. However, this business model, centralized around freight brokers, also limits collaboration opportunities among shippers and carriers and further aggravates the problems in the trucking industry.

The global trucking industry has been undergoing a digital transformation in recent years, thanks to the adoption of GPS, Internet of Things (IoT), mobile and Internet technologies, and data analytics. However, more innovative information and communication technology (ICT) solutions are still needed to encourage collaborative business models in the industry, by addressing the trust problems among the involved parties.

As an emerging technology intrinsically supporting decentralized and trustless business models, the blockchain has the potential to disrupt the trucking industry by eliminating the need for intermediaries between shippers and carriers. However, despite the potential that blockchain technology offers, there is a gap in the literature around understanding the application areas of this new technology in the logistics industry. In a recent study, blockchain application areas (BAAs) in supply chain transactions, their likelihood of being implemented, and their impact were investigated through a multimethod approach, combining an extant literature review, a Delphi study, and surveys completed by 151 business managers [1]. According to the findings of that study, even though the "logistics and delivery systems" BAA was initially not identified in the literature search, it surfaced during the Delphi study, and it ranked among the top three BAAs in terms of application likelihood. The results of that study clearly indicate the gap in the literature on the potential of blockchain technology for logistics and delivery systems. Our study aimed to help fill that gap in the literature by exploring a potential application area of blockchain technology in the trucking industry.

More specifically, this research aimed to achieve the objective of utilizing blockchain technology and other relevant technologies to improve collaboration among shippers and carriers in the trucking industry. To achieve this objective, this study investigated the following specific research questions:

1. Can the transportation control tower concept from the logistics literature be extended by operationalizing it in a decentralized fashion on a blockchain network, where the need for a neutral and independent trustee is eliminated?
2. How can we address the scalability and privacy issues of transactions of trucking operations managed on the blockchain?

This paper contributes to the literature in several ways. Firstly, to the best of our knowledge, this is the first study addressing the collaboration problem in the trucking industry from an information systems perspective, even though the importance of ICT solutions in improving collaboration has been acknowledged in a variety of EU, WEF, and OECD reports. Secondly, our work presents a unique use case for blockchain technology in the logistics industry: a decentralized transportation control tower, designed to achieve the same functionality as traditional trustee models without the need for a trusted intermediary. Finally, this study presents a solid business case, where integration with privacy-preserving off-chain (storage and computation) approaches addresses the privacy and scalability issues of blockchain applications.

The rest of this paper is structured as follows. In Section 2, the literature on the economic, social, and environmental impacts of the global trucking industry; the collaboration types in the trucking industry; the transportation control tower concept; and the use of ICT and blockchain solutions in the trucking industry is reviewed. In Section 3, the design science research (DSR) method, the main methodology in this study, is explained; the research relevance is presented by investigating the structure and leading problems of the trucking industry; and the design artifact, together with its system architecture, is generated based on the findings in the literature and the research relevance. In Section 4, the opinions of blockchain technology experts and trucking industry professionals are shared in order to evaluate the proposed design artifact in terms of its contribution to the knowledge base, as well as its technical viability and application in the trucking industry. In Section 5, the managerial implications of the proposed design artifact are discussed in detail. Finally, the concluding remarks and future research directions are provided in Section 6.

2. Literature Review

2.1. Impact of the Trucking Industry on Economy, Society, and the Environment

Road freight transportation, or trucking, is the primary form of shipping for domestic, trans-border, and international cargo, representing over 70% of the global freight bill, and an even higher percentage of cargo value around the world. Generating a significant proportion of the GDP in many nations, road freight transport is the backbone of the global economy and is vital to production, distribution, reverse logistics, and any type of mobilization of goods [2–5].

From a social perspective, road freight transportation touches every individual in society by employing millions of people and providing access to jobs, housing, and goods and services. A complete halt of trucking operations for a single week would result in serious disruptions in meeting the most basic needs of a society, such as food supply, waste collection, and medical services [6,7]. This fact became painfully clear during the COVID-19 pandemic, where employees in the logistics sector had to work relentlessly to provide for the basic needs of people under lockdown. During this period, Amazon Prime deliveries took as long as a month for some items that would usually arrive in two days, as the e-commerce giant struggled to keep up with the surge in demand for hygiene products. However, although trucking has a major social impact on the well-being of a population, the trucking industry is currently suffering from low social value and comparably heavy work conditions, due to fierce competition in global markets [8]. Drivers complain about long working hours (traveling 120 K miles annually, with 240 days away from home on average [9]), and low/delayed payments. Carriers suffer from driver shortages and low rates of driver retention. Shippers are challenged by high transportation costs, resulting from empty miles and the low level of load factors.

On the other hand, despite growing attention to green energy in recent years, global freight transport is still heavily dependent on fossil fuels (mostly oil), and produces a significant fraction of the greenhouse gases released into atmosphere globally. In fact, air pollution, high noise levels, and congestion/accidents—due to increased traffic from heavy-duty trucks—are major threats to the environment, especially in metropolitan areas [10,11]. Since trucking demand is expected to increase in the coming years, in parallel to the growth of e-commerce, these problems will only increase in significance in the future [12].

Due to the aforementioned economic, social, and environmental impacts of road freight transportation, policy makers and organizations in the trucking industry around the world are seeking innovative business models and technology solutions for mitigating the risks and threats of road freight transportation.

The main difficulty in generating solutions is the fact that road freight transportation is a complex operation, involving many parties in the process, including shippers, carriers, freight brokers, regulators, insurance companies, and financial companies (banks or factoring companies). Bringing so many different parties together, and resolving conflicts as they arise, are significant challenges for the trucking industry, which is more or less still operating based on 30-year-old business models in most parts of the world [13]. Unfortunately, traditional business models, where shippers and carriers maintain an indirect relationship with each other through middlemen (brokers), are not helping to resolve these highly complex, multi-faceted problems. In fact, these problems have already been addressed in numerous industry reports generated by the European Union (EU), the World Economic Forum (WEF), the Organization for Economic Co-operation and Development (OECD), and various research organizations [14–16]. In these reports, improved collaboration among the parties involved is repeatedly highlighted as a key concept. Moreover, the development of innovative information and communication technology (ICT) solutions for collaboration is recommended as the key solution for addressing the current problems of the trucking industry.

2.2. Collaboration Types and the Transportation Control Tower Concept

Collaboration in logistics is achieved when two or more parties (shippers, customers, carriers, or 3PLs) exchange or share resources (tangible or intangible) such as trucks, or demand information with the goal of generating benefits that cannot be achieved individually. The intensity of collaboration among partners can range from information exchange, to joint planning, to joint execution, to a strategic alliance [17].

Collaboration in logistics can be realized in two forms: vertical collaboration and horizontal collaboration [18]. In vertical collaboration, partners at different levels of a supply chain (such as a shipper and a carrier) share or exchange resources [19]. In horizontal collaboration, competing organizations operating at the same level of a supply chain (such as two shippers or two carriers) build a partnership to increase the value gain and to better utilize their resources [20].

The supply chain management literature has an abundance of studies on vertical logistics collaborations [21,22]. A large number of studies have examined vertical collaboration models between manufacturers and retailers. Among the vertical collaboration models, Vendor-Managed Inventory (VMI) and Collaborative Planning, Forecasting, and Replenishment (CPFR) have generated great interest among researchers and practitioners in the supply chain domain [23–25].

In recent years, there has been an increasing interest among researchers around analyzing concepts, methods, and mathematical models related to horizontal collaboration in logistics and transportation domains [26–29]. The focus on those studies has been generally on the application of game theory to coalition formation and gain sharing issues, the mechanism of design for exchanging requests, and developing optimization models for collaborative transportation planning. However, surprisingly, ICT issues and opportunities have received less attention in the literature, despite the importance of real-time information exchange in horizontal collaboration [26].

Both vertical and horizontal collaboration practices are limited today in the trucking industry, where transactions are heavily orchestrated by freight brokers. However, considering the size and fragmented structure of the carrier market, horizontal collaboration among carriers will be particularly important in addressing the sustainability problems of the trucking industry at the strategic level. With horizontal collaboration, carriers can increase productivity for core activities (implementing joint route plans, decreasing empty hauling, increasing load factors, reducing nights away from home, etc.), and reduce costs related to non-core activities (vehicle purchasing, fuel, training, etc.). Furthermore, horizontal collaboration also enables small-or medium-sized carriers to tender with large shippers on larger contracts that they would not be able to fulfill individually due to capacity constraints. Scaled up carriers can offer a better quality of service at lower costs to their customers, for example, in terms of speed, frequency of deliveries, geographical coverage, and reliability of delivery times.

Information sharing among collaborating parties (for example, operational plans, existing orders, current and future capacity levels, etc.), alignment of individual and joint goals of collaborating parties, existence of rapid dispute resolution mechanisms, and availability of ICT infrastructure for faster and secure data exchanges among partners are facilitating factors for horizontal collaboration in the trucking industry. On the other hand, difficulties in finding a reliable business partner, risks related to the misuse of sensitive information by malicious partners, challenges in sharing costs and gains fairly among partners, and the lack of ICT solutions are impediments to horizontal collaboration in the trucking industry [30–34].

It should be noted that information sharing among involved parties is both a facilitator and an obstacle to the success of horizontal collaboration in the trucking industry. A carrier's ability to earn the trust of its competitors is one of the most important factors for achieving collaboration among carriers. The problem is further complicated due to the increasing competition in the trucking market, as well as the lack of effective coordination between the key parties involved [35]. Transparently sharing business plans and other relevant business information with partners contributes to the growth of trust among partners, and reinforces the alignment of the individual and joint goals of partners. However, misuse of that information by a malicious partner might have serious consequences for the other partner. Depending on the initial strengths and weaknesses of the partners and how these strengths and weaknesses change over time, smaller companies in a partnership might lose clients or be pushed out of the market completely over time.

Transportation control towers or trustee organizations are fairly new concepts being discussed in the logistics literature, to eliminate the trust issues among involved parties when practicing horizontal collaboration in the trucking industry. Basically, a trustee is an independent, neutral, and reliable third party that collects data from collaborating parties, keeps the shared data strictly confidential, and processes the data with the goal of maximizing gains for all partners [36–38].

The trustee—a central independent third party—concept sounds promising in theory; however, a mechanism is still needed to ensure the neutrality and fairness of the trustee in its decisions when consolidating loads from different shippers, delegating the loads to carriers, and distributing the gain to participants. In addition, this tight-coupling business model with an independent trusted organization bears the single point of failure risk for the industry. If the trustee loses its neutrality or cannot function any longer for whatever reason, the financial impact would be a huge burden for the involved shippers and carriers, considering the sizable economic activity of the trucking industry. For this reason, the trustee concept needs to be bolstered by an innovative ICT solution for ensuring the neutrality of the trustee, while also allowing shippers and carriers to validate the trustee's decisions without compromising the privacy of shared data.

2.3. Use of ICT Solutions and Blockchain in the Trucking Industry

Cloud computing, big data, advanced data analytics, and Internet of Things (IoT) technologies have impacted the trucking industry in recent years [16]. These ICT innovations are transforming businesses by providing better connections through mobile and web technologies, and generating smarter decisions with data analytics. While these solutions are improving the efficiency of the daily operations of carriers, they have not been successful so far in promoting horizontal collaboration among carriers in the trucking industry.

In addition, online freight matching platforms have gained popularity recently in the trucking industry. Acting as centralized electronic marketplaces, these platforms match shipper demand for carrier/trucking capacity using mobile or web-based technology applications. In a nutshell, shippers/freight brokers post their load requests for the spot market on these electronic marketplaces, and carriers offer their rates digitally for these loads. Once a load is matched with a carrier, the status of the cargo is tracked on the platform during its entire journey. However, these platforms mainly rely on the reputation of participants, and they suffer from entry barriers for new participants [39]. In fact, it becomes extremely difficult for a party to switch to another platform once it adapts to the technology and establishes a reputation on a particular platform [40,41]. In addition, dispute resolutions with a trusted third party take too long in centralized electronic marketplaces [39,42]. Finally, shut-down of the platform in extreme cases, and misuse of confidential data collected from all stakeholders, are other potential risks associated with these centralized marketplaces [39]. Hence, online freight matching platforms are not satisfactorily overcoming the weaknesses in regards to practicing horizontal collaboration in the trucking industry at present. In addition, the impact of these platforms on the overall trucking industry has been quite limited, since they are mainly used for spot market transactions, which are a considerably smaller proportion of the industry compared to contract market transactions (10% vs. 90%) [43].

Finally, blockchain technology has emerged in recent years, and has already disrupted many industries. Businesses that could previously run only through a trusted intermediary can now operate in a decentralized fashion, without the need for a central authority, and achieve the same functionality with the same amount of certainty. This was simply not possible before. The absence of a trusted intermediary means faster reconciliation between the transacting parties [44]. Even though it initially gained popularity in the finance industry by allowing the transfer of cryptocurrencies (for example, Bitcoin and Etehereum) between parties, it has found use cases in other industries as well.

A blockchain is essentially a distributed database of records, or a public ledger of all transactions and digital events that have been carried out and shared among all participants in a network. Each transaction is verified by consensus of a majority of the participants in the network before being recorded into the ledger with cryptographic functions [45,46]. The records, once entered into the public ledger, can never be erased, and they cannot be altered retroactively without alteration of all subsequent blocks and the consensus of the network functions [45]. Smart contracts are one of the most important applications of blockchain technology. A smart contract is an executable code that runs on the blockchain to facilitate, execute, and enforce the terms of an agreement between untrusted parties, once the pre-defined rules have been met [46].

There are two main types of blockchain: public and private. The sole distinction between them is related to who is allowed to participate in the network, execute the consensus protocol, and maintain the shared ledger. A public blockchain network is completely open and anyone can join and participate in the network, to conduct transactions or validate the transactions of others (for example, bitcoin miners). One of the drawbacks of a public blockchain is the lack of privacy of transactions, since they are broadcast to every single participant (node), and every node thus keeps a complete record of the entire transaction history. On the other hand, a private blockchain is a permissioned blockchain which is hosted on private computing networks, and uses an access control layer to govern who has access to the network. Participants need to obtain an invitation or permission to join the network. In contrast to public blockchains, transactions are validated by a pre-selected set of participants who have been vetted by the network owner, and only the entities participating in a transaction will have knowledge of it; others will not be able to access it. One of the biggest drawbacks of a private blockchain is the inherent centralization that they use to offset the scalability and privacy problems of public blockchains. When you are part of a private blockchain, by design you are placing your trust in a central source.

Due to data protection (privacy) concerns, most commonly organizations have preferred deploying private solutions in lieu of using public blockchains in the supply chain industry. For example, TradeLens—a global commercial blockchain platform developed by the joint venture of IBM (Armonk, NY, USA) and Maersk (Copenhagen, Denmark) in 2018—reduced paperwork and improved the workflow and visibility of containers in international maritime transport [47]. Participants of the platform are able to track the progress of cargo during its entire journey, and can access to customs documents, bills of landing, and any other details of the transactions recorded in the blocks. Furthermore, using IBM's blockchain solution based on Hyperledger Fabric, Walmart has successfully completed blockchain pilots for tracking the provenance of pork in China and mangoes in the Americas. At the end of the pilot, the time for tracking mango origins was reduced from seven days to 2.2 s [48]. Similarly, Chinese retailer Jingdong (Bejing, China) actively uses blockchain technology to track the entire process of food production, processing, and sales over its food supply chain systems [49].

Private blockchains enable secure and real-time exchange of supply-chain data and paperwork for an organization or a group of organizations where the entities are known and trust each other or the network owner. However, due to the fragmented structure of the trucking industry (for example, 920 K carriers in the USA [50]), with participants who do not necessarily trust each other, private blockchains would not sufficiently eliminate the trust problems and promote collaborative business models in the trucking industry. Instead, a public blockchain solution with support for privacy-preserving transactions is needed to encourage both vertical and horizontal collaboration among shippers and carriers, without the need for a trusted intermediary. To the best of our knowledge, no such blockchain solution has emerged yet in the trucking industry.

This study aimed to fill this gap in the literature, by proposing the design artifact and the system architect of a transportation control tower concept implemented in a decentralized fashion on a public blockchain network. The confidentiality of trucking transactions was ensured through off-chain privacy-preserving computation and storage solutions integrated with the blockchain.

3. Materials and Methods

We adopted design science research (DSR) methodology in this study to create a blockchain-based design artifact for improving collaboration in the trucking industry. In a nutshell, design science is a research paradigm aimed at creating scientific knowledge by designing and building useful artifacts to address business problems. In information systems research, the design–science paradigm seeks to extend the boundaries of human and organizational capabilities by creating innovative artifacts that solve either a hitherto unsolved problem, or a known problem, in a more effective or efficient manner [51].

A DSR is represented by three cycles between the environment that the research problem originates from and the knowledge base that includes the solution approaches (see Figure 1). Quoting from Hevner, "*the Relevance Cycle connects the contextual environment of the research project with the design science activities. The Rigor Cycle connects the design science activities with the knowledge base of scientific foundations, experience, and expertise that informs the research project. The central Design Cycle iterates between the core activities of building and evaluating the design artifacts and processes of the research*" [52].

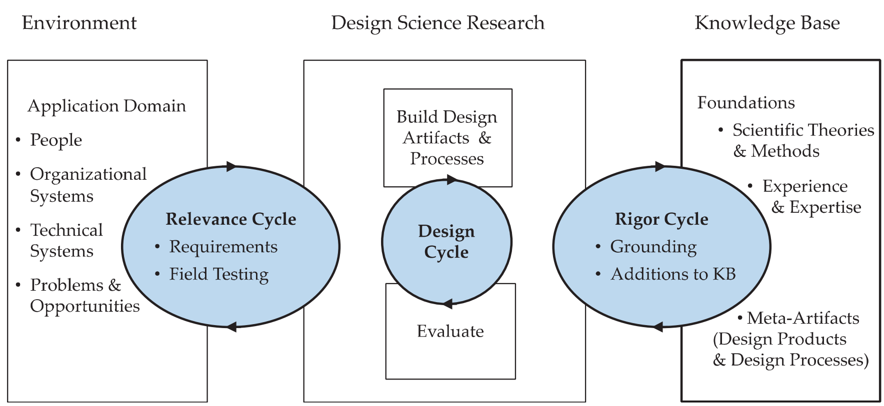

Figure 1. Design Science Research (DSR) cycles adapted from Hevner's study [52].

The theoretical rigor for this study has already been provided in the literature section above, where the literature was reviewed to investigate the impact of the trucking industry on the economy, society, and the environment, the critical success factors for collaboration in the trucking industry, the transportation control tower concept, and the use of ICT and blockchain in the trucking industry. In the rest of this section, the relevance cycle and design cycle will be presented in detail.

3.1. Establishing the Research Relevance

In this section, a snapshot of the trucking industry is taken to obtain a deeper understanding of the involved parties, existing business models, and the major problems, through industry reports and a semi-structured interview conducted with executives at a non-profit trucking industry organization in Turkey.

3.1.1. Structure of the Trucking Industry

According to the American Trucking Association (ATA), the trucking industry generated $796.7 billion in gross freight revenue (primary shipments only), employing 3.5 million drivers in the USA, which represents 80.3% of the nation's freight bill, in 2018 [50]. Being such a major economic activity and having strong ties to all other industries, the trucking industry is one of the leading indicators for the direction of the overall economy around the world.

Freight transportation simply involves the movement of raw materials, components, and finished products from one location to another within a supply chain network. The shipper, carrier, freight broker, and consignee are the four main parties involved in road freight transportation. A shipper is the person or company who is usually the supplier or owner of the commodities being shipped. The shipper physically tenders the goods to the carrier at the origin. A carrier is a person or company that transports goods for any person or company, and who is responsible for any possible loss of the goods during transport. A consignee is the person or company who is designated to receive the shipment. The consignee and shipper could be same party if the shipper ships the cargo from the origin to one of its related branches or locations. Finally, a freight broker is an individual or a company who brings together a shipper, who has goods to transport, with an authorized motor carrier, who wants to provide that service. Without taking possession of the freight, the broker facilitates communication between the shipper and the carrier (see Figure 2).

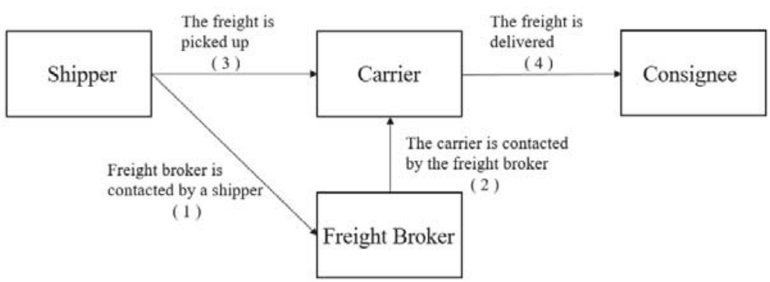

Figure 2. Life of a brokered freight load.

Today, the trucking industry is heavily orchestrated by freight brokers, and shippers and carriers depend on them for different reasons. Shippers want to do business with trusted carriers who have more than the legal minimum insurance, with drivers with stellar safety records, with those who have expertise in special areas—like hazmat or refrigerated shipping—and those who can be counted on to deliver reliably. Managing freight transportation in-house requires complex processes for shippers, such as finding reliable carriers, preparing paperwork and contracts, scheduling and synchronizing pick-ups, tracking cargo, and managing insurance, damage claims, and payments. Rather than dealing with these complexities on their own, shippers typically prefer working with freight brokers or third-party logistics service providers (3PL) to manage freight transportation activities. According to a 2017 industry report by Armstrong & Associates (a market research company, Milwaukee, WI, USA), 90% of Fortune 500 companies rely on 3PLs to control their logistic costs, and to increase supply chain efficiency [53]. Therefore, shippers rely on freight brokers to find trusted carriers for their freight shipments.

On the other hand, the carrier market is extremely fragmented, such that 90% of carriers have fewer than six trucks in their fleet in the USA [50]. Under such a competitive market, carriers desire to have consistent loads and minimize their idle times and empty miles on the road, to reduce their costs. Carriers have different preferences in regards to the types of lanes on which they operate. Some carriers prefer working with dedicated lanes, where they serve the same customer on regular routes and schedules, while others prefer long hauls where they spend a couple of weeks on the road, working with different customers throughout the entire haul. Nevertheless, they all want to do business only with trusted shippers, who respect the detention times during loading and unloading and who make payments on time. For these reasons, carriers rely on freight brokers to find profitable loads from trusted shippers in a highly competitive and fragmented market.

Freight brokers establish their own network of trusted shippers and carriers over time, and using that network, they act as a trusted intermediary in matching load requests from shippers with the transportation capacity of carriers, in exchange for a commission charged to both parties. Unfortunately, this centralized business model, controlled by freight brokers, limits the level of collaboration among shippers and carriers in the industry. Furthermore, considering the fact that freight brokers want to maximize their own profits, their objectives may not always align with those of shippers, carriers, and sustainable freight transportation efforts. For example, a freight broker might be inclined to match a certain load request with a certain carrier, regardless of concerns about efficient and sustainable trucking operations, as long as higher revenues can be achieved by matching them [54,55]. Inefficiencies and non-optimized business operations due to the match maker role of freight brokers and the lack of collaboration among carriers in the trucking industry have led to a number of serious problems for the economy, society, and the environment. We will elaborate more on those problems in the next sub-section.

3.1.2. Problems of the Trucking Industry

Below is a summary of the leading problems of the trucking industry based on industry reports and the logistics literature.

- High levels of carbon emissions: According to the OECD, globally, more than one-third of transport-related CO_2 emissions, and 7% of total energy-related CO_2, come from road freight transport [56].
- High percentage of empty-miles: Truckers drive between 20% and 50% of their miles empty in the US and Europe, mainly due to the unavailability of nearby loads headed in that direction [14,15,36]. These empty miles mean that more fuel is consumed, more carbon is emitted, drivers spend more hours sitting idle, and customers end up paying more.
- Low level of load factors: The load factor in trucking is defined as the ratio of the average load to total vehicle freight capacity. For non-empty running trucks in the USA and Europe, the average load factor is estimated to be around 60% [14,36,57].
- Poor work conditions (wellness) of drivers: In a survey of the National Institute for Occupational Safety and Health (NIOSH), it was found that obesity (69% vs. 31%), morbid obesity (17% vs. 7%), diabetes (14% vs. 7%), and cigarette smoking (51% vs. 19%) were considerably more prevalent among long haul drivers compared to the national working population in the USA [58].
- Driver shortage: In 2018, the trucking industry in the US was short by roughly 60,800 drivers, which was up nearly 20% from the 2017 figure of 50,700. If the current trend continues, the shortage is expected to grow over 100,000 in the next five years [59].
- Detention/delay at customer facilities: Detentions over two hours typically impact drivers' ability to comply with the hour-of-service (HOS) rules, and force drivers to park in unauthorized or undesignated parking areas if they run out of available on-duty hours before reaching a safe parking location. Moreover, only 29.3% of carriers report that they are able to collect all of the detention fees they bill to customers [12,60].
- Extended payment wait-times: 30 days after proof-of-delivery/invoice is the industry average in contracts for receiving payments, i.e., brokers being paid by shippers and carriers being paid brokers. Faster payments come with additional commission cuts via Quick Pay or Factoring services [61].

In addition to reviewing the industry reports, an initial semi-structured interview was conducted with executives from the International Freight Forwarder Association (UND)—a non-profit organization founded in 1974 to address the problems of the logistics industry in Turkey—to better understand the problems from the perspective of the implicated parties.

Confirming the aforementioned problems for the trucking industry, they emphasized the importance of collaborative business models for addressing these issues in the long term. However, they also noted that even though the industry has been going through a digital transformation in recent years, it is still far from a being collaborative one, mainly due to trust issues among industry players. They reiterated that more innovative ICT solutions are needed to address the trust problems, and facilitate collaboration among shippers and carriers in the trucking industry.

3.2. Generating the Design Artifact

Based on our findings from the relevance and rigor cycles of the DSR, here we present the design cycle where the design artifact was generated. We argue that this is an innovative approach to extend the transportation control tower concept from the collaboration literature, by operationalizing it digitally in a decentralized fashion on a public blockchain. The proposed system should eliminate the concerns related to the neutrality of the trustee, and the single point of failure risks intrinsic to centralized trustee models.

3.2.1. Overview of the Blockchain-Based Transportation Control Tower Concept

The digital transportation control tower brings together all stakeholders in the trucking industry, including shippers, carriers, insurance companies, regulators, and other parties, on a blockchain platform that supports smart contract functionality. In essence, each user of the platform has a unique account on the blockchain, and a smart contract is created for executing the terms of every single workflow of a shipment on the platform, such as loading the cargo, detention/delay conditions, unloading cargo, auditing, post-delivery payments, and conflict resolution. For example, the arrival time of the carrier at the origin location and the pick-up time of the cargo can be recorded on the blockchain. If the carrier faces an excessive delay upon arrival for the pick-up of the cargo, the related smart contract terms are executed automatically to charge detention fees to the shipper. Similarly, every state update during the shipment, such as the hours-of-service status, the status of the cargo, delays due to traffic, etc., is verified and validated on the platform, and then recorded into the immutable ledger. The design of a blockchain-based transportation control tower for the trucking industry is represented below in Figure 3.

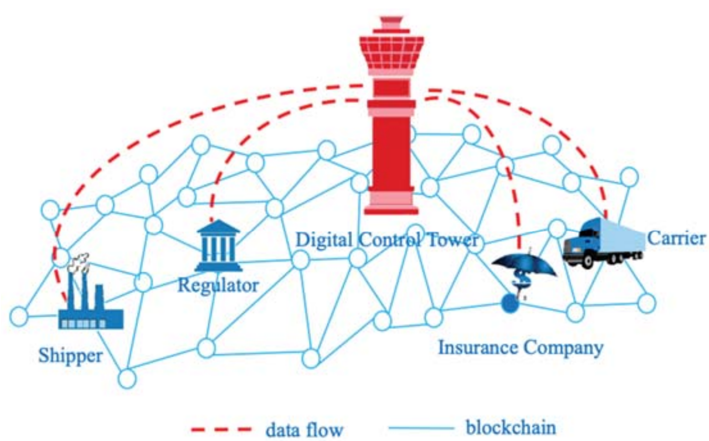

Figure 3. A transportation control tower running on a blockchain network.

While the platform could be used for executing an individual shipment contract between a shipper and a carrier without the need for a broker, its full potential is achieved when all shippers and carriers start sharing their business plans with a privacy-preserving decision algorithm (digital trustee) "integrated" within the blockchain network. Here, we use the word "integrated" purposefully: the decision algorithm, which is basically a recommendation engine to match shippers and carriers, stores large amounts of private input data and runs complex computations off-chain (outside the blockchain), and its decisions are verified and validated collectively by everybody on the blockchain.

Based on the requirements of platform users (shippers and carriers), any collaborative models from the logistics literature can be included in the recommendation engine, such as the relay trucking model, bundling shipments, backhauling, roundtrips, etc. However, the modeling details of the decision algorithm and its performance evaluation are outside the scope of this conceptual research. Further studies are needed to adapt the collaborative models and other relevant approaches from the logistics literature into the decision algorithm of the design artifact during the implementation phase. For example, Path Choice Problem (PCP) and Vehicle Routing Problem (VRP) paradigms can be studied to optimize the routes for the trucks once the matching between shipper and carrier has been finalized on the blockchain platform [62]. Transportation System Models (TSMs) and multiple-criteria decision methods can be instrumental for simulating the system behavior, to measure the performances and evaluate conflicting interests among the involved parties [63,64].

There are two main reasons the decision algorithm does not directly run on the blockchain network. First, from a scalability perspective, storing large data sets and executing complex computations directly on the blockchain is very expensive and not allowed in public blockchains; otherwise, every node on the blockchain would have to have high computational power and storage capacity to undertake the same computations for verification and validation purposes, as well as to replicate the ledger locally for data integrity purposes. Second, from a privacy perspective, storing the original data or the inputs off-chain and keeping corresponding hash values on-chain ensures that the sensitive information collected from collaborating partners will not be publicly visible on the blockchain. Therefore, moving complex computations and large data storage needs to off-chain systems, and verifying and validating their results on the blockchain enhances the capability of public blockchain applications in terms of scalability and privacy concerns.

In a nutshell, shippers and carriers send their input (load requirements, capacity availabilities, and other potentially sensitive information) to the privacy-preserving decision algorithm running outside the blockchain. The business rules or codes of the decision engine are visible to everybody on the blockchain network, but the input is not accessible to anybody on the blockchain. This ensures the confidentiality of the data collected from collaborating parties. The decision engine processes the collected data and produces load orders by matching shippers and carriers according to previously agreed business rules. Finally, the results of the decision engine, together with its digital signature, are verified and validated by users on the blockchain, without compromising the confidentiality of the input data sent to the decision engine earlier. This workflow ensures that the decisions are not generated by any malicious party or system, and they are in line with the previously agreed business rules. Eventually, the decision algorithm acts as a neutral trustee to maximize the gains for collaborative parties, while minimizing waste and negative impacts on the environment. Finally, the platform is free from the single point of failure risk because the decision algorithm can be run anywhere, and the ledger of transactions is replicated, shared, and synchronized across the entire network.

Off-chain storage (for example, IPFS and Swarm) and off-chain computation (for example, zkSNARKs) are promising approaches for addressing the privacy and scalability problems of standard blockchain architecture [65]; however, a more detailed discussion on these approaches should be the topic of another study, as it is outside the scope of the current one.

The system architecture of the proposed design artifact is presented in the next subsection.

3.2.2. System Architecture of the Blockchain-Based Transportation Control Tower

The system architecture (see Figure 4, adapted from [66]) has five layers: the infrastructure layer, blockchain layer, data analytics layer, applications layer, and users layer.

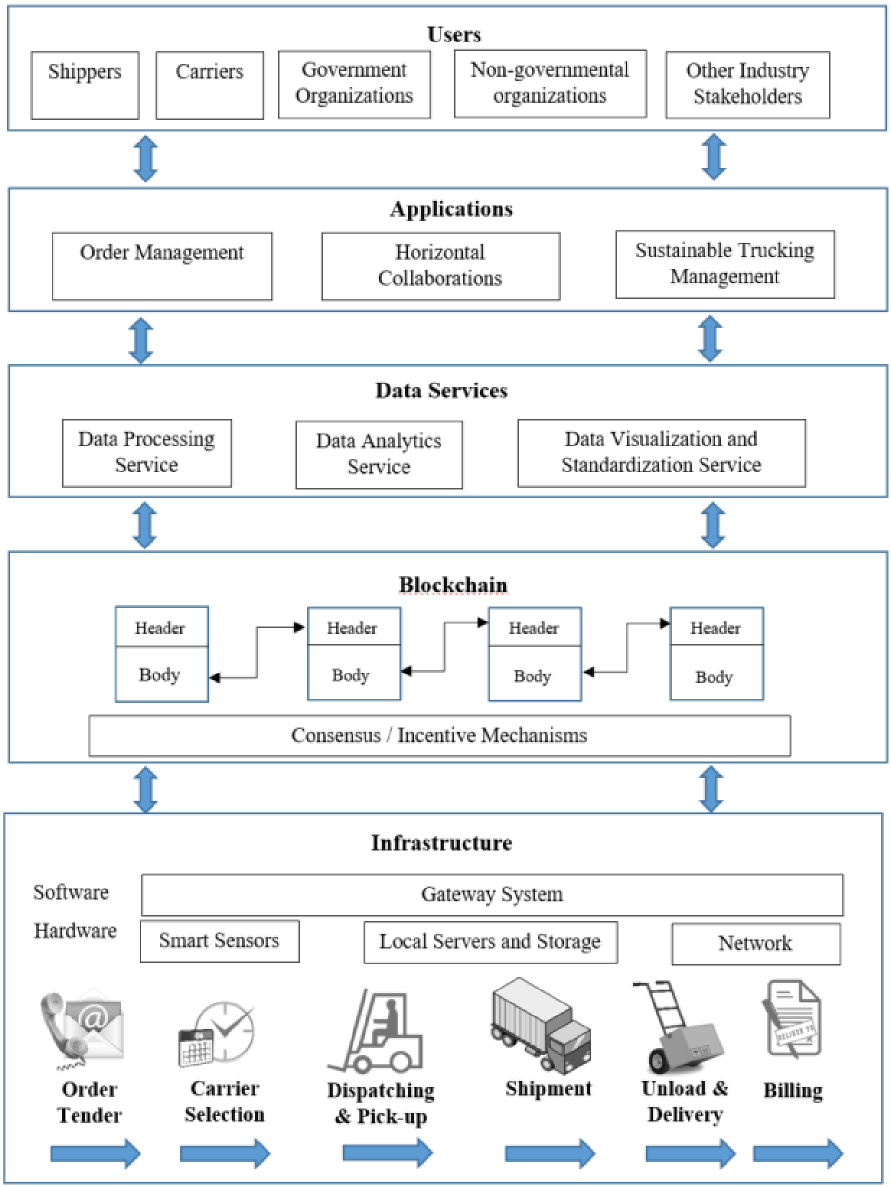

Figure 4. System architecture of the blockchain-based transportation control tower platform.

A generic lifecycle of a trucking order is presented at the bottom of the infrastructure layer. During its life cycle, a trucking order goes through the phases of order tendering, freight scheduling, dispatching, loading, transition, unloading, and billing. At each phase, the data from the trucking operations are generated, transmitted, and recorded into local storage or networks, to be utilized in the upper layers. The blockchain layer processes and records the data transmitted from IoT devices into chained blocks on the network. The data analytics layer connects the blockchain layer and the applications layer through cleansing, processing, analyzing, and visualizing the transactional data from the network. In the application layer, critical trucking applications use the data in decision-making processes. Finally, at the top of the architecture, trucking industry actors utilize the system through the users layer.

It should be noted that the proposed blockchain-based system architecture is powered by two other major technologies, namely IoT and big data analytics. IoT sensors play a critical role in collecting data and pushing the transactions to the blockchain network automatically, with minimal human involvement during the life cycle of a trucking order. On the other hand, big data tools are equally important in processing the large volumes of data produced by IoT devices, and extracting insights from the data, such as CO_2 emissions, empty hauling, etc.

From the bottom-up, the infrastructure layer consists of the hardware layer and software layer. In the hardware layer, IoT devices such as QR codes, RFID tags and readers, sensors, and GPS are used to collect the data automatically at each stage as the trucking order progresses through its life cycle. At the software layer, an IoT gateway software is used to transfer the collected data at each stage of the order life cycle to local databases, and/or cloud databases. After the operations through the gateways, the data and information from the infrastructure layer become available to the blockchain layer. For example, RFID tags and readers can be used to mark the arrival and departure times of the driver at the pickup location of the cargo. Once that information has been verified (consensus) and recorded into the blockchain, later it can be used for detention charge calculations for the shipper in the case of excessive waiting at the pickup location.

The blockchain layer is responsible for processing and recording the data transmitted from IoT gateways during activities in all stages of the trucking order life cycle. In a nutshell, the transactional data generated from trucking operations are verified, secured, and placed into a block in the blockchain network by miners, who share their computational powers in order to validate the legitimacy of a block of transactions. Anybody on a blockchain network can become a miner by installing and running special mining software that enables their computers to communicate securely with one another. A consensus mechanism is required to ensure that all the nodes in the network agree on a single state of the blockchain network, while multiple miners continuously add new blocks into the chain. Furthermore, a reward mechanism is also required to motivate the participants of the blockchain to act as miners and share their computational power, in order to keep the blockchain network up and running. Finally, it should be noted that only limited data is recorded on the blockchain network, in order to honor the privacy of transactions and minimize the computational power and data storage requirements for the miners. For that reason, once transactions are approved by the consensus algorithm, the hash values corresponding to transaction details are stored in the blockchain network, while the original object data are stored off-chain in the cloud storage environment servers, or in a distributed file system such as IPFS or Swarm.

The data services layer provides three key services to be used by applications in the upper layer: a data processing service, data analytics service, and data visualization service. The data processing service provides necessary tools to clean, classify, and sort the data, as well as run calculations on the extracted data. For example, CO_2 emissions from trucking operations can be calculated in this service. The data analytics service is used to conduct more sophisticated analyses on the processed data, by running techniques from machine learning, statistics, and data mining disciplines. For example, backhaul optimization can be fulfilled in this service in order to minimize the empty miles on the road. In the data visualization and standardization service, the processed and analyzed data are presented graphically to users, and formatted in common formats (XML, JSON etc.), to be shared by other systems.

The applications and user layers of the system architecture will be discussed in Section 5, along with the managerial implications for the trucking industry.

4. Results

Design science research is completed by assessing the contribution of the final design artifact to the knowledge base, as well as its application in the environment, to address the business requirements or problems. In this section, the proposed design artifact is evaluated based on the expert opinions of blockchain technology experts and trucking industry professionals. Please see Tables A1 and A2 in Appendix A for more information about the interviewees, and the questions asked to them.

4.1. Contribution to the Knowledge Base

The proposed design artifact itself is our contribution to the knowledge base, because to our best knowledge, it is the first blockchain application designed for enabling collaborative business models in the logistics industry.

In addition, the proposed system contributes to the knowledge base by extending the transportation control tower concept from the logistics literature. More specifically, running the transportation control tower concept in a decentralized fashion on a blockchain network eliminates the risks intrinsic to centralized trustee models, such as the loss of neutrality of the trustee, or the single point of failure in the system due to the inability of the trustee to function for any reason. The proposed system ensures the confidentiality of sensitive data on the platform through privacy-preserving off-chain computation and storage solutions. A decision algorithm processes the confidential data off-chain on behalf of the participants, maximizing the gains for them. Even though the inputs to the decision algorithm are confidential and not visible to anybody, the logic of the decision algorithm is known to participants, and transactions can still be validated by participants on the blockchain without compromising confidentiality, before being recorded into the distributed ledger. Once a decision algorithm is designed and agreed upon by participants, no transactions can happen on the blockchain against the rules of that algorithm. This ensures the neutrality of the decisions on the platform, and it is expected to encourage both shippers and carriers to engage more in horizontal collaboration practices.

4.2. Contribution to the Application Environment

In order to assess the viability of the design artifact and its potential impacts in the logistics industry, we asked for expert opinions from professionals in blockchain technology, and experts from the transportation industry.

The viability of the proposed design artifact was evaluated by two blockchain technology advocates, both with 20+ years of experience on the development of large-scale information systems in Turkey. The first interviewee, who is also a founder of a blockchain start-up company, confirmed that blockchain technology offers many opportunities for the logistics industry. In fact, he evaluated the technology as revolutionary for all industries because of its support for decentralized business models, and the immutability of the transactions on the network. Pointing to the fact that domestic and international supply chain operations involve too many parties, too much paperwork, and complex processes, he argued that by managing those transactions and processes via smart contracts on a blockchain network, the logistics industry might benefit from reduced paperwork, improved payment and pricing processes, faster invoice reconciliation and dispute resolution, and improved compliance with regulations, improving the provenance of goods, and reducing the risk of fraud in transactions. For the trucking industry, he considered that blockchain technology could simply be used to track the progress of a particular cargo during its journey (for example, load, unload, detention, location, etc.), and facilitate the fund exchanges between the shipper and the carrier upon delivery. In that sense, existing online freight matching platforms might be interested in utilizing the technology to offer a better experience to their users (for example, shippers and carriers). On the other hand, he also confirmed that a more holistic solution to enable horizontal collaboration in the industry, as suggested in our design artifact, requires complex computations (for example, bringing multiple carriers together for a single load order, splitting gains, sharing costs, etc.), and this would be very expensive to handle on a blockchain network. In addition, he also noted that current smart contracts are designed to be executed by all miner nodes, and transaction details are visible entirely on-chain. In order to improve the scalability and privacy on the blockchain, he was supportive of the idea of moving complex computations and private data off-chain, while validating the outputs of those computations on-chain. In fact, he considered our design artifact as a good use case of this. However, he also underlined that off-chaining approaches are still in their infancy in the blockchain community, and there are not many mature applications yet. Therefore, it might take some time for off-chaining solutions to gain maturity to the extent that our design artifact could go live in production. Nevertheless, he provided examples of ongoing initiatives of off-chaining computation approaches (for example, zkSNARKs, Bulletproofs, zkSTARKs, Enclave Systems, and TrueBit), as well as off-chaining storage approaches (for example, IPFS, StorJ, and SWARM), which might be useful for implementing our design artifact. The second interviewee, who was also a columnist at an international weekly business journal, shared similar perspectives with the first interviewee in regards to the potential of blockchain technology for the overall logistics industry. He found our design artifact innovative, and considered it a good example of the integration between decision support systems and blockchain technology. He argued that computing and storing state updates completely on-chain considerably limits the application areas of blockchain technology. He affirmed that, as off-chaining solutions mature, similar systems could be designed for different business problems requiring complex and privacy-preserving computations in other industries as well. Finally, the third interviewee, who was the co-founder of a blockchain discussion platform, stated that there is a great interest within the logistics industry to utilize blockchain technology, mainly in order to improve their daily processes and reduce paperwork, wasted resources, and time. In that sense, he evaluated our design artifact as an innovative solution to address many problems in the logistics industry. However, he also shared his concern regarding the fact that the trucking industry lags a bit behind technological advancements, and any innovative solution might face technology adaption challenges in the industry. Finally, he considered the lack of regulatory clarity, governance issues, integration with legacy systems, and interoperability issues between different blockchains as being among the other challenges for blockchain technology.

The application of our design artifact to the trucking industry was assessed through a number of interviews conducted with industry experts in Turkey and the USA. Initially, we conducted interviews with professionals from different sized carriers in Turkey. One common observation from these interviews was that none of the interviewees had previous experience with blockchain technology. The transportation planning manager at a large-sized asset owner carrier company (5000+ trucks) and the business development manager at a medium-sized asset owner carrier company (200+ trucks) in Turkey stated that they already have a direct relationship with most of their customers, and they also provide freight brokerage services in the industry by sub-contracting certain loads to smaller carriers. Therefore, they were not interested in a system design where the freight broker role is replaced with a decision algorithm powered by a blockchain. In addition, they both claimed that the reputation of the carrier is very important for shippers, and even though the terms of business are enforced through smart contracts on the blockchain, the proposed design artifact would not be able to convince shippers to do business with a group of unknown small carriers brought together by a decision algorithm to fulfill a load request. That being said, they also stated that blockchain technology could still be useful for reducing complex paperwork, especially for international shipments (for example, customs clearance), faster conflict resolution, and faster payment management. On the other hand, an owner operator of a small carrier shared that he is too dependent on freight brokers in order to find loads in the market, and he is not happy with the commissions paid to those brokers. In fact, he reported being excited with the idea of eliminating brokers and being able to engage in direct business with shippers. As long as his sensitive data remains confidential, he was interested in collaborating with other carriers on a blockchain-based transportation control tower platform. In securing the terms of business via smart contracts, he was even interested in monetizing his trailer by sharing it with other carriers and gaining commission from its operations on the platform. However, the owner operator also shared his concerns around the cost of the platform for him, the required technology literacy, and the technical support requirements. From the interviews with carriers, it is clear that even though the proposed design artifact has not received much support from large and medium size carriers with freight brokerage services, considering the fragmented structure of the trucking industry (90% of carriers have less than six trucks in the USA), the proposed design artifact offers unique opportunities for the majority of the carriers market, despite the technology acceptance challenges.

Next, we conducted interviews with the vice president of engineering and director of transportation operations at a leading beverage company in the USA. Sharing his vision on the potential of blockchain technology for overall supply chain operations, the vice president stated that the company is investing in the technology to increase the transparency and traceability of items along the entire supply chain, as well as to reduce the carbon footprint of their operations. He evaluated our design artifact as an innovative approach for a paradigm change towards decentralized business models in the logistics industry, and he expressed his support for implementation of a proof-of-concept (POC) solution in order to assess the performance of the proposed system. On the other hand, the director of transportation operations stated that currently they are highly dependent on freight brokers in order to secure transportation capacity from reliable carriers when needed, especially during peak seasons, and depending on the availability of alternative freight brokers in a region, the company might have to pay high commissions to those brokers at times. The director noted that they need to trust freight brokers at the end of the day to assess the eligibility of assigned carriers for their cargo delivery. However, he considered that the proposed design artifact could offer several benefits to them. First, the platform would bring them together with a pool of carriers beyond the reach of their own freight brokers. Moreover, since the records are immutable on the blockchain, they would also have the opportunity to check the past activities of carriers transparently on the platform, to make sure they were eligible to pick up their cargo. The director noted that those records would be critical for evaluating the performance of carriers, as well as ensuring the proper execution of regulations. He provided an example: a trailer which was used to deliver poultry products cannot be used for delivering beverage products, due to the risks of salmonella bacteria. The director also commented that the proposed design artifact or platform could also be used for monetizing the excess capacity of his private fleet (trucks or trailers) during the off season. Finally, as long as the sensitive data remained confidential, the director also shared his interest in collaborating with other shippers on joint shipment plans to reduce costs and carbon emissions from empty miles. Both the vice president and director at the beverage company agreed that the proposed design artifact has the potential to streamline inefficient processes, improve visibility of cargo movements, improve compliance with regulations, and reduce costs and waste via direct connection with reliable carriers.

Finally, we conducted a focused group interview at the International Freight Forwarders Association (UND)—an industry organization founded in 1974 to address the problems of road freight transportation companies in Turkey. The participants included government officials from transportation and customs administration, an executive of a software company, a customs and trade consultant, and high-level executives at the UND. The purpose of the interview was to understand the current blockchain initiatives for the logistics industry in Turkey, and discuss the potential of our proposed design artifact for the industry. In general, the participants agreed that blockchain technology has the potential to solve many pain points in road freight transportation, and they considered customs clearance as one of the initial application areas that blockchain could be instrumental for, in terms of reducing the time and resources wasted. However, the executive of the software company noted that even though the industry is ready to adopt this emerging technology, there are a few sets of challenges that have been responsible for the slow adoption of blockchain technology, such as scalability, privacy and regulatory issues, interoperability issues, high energy consumption, lack of standardization among blockchain networks, and a lack of talent to develop and maintain blockchain platforms. On the other hand, regarding our design artifact, even though it has a more complex implementation compared to completely on-chain use cases, the government officials and UND executives confirmed that it has the potential to improve the level of collaboration in the overall logistics industry, and eventually reduce carbon emissions from operations, and they shared their interest in contributing to our research in the future.

5. Discussion

In this section, the managerial implications of the proposed design artifact for the trucking industry are discussed in detail based on the system architecture provided earlier, in Section 3.

All parties involved in trucking operations can benefit from the proposed design artifact. Shippers can create load tenders, search reliable carriers, prepare smart contracts for the terms of agreement, and execute the contract on the blockchain without the need for a trusted intermediary or a freight broker. Similarly, carriers can directly make themselves visible to shippers on the blockchain network, and build their reputation by delivering excellent service to shippers. In addition, government and non-government organizations (NGOs) can monitor trucking activities on the blockchain network using data services. For example, the related government organization can check the transactions on the blockchain network to see if the hours of service regulation have been violated for shipments. Similarly, NGOs can analyze the vertical and horizontal collaboration opportunities for shippers and carriers in the industry, in order to reduce CO_2 emissions and empty driven miles from trucking operations. Governments and NGOs can together promote sustainable trucking activities in the industry based on the snapshot of the industry from the blockchain transactions. Furthermore, other industry stakeholders can also use the system. For example, the insurance details of carriers and shippers can be recorded on the blockchain network, and the terms of insurance can be coded into a smart contract to be executed by insurance companies when the need arises. Finally, freight brokers can still exist as users of the system, by providing technology consultancy to their clients. For example, they can manage the transactions of client carriers who lack the necessary technology skills to utilize the system.

The application layer provides at least three key application areas for the trucking industry; namely, order management, horizontal collaboration, and sustainable trucking management.

Trucking orders in contract (long term) or spot (one time) markets are traditionally managed by freight brokers. This indirect relationship between shippers and carriers leads to prolonged reconciliation processes, and it also limits the level of vertical collaboration between shippers and carriers. In a nutshell, freight brokers secure the capacity of reliable and available carriers (holding the necessary insurance, good driver records, etc.) on behalf of reliable shippers (respectful of detention times, make payments on time, etc.). Once a load is tendered to a carrier, the freight broker monitors the progress of the cargo throughout the order lifecycle, and provides updates to the shipper on the status of the cargo. In addition, the freight broker provides an escrow service for the shipper and carrier by holding the billed amount on their behalf until both parties have met their obligations for the shipping agreement. On the other hand, in our proposed system architecture, a privacy-preserving decision algorithm, whose decisions are verified and validated by miners on the blockchain, replaces the match maker role of freight brokers. Once a shipper and carrier match each other on the platform, a smart contract automatically executes the terms of the load order (including the escrow services) on a contract (long-term) or spot market agreement. In addition, immutable, traceable, and transparent records are added to the distributed ledger for every single state update of the shipment, and those records are available to everybody on the platform. On the platform, both shippers and carriers build their reputation over time based on their performance records on the network (for example, safe driving records, delivery on time, respect of detention hours, payments are on time, etc.). With this level of transparency, supported by smart contract technology, shippers and carriers have the opportunity to engage in direct business with each other (vertical collaboration), and have access to wider markets beyond the reach of their freight brokers.

In addition to improving the vertical relationship between shippers and carriers, the proposed architecture based on blockchain and smart contract technology promotes horizontal collaboration in the trucking industry as well. For example, the decision algorithm on the platform can bring multiple carriers with a good reputation together to fulfill a single large load order of a shipper, which they cannot tender individually. This allows small carriers to increase their market share by doing business with large shippers, and it also helps large shippers reduce their dependency on large carriers through receiving more competitive offers from smaller carriers for their load requests. Furthermore, smart contracts can be designed on the platform to support relay trucking models, where two truck drivers swap trailers at a meeting point, and head to their home terminals with the new loads, taking them closer to their final destinations. Enabling truck drivers to spend more nights at home, relay trucking is considered one of the main solutions to driver shortages/retention issues and excessive empty mile in the trucking industry. In fact, relay trucking has been widely examined in operations research and in the transportation literature [67–69]. However, it has not been widely practiced in the trucking industry so far, due to the complexities of transactions and the high level of trust needed among partners.

As discussed earlier in Section 3, the trucking industry suffers from important sustainability problems, such as poor working conditions for workers, CO_2 emissions from truck operations, high level of empty miles of trucks on the roads, and a low level of load factors. The availability of immutable data generated from trucking operations in the industry and data analytic services can be used to find the root cause of these problems at a granular level based on historical transactions, and can help to promote the necessary solutions or policy changes accordingly.

6. Conclusions

Employing millions of people, and generating a significant portion of GDP in economies around the world, the trucking industry has significant impacts on the three pillars of sustainability: the economy, society, and the environment. However, the global trucking industry has also been suffering from serious problems for long time, such as poor working conditions of drivers, driver shortages and retention issues, extended payment times, and increased costs as a result of a low level of load factors and high percentage of empty miles. Any improvement in these issues would result in higher productivity and lower costs for the economy, improved working conditions and a reduced risks of accidents for society, and reduced carbon emissions and pollution for the environment. That being said, old business models and existing ICT solutions are not helping much in addressing these problems. In their industry reports, the EU, the WEF, and the OECD acknowledge the importance of collaboration among shippers and carriers in order to establish a sustainable freight transportation system, and call for more innovative technology solutions to foster collaboration in the trucking industry.

In this paper, we presented the overall structure and leading problems of the trucking industry based on a literature review, industry reports, and interviews. Following that, we discussed the role of horizontal collaboration in achieving sustainable trucking, as well as the barriers and facilitators for achieving collaboration.

Even though information sharing is essential to a successful collaboration experience, carriers perceive sharing sensitive business plans with their competitors as a threat to their future market positions. The transportation control tower concept was proposed in the logistics literature for solving this, such that a neutral and independent trustee would collect sensitive information from collaborating parties, keep it confidential, and process it for the maximum benefit of all collaborating parties. However, the trustee concept itself also suffers from trust-related concerns due to the risk of a trustee losing its neutral position and favoring a particular carrier in its decisions when confidentially processing collaboration data.

We extended the trustee concept from the literature by operationalizing it digitally, in a decentralized fashion, on a public blockchain network. In contrary to traditional trustee concepts, the proposed design artifact ensures the neutrality of the digital trustee in its decisions, as well as preventing the single point of failure problem intrinsic to centralized trustee models. In addition, the design artifact safeguards the confidential information of shippers and carriers on the public blockchain via integration with privacy-preserving off-chain computation and storage solutions.

We evaluated the viability of the proposed system, and its potential for the logistics industry, through expert opinions. Interviews with blockchain experts revealed that our design artifact is an innovative use case for the logistics industry, wherein the scalability and privacy issues of blockchain technology can be addressed through integration with off-chain computation and storage solutions. However, as blockchain is still an emerging technology, off-chaining approaches are still in their infancy, and further research is needed in that domain in order to develop a mature implementation of our design artifact. Even though the proposed system was not welcomed in the interviews with professionals from large and medium-sized carriers providing freight brokerage services in the industry, it received support from small carriers, which constitute the largest percentage of the carriers market, along with shippers and policy makers. In fact, interviewees at a large beverage company in the USA, and UND executives in Turkey, found the proposed system quite disruptive to the industry, and offered their support for a proof-of-concept implementation in the future stages of our research.

There are ample research opportunities to explore the potential application areas of blockchain technology in the logistics industry. Firstly, further investigation is needed to understand the attitudes of large and medium carriers against decentralized business models, as suggested in our design artifact, as well as to develop business models where they could also benefit through monetizing their excess resources, or providing technology consultancy to other carriers less competent with the technology. More studies are needed to investigate existing off-chaining approaches, to evaluate their advantages and disadvantages in implementing our design artifact. In addition, a prototype solution needs to be developed to measure its performance and understand the technology acceptance issues in the trucking industry. Furthermore, the proposed design artifact can be adapted for solving similar problems in other industries where collaboration matters. Finally, similar to any other research in the blockchain domain, further studies are needed to address the problems of wider adoption of the technology in the logistics industry, such as regulatory clarity, high energy consumption, governance issues, GDPR-related concerns, lack of standardization, and a lack of technical talent.

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Appendix A

Tables A1 and A2 present more information regarding the interviewees, and the semi-structured questions asked during those interviews.

Table A1. Interviews with transportation industry experts.

Company	Interviewee Title/Role
1. A large carrier in Turkey (≥5000 trucks)	Transportation Planning Manager: Coordinating with customers to schedule cargo pick-ups and developing strategies to minimize the empty miles of truck fleet
2. A medium carrier in Turkey (≥200 trucks)	Business Development Manager: Establishing relationships with shippers and sub-contracting for freight brokering operations
	General Manager: Driving the growth strategies and investment decisions for the company
3. A small carrier in Turkey	Owner Operator and Driver: Transporting farm products (potatoes and onions) for a grocery chain
4. Focus group interview at International Freight Forwarders Association (UND) in Turkey	Customs Administration Manager: Ensuring the proper execution of customs laws and regulations, as well as, where applicable, policies and means Researcher at Ministry of Transportation: Developing strategies for reducing the traffic of heavy trucks in urban areas
	VP at a Software Company: An executive at a leading software company providing blockchain-based software solutions in the international trade and supply chain management domains Blockchain Engineer: Developing decentralized applications using smart contracts
	Customs and Trade Consultant: Providing consultancy services in customs compliance, corporate governance, project management and implementation, supply chain security, trade facilitation, and minimizing administrative inefficiencies
	Strategy Development Manager at UND: Conducting sector and market research for seeking new business opportunities and projects, establishing sustainable customer relationships, and carrying out process improvements in the industry Executive Committee Member at UND: Coordinating with stakeholders in Turkey and foreign counterparts in Russia and the European Union to address the problems of Turkish carriers transporting international freight Technology Relations Member at UND: Managing relationships with industry and technology consultants for accelerating the digital transformation in the industry
5. A leading beverage company in the US	Director of Transportation Operations: Establishing relationships with freight brokers and planning the shipments with carriers
	Vice President of Engineering: Managing R&D activities in the organization

Semi-structured interview questions for industry experts from the transportation area

1. What is the structure of the road freight industry in your country?
    a. How many people are working in the industry?
    b. What is the contribution to the economy?
    c. What are the key players in the industry (i.e., carriers, shippers, brokers etc.)?
2. What are the most common business models executed in the industry?

   a. How do shippers and carriers match each other?
   b. What is the split of contract business vs spot market business?
   c. What is the role of brokers?
   d. What is the level of direct collaboration among carriers or among shippers?
3. What are the most important problems of the industry?
4. What are the factors aggravating (weaknesses) those problems?
5. What could be done to help with those problems?
6. What do you think about horizontal collaboration with another carrier?
7. What is the level of technology usage in the industry?
   a. Cloud technologies, data analytics, mobile applications
   b. Do you use electronic load marketplaces?
      i. What are the pros and cons of those platforms?
8. What is your experience with blockchain technology?
9. (After explaining blockchain technology and our design artifact)
   a. What do you think about collaborating with other carriers on a platform similar to our design artifact?
   b. What could be the potential problems with such a system?
   c. What else would you desire to see in that system?

Table A2. Interviews with blockchain technology experts.

Company	Interviewee Title
6. An international weekly business journal in Turkey	Blockchain and Cryptocurrency Expert: Contributing writer on new media, digital transformation, and cryptocurrencies with ≥20 years of experience as an executive manager in the telecommunication and software industry
7. Blockchain start-up in Turkey	Blockchain Entrepreneur: Founder of a software start-up companies in Turkey with ≥20 years of experience in software engineering and development of a decentralized system, and a well-respected speaker, educator, and consultant on blockchain technology in Turkey
8. Blockchain Turkey platform	Co-founder: Coordinating with stakeholders from different industries for establishing a sustainable blockchain ecosystem in Turkey to foster innovative business models in those industries

Semi-structured interview questions for blockchain technology experts

1. What is blockchain technology?
2. What makes that technology a disruptive one exactly?
3. Where is blockchain technology on the hype cycle?
4. How mature is the technology at the moment?
5. How could that technology be useful for the transportation industry?
6. (After explaining current business models in road freight transportation industry)
   a. Can we use this technology to reduce or eliminate trust-related concerns among carriers and foster collaboration among them?
7. Can we integrate complex optimization and data storage systems with blockchain technology?
   a. How can we push complex calculations and data storage requirements to off-chain, but still benefit from the advantages of blockchain technology?
8. What are the other challenges for organizations when they want to use blockchain technology for their businesses?

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Article

The Architectural Design Requirements of a Blockchain-Based Port Community System

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Abstract: This paper presents the value proposition of blockchain for Port Community Systems (PCS) by dissecting the business processes in port logistics and unfolding functionalities of blockchain in lowering the transaction cost. This paper contributes to the research by a detailed technical assessment of the plethora of currently available blockchain platforms and consensus mechanisms, against the identified requirements in this specific use case. The results of this technical assessment highlight the central value proposition of blockchain for landlord ports, which is independency from a central authority as the controlling agent. Bridging between two research domains of Information Technology and Logistics, this paper proposes the preferred architectural design requirements of a blockchain-based PCS, including provisioning private sidechains, modular design with inter-chain interoperability, and encrypted off-chain data storage. Availability—the readiness for correct service, and reliability—the continuity of correct service, are heavily reliant on the right choice being made for blockchain design for such a complex use case. A preliminary comparative analysis among different decentralisation levels in this paper suggests that a permissioned public blockchain offers the best trade-off in performance measures for this use case. This technical review identifies six research agenda from a design perspective.

Keywords: supply chain; logistics; freight transportation; distributed ledger technology; maritime transportation; international trade

1. Introduction

The international trade and supply chain, deluged by a growing complexity of information and physical transactions, face critical challenges such as compliance, traceability, governance, higher transaction costs, and security [1]. Despite the high monetary valuation of the transactions and the regulatory scrutiny, the core data infrastructure in the maritime logistics is currently unable to keep pace with digitisation trends [1].

Increasing the efficiency and productivity of supply chain as the primary driver of competitiveness among adjacent ports has led to developing integrated information exchange platforms or so-called Port Community Systems (PCS) in a number of modern ports. PCS development has gone through various transformation waves and the ongoing latest wave, started in 2018, concerns the PCS evolution by new concepts like blockchain and Artificial Intelligence [2]. There is extensive research on PCS and the impacts of information exchange platforms on the port performance [2–8]. However, despite the strong practical potential of these new trends, the integration of blockchain and PCS has not been explored in the academic literature [2].

In the absence of PCS, a significant number of transactions can be impacted by data discrepancies and disputes due to lots of paperwork, multiple stakeholders, and human mistakes. While PCS reduces these costs, similar to any centralised platform, additional charges emerge for maintaining the security and immutability of data in the platform. Furthermore, implementing a centralised PCS does not seem a viable solution since the logistics operators are less likely to share their business information with the port authorities, particularly in landlord ports [9]. This is where blockchain technology can circumvent the PCS adoption barriers and pave the road for horizontal and vertical industry integration.

Blockchain is an open-source and distributed platform that allows a more efficient, transparent, and trustworthy flow of transactions between companies and individuals by removing the middleman and cutting out the costs, time-lapses, and inter-parties lack of trust issues, while also maintaining the privacy, immutability, and business data confidentiality [10]. Blockchain technology has been identified globally as a potential tool to disrupt many industries, including the supply chain and logistics industry. It is worth mentioning that the complex multi-level permissioning schemes and the distributed feature of blockchain are something that can be achieved with existing databases. What makes blockchain stand out compared to centralised digital enterprise solutions is the capacity to build trust without relying on a single authority to provide administrative control over the system or business rules. In other words, what differentiates a blockchain-based PCS from a centralised PCS is solving the "who" problem, such as the following questions: Who owns the data? Who is allowed to edit/change/delete the data? Who creates the database and maintains it? Who ensures the validity of data and verifies the transactions and claims?

Accordingly, a number of international ports have committed to delivering a pilot blockchain-based platform, including the Port of Antwerp, Port of Rotterdam, Port of Valencia, Associated British Ports (ABP), Port of Abu Dhabi, Port of Montreal, and Port of Busan in South Korea. TradeLens, a product of a partnership between IBM (multinational technology and consulting company) and Maersk shipping line, is keeping ahead in a race with other products such as CargoX [11]. More recently, nine shipping lines and terminal operators also announced their 'declaration of intent' to form a blockchain consortium as the Global Shipping Business Network (GSBN) and shareholders of CargoSmart Limited—a blockchain-based logistics initiative (https://www.maritime-executive.com/article/nine-companies-sign-up-for-global-shipping-business-network).

Notably, these pilot projects have deployed various blockchain platforms with different architectural designs. Given the competitive nature of these businesses, the criteria for choosing the specific design and benchmarking the performance of these pilot projects have not been reported in detail. For example, one of the critical decisions is the level of decentralisation, which defines if a blockchain architecture is public, private, or permissioned (consortium). The literature of Information Technology provides flowcharts and general guidelines about the suitability of public, private, permissioned, or hybrid blockchains [12,13]. However, to the best of our knowledge, these criteria have not been systematically fine-tuned for a blockchain-based PCS platform, at least in the academic literature.

Integration of blockchain and supply chain are expected to become new research hotspots in the supply chain and logistics domain, particularly with the digital supply chain innovations, advances of enterprise blockchain solutions, Internet of Things (IoT), and implementation of national strategies [14]. In the academic literature, the interest in blockchain and its business applications has been steadily growing over the last few years [15]. The literature on the application of blockchain in the supply chain can be grouped into five categories as: (i) business model and business process implications [16–19], (ii) descriptive assessment of potentials and challenges [20–26], (iii) simulation models [27–30], (iv) single or multiple case study approach [31–36], and (v) survey-based methodology to analyse the adoption behaviours [37–42].

In the maritime supply chain domain, Yang [11] explored the factors affecting intentions to use blockchain on a sample of 38 shipping experts in Taiwan. The results of interviews reconfirmed that intention of using blockchain positively associates with three factors as: (i) digitalising and easing paperwork, (ii) customs clearance management, and (iii) standardisation and platform developments.

Notably, the differences of blockchain architectures have been overlooked in the scientific literature of blockchain in the supply chain domain, which affects the generalisability of the findings. Even more surprisingly, there exists confusion and often generalisation of different types of blockchain and consensus algorithms in the literature. For example, many blockchain technology assessments have been made based on the assumption that all blockchain projects utilise the same consensus mechanism, such as Bitcoin—Proof of Work (PoW). Notably, there is no assessment of the various consensus mechanisms in the supply chain and logistics domain. A thorough investigation into the existing platforms, properties, and challenges would be valuable to future investment decision making by practitioners. Hence, the critical research gap concerns architectural design choices for this specific use case. This paper aims to fill this gap by a thorough investigation of the existing blockchain platforms, particularly reviewing the technical properties and challenges in the port logistics. This review aims to answer the following questions:

- What is the value proposition of blockchain in the port logistics?
- What is the preferred architectural design of a blockchain-based PCS platform?

Contributions of this paper are as follows. First, the value propositions of blockchain for port logistics are dissected based on the Transaction Cost Economics (TCE) theory. From a socio-economic perspective, the first step to understand the necessary conditions for the adoption of blockchain is studying the transaction cost and value attribution in this specific setting. Second, a critical review is undertaken on the blockchain components, quality attributes, and the main existing platforms, namely Enterprise Ethereum solutions and Hyperledger solutions. The third contribution involves cross-validating the system attributes of these platforms with the business requirements in the port logistics. Based upon this cross-validation, recommendations of the architectural design requirements are made with the aim of lowering transaction costs. Lastly, six new research agenda are specified.

The remainder of the paper is comprised of the following sections. Section 2 presents an overview of blockchain components, and reviews two market-ready blockchain platforms. Section 3 presents an overview of the port logistics process. Section 4 presents the value creation of the blockchain. Section 5 presents the suggestive findings of a blockchain-based PCS platform design requirements. Section 6 discusses possible areas for future research, and Section 7 draws conclusions from this study and provides closing remarks.

2. Overview of Blockchain

This section unfolds the main blockchain components, the performance measures, and reviews the most applicable blockchain platforms in the supply chain and logistics use-cases.

2.1. Blockchain Components

Blockchain platforms are categorised into three types, namely, public, private, and permissioned blockchains. The permissioned blockchain is defined as a system where one or more authorities act as a gate for the participation of other members. Permissioning in blockchain can be done at multiple levels, for example, permission to join the network (and thus read information from the blockchain network), permission to initiate transactions, or permission to validate ledgers.

As depicted in Table 1, public permission-less networks currently suffer from a number of challenges that make them problematic for enterprises. They are notoriously unscalable and expensive to use. Generally, private blockchain platforms do not suffer from the throughput, latency, and scalability problems as much as public blockchains do. Nevertheless, private blockchains are subject to debates and critics since they create another form of power-broking middleman and defeat the whole purpose of the blockchain.

Table 1. The level of decentralisation and blockchain properties (adopted from Reference [43]).

		Throughput, Latency, and Scalability Efficiency	Integrity and Security Efficiency	Transaction Cost-Efficiency
Public blockchain	Permission-less	+	+++	+
	Permissioned	++	++	++
Private blockchain	Permission-less	+++	+	+++
	Permissioned	+++	+	+++

By and large, however, all these blockchain platforms consist of common features, namely, a sequence of blocks of distributed ledgers across peers (client nodes), validation algorithm, cryptography (hashing system), data storage layer, communication channels, and smart contracts (Figure 1). The following subsections explain the blockchain components in more detail.

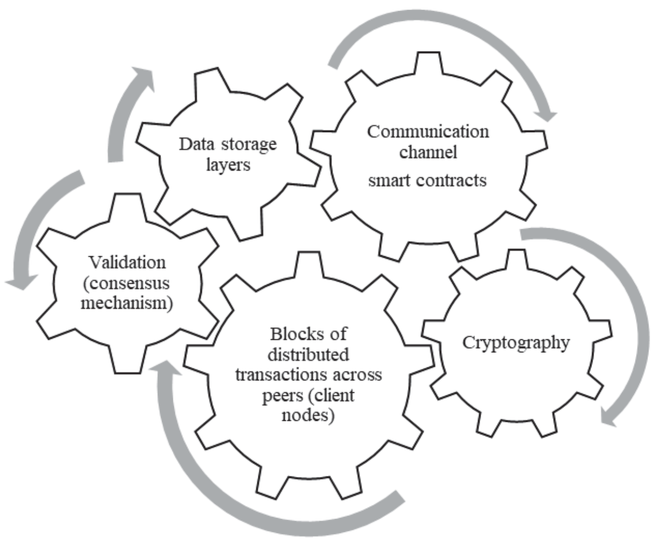

Figure 1. Blockchain features.

2.1.1. Cryptography

Cryptographic mechanisms or so-called hashing algorithms provide the security of a blockchain network by encrypting the transaction data. There are various cryptographic hash functions, but all are common in having an 'avalanche effect', which means even a small change in the input will be drastically reflected in the hash. Interested readers are referred to [44], who describes the various cryptography algorithms in detail.

2.1.2. Blocks of Distributed Transactions

Following the notations of Ethereum [45], the blockchain data structure is defined as a transaction-based state machine where ledgers of transactions link two states, as follows:

$$\sigma_{t+1} \equiv \gamma(\sigma_t\ ,\ T) \tag{1}$$

where γ is a state transition function. Transaction T is an encrypted instruction constructed by a blockchain node (user) and can represent either a message call or a new autonomous object (used for contract creation). This instruction roughly consists of a transaction proposal and a transaction receipt. Transaction proposal is sent by a client node to the validating nodes and contains information about the transaction, such as sender, the account whose code is to be executed, value, and computational costs. Transaction receipt contains the results after the execution of the transaction, namely the validator's signature and timestamp of execution. Accordingly, transaction T is presented as:

$$T \equiv \begin{cases} (T_n,\ T_p,\ T_g,\ T_t,\ T_v,\ T_i,\ T_w,\ T_r,\ T_s) & \text{for contract creation} \\ (T_n,\ T_p,\ T_g,\ T_t,\ T_v,\ T_d,\ T_w,\ T_r,\ T_s) & \text{for message calls} \end{cases} \quad (2)$$

where T_n is the number of transactions, T_p is the computational costs of transaction execution, T_g is the maximum amount of computational costs, T_t is the address of the recipient, and T_v is the amount of transferred value. The combination of T_w, T_r, and T_s represents the signature of the sender, including the chain identifier, private key, and timestamp, respectively. T_i and T_d specify the account initialisation and input data of the message call, respectively. Transactions (T_0, T_1, ...) are then collated into blocks using a cryptographic hash as a mean of reference. Accordingly, the block-level state transition function can be re-written as:

$$\sigma_{t+1} \equiv \Pi(\sigma_t\ ,\ B) \quad (3)$$

Accordingly, blockchains attain immutability from the hashing algorithm and creating a block of ledgers. Block B is constructed of:

$$B \equiv (H,\ T,\ U) \quad (4)$$

where H is the block header, T is the information corresponding to the list of compromised transactions, and U is the block metadata that contains information about this block such as the set of other block headers that have the same parent or so-called Ommer blocks. Figure 2 presents a simplified schematic of blocks and transactions.

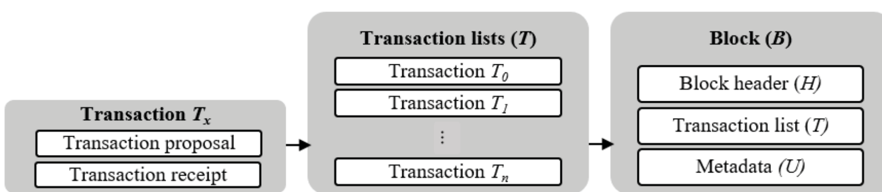

Figure 2. Simplified illustration of blocks and transactions.

Block header itself compromises of the hash of several other pieces of information which are useful for serialisation of blocks, such as a hash of the parent's block H_P, a hash of the Ommer list of this block H_o, timestamp, and a number of other information. The ledger structure varies across various blockchain platforms. For example, Bitcoin ledgers are presented in a list, while in others, are either as a directed acyclic graph of blocks (e.g., Hedra Hashgraph, which is an enterprise public blockchain), or the abstract logical view of the transaction history of a global graph of transactions (e.g., R3 Corda, which is an enterprise public blockchain).

In public blockchain protocols, a transaction passes through consecutive phases before being considered as committed (shown in Figure 3). First, after the transaction submission, it is announced in a pool. If the previous transactions (so-called parents) are yet unknown, the transaction inclusion will be delayed, waiting for the parent transactions to arrive. However, validators might decide to drop the transaction from the pool, which in that case, it is called an 'orphan' transaction. A transaction may also contain a parameter, so-called 'lock time', declaring it as invalid until the block with a certain sequence number has been validated. Lock time enables setting an 'execution date'. Waiting for a higher number of confirmation blocks may increase confidence in integrity and durability of transactions but will harm the latency and the throughput of the system.

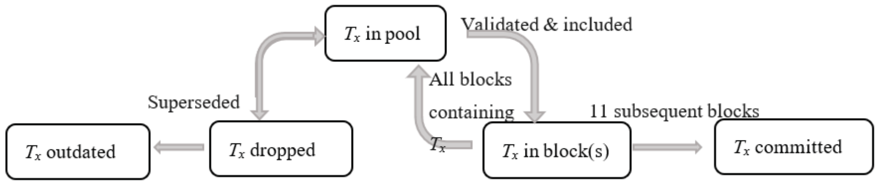

Figure 3. Transaction inclusion in Ethereum (adopted from Reference [46]).

2.1.3. Validation

The block finalisation is achieved through a validation process, which is bolstering a block over any other potential competitor blocks. Block-finalisation state transition function is defined as:

$$\Pi(\sigma_t, B) \equiv \Omega(B, \gamma(\gamma(\sigma_t, T_0), T_1), \ldots) \quad (5)$$

where Ω is the block finalisation state transition function which commonly compromises of four actions: (i) validating transaction, (ii) validating Ommer transactions, (iii) verifying state and mapping a block to its initiation state, and (iv) applying rewards.

Accordingly, block finality is an essential blockchain property which affirms that once the confirmed blocks are committed, they cannot be revoked, arbitrarily changed, or reversed. In the literature, two types of finality are defined, namely probabilistic and absolute finality. Probabilistic finality refers to public blockchains such as Ethereum, in which the probability of transaction finality increases as the block length increases. Absolute finality is mostly achieved in permissioned or private protocols such as Hyperledger, in which the finality is immediately obtained once it is validated. Notably, the finality of public blockchains can be affected by transaction reordering. Hence, in order to keep the integrity (i.e., time ordering) of transactions, it is essential that a suitable transaction lock time is set up, and also, high-speed links between certain nodes in public blockchains are provided [46].

A set of rules and validation procedures is called a consensus algorithm, which maintains the coherency between multiple participating nodes. The consensus mechanism is one of the blockchain pillars, even in permissioned and private blockchains. The role of the consensus mechanism becomes more important where there are untrusted and unknown nodes in the network. The choice of consensus protocol impacts performance measures such as security and scalability.

Proof of Work (PoW) is the most common consensus mechanism used in public blockchains such as Bitcoin and Ethereum, which is notorious for its computationally heavy and energy-consuming mining process. However, this is intentional, and the reason is that it prevents anyone from easily taking over the network (explained in the Appendix A). Thus, PoW is very suitable for high levels of decentralisation where anyone (including attackers) can participate in the network. In permissioned public blockchains, nodes are intrinsically more trusted than those in the permission-less public blockchains. As such, the PoW consensus mechanism may be overly burdensome, and other mechanisms may provide 'enough' trust to run a distributed system [47]. Hence, several consensus algorithms have been developed. Notably, there is no perfect consensus mechanism, and there is always a trade-off between these mechanisms in terms of throughput, latency, security, and scalability [48].

Fault tolerance, as another important aspect of blockchain, refers to the possibility that consensus agreement occurs. Higher fault tolerance translates into higher reliability. Notably, these consensus mechanisms can be combined for a greater outcome. For example, the hybrid PoW and Proof of Stake (PoS) deployed in Neo and Zililiqa blockchains requires much lower amounts of energy than PoW, while it provides higher integrity compared to PoS.

A comparison of the leading consensus algorithms is depicted in Table 2, which is summarised based upon an extensive review of various platforms in the IT literature [43,47–50]. This comparison includes the relative performance measures, transaction costs, fault tolerance, and block finality.

Table 2. Comparison of consensus algorithms (developed by the author from the studies in References [43,47–50]).

Consensus Algorithm	Description	Applications	Advantages	Challenges
Proof of Work (PoW)	Based on the information of the previous block, the different nodes calculate the specific solution of a mathematical problem. Computational power is required to solve the math problem. The first node that solves this math problem can create the next block and get a certain amount of reward in terms of Ether, or any other kind of token.	Suitable for public permission-less blockchains, e.g., Bitcoin and Ethereum	Good scalability, 50% Byzantine fault tolerance	High computation and power consumption, probabilistic finality
Proof of stake (Pos)	In PoS, those who hold tokens can "stake" their tokens (staking means to temporarily place the tokens in a locked smart contract—until staking is over) and in exchange, confirm transactions and receive rewards based on the relative number of tokens held. PoS does not need relative computing power required in PoW but needs at least the same held stake of the transaction cost.	Suitable for public permission-less blockchains, e.g., Hedra Hashgraph, EOS, Qtum, and Nano	Less consumption and computation power compared to PoW, good scalability, 50% Byzantine fault tolerance	Inequality since wealthier stakeholders are more likely rewarded, probabilistic finality
Zero Proof of Knowledge (ZPK)	In ZKP, there are two key actors, namely prover and validator. The prover gets some authenticated secret knowledge. The validator request on prover's data. The prover computes the response and constructs the proof of correct computation. The validator applies ZKP algorithm to ensure the answer is correct. Cryptography is complex and computationally expensive. However, the third version, released in 2020, combines up to 20 transactions together, thereby reducing costs.	Suitable for public permission-less blockchains, e.g., EY Ops Chain, EY Blockchain Analyzer, Blocknet	Computational efficiency due to no encryption, good scalability, protecting the privacy	Probabilistic finality
Proof of Importance (PoI)	POI not only rewards nodes with a large account balance (similar to PoS) but also takes into account how much they transact to others and who they transact with and give them a score. In PoI, a participant with a higher score has an increased possibility of being selected as a validator.	Suitable for public permission-less blockchains, e.g., NEM	Less consumption and computation power compared to PoW and PoS, good scalability, 50% Byzantine fault tolerance	Major supply chain actors and more prominent companies get rewarded more, probabilistic finality
Proof of Authority (PoA)	PoA is a modified form of PoS where instead of stake with the monetary value, a validator's identity performs the role of stake. PoA uses a Byzantine Fault Tolerance algorithm which relies on a set of trusted validators.	Suitable for permissioned blockchains, e.g., Parity	Negligible power consumption, high performance in terms of throughput and latency, absolute finality	Need for trusted validators, 33% Byzantine fault tolerance

Table 2. *Cont.*

Consensus Algorithm	Description	Applications	Advantages	Challenges
RAFT	Raft uses a crash fault tolerance consensus mechanism, developed by researchers at Stanford University. It generally contains five server nodes. Up to two nodes are allowed to crash at the same time. The server node has three states: leader, follower, and candidate. There is only one leader in a term, and the leader is responsible for handling all clients' requests. Raft followers blindly trust their leader.	Suitable for permissioned blockchains, e.g., Quorum	Absolute finality, efficient storage saving, faster block time compared to other consensus algorithms, 50% crash fault tolerance.	Poor scalability, integrity issue since the leader is always assumed to act honestly.
Practical Byzantine fault tolerance (PBFT)	A validator verifies the proposed block just like PoW in an untrusted environment. Each node in the network publishes a public key. Then, when messages come through a node, it is signed by the node to verify the message as being the correct format. Once enough identical responses to the message are reached, the consensus that the message is a valid transaction is met. The list of validators that get involved in voting for each block can be dynamically expanded or reduced by asking existing validators to vote.	Suitable for permissioned blockchains, e.g., Hyperledger and Cosmos	Negligible power consumption, high performance in terms of throughput and latency, absolute finality, reduced time between blocks	Poor scalability, no guarantee on the anonymity, need for trusted validators, 33% Byzantine fault tolerance
Istanbul Byzantine fault tolerance (IBFT)	IBFT is similar to PoA and modification of PBFT. Each block requires multiple rounds of voting by the set of validators to arrive at a mutual agreement. Agreements are recorded as a collection of signatures on the block content.	Suitable for permissioned blockchains, e.g., Enterprise Ethereum solutions, Pantheons and Quorum	Negligible power consumption, high performance in terms of throughput and latency, absolute finality, reduced time between blocks	Poor scalability, no guarantee on the anonymity, need for trusted validators, 33% Byzantine fault tolerance

2.1.4. Data Storage

A data management strategy in order to increase the performance in blockchain-based projects is to store raw data off-chain and to store the metadata, hashes, and small-size critical data on the main chain. Many kinds of data are also better stored off-chain, for scalability reasons, for confidentiality reasons (private data), or for dealing with legacy databases. Therefore, another important architectural choice concerns the off-chain data storage.

2.1.5. Communication Channels and Smart Contracts

Transactions can be created through a smart contract, which is an automatic and self-executing contracting application. The idea of smart contracts was first proposed by [51], which combined computer protocols with user interfaces to execute the terms of a contract. Many blockchain platforms enable smart contracts. Reduction in payment reconciliation time and cost is the most important advantage of smart contracts in supply chain use-cases. Additionally, transactions which are sent from unauthorised agents, or in a wrong point of the process, can be automatically rejected, which prevents double-spending and human mistakes [52]. Interested readers are referred to a study by the authors of Reference [53], who provide a comprehensive review of various smart contracts.

Transactions in different blockchain platforms can be structured in different ways. In permissioned blockchain, transactions are only distributed to parties of interest via communication channels, to limit the distribution of transactions further while attesting to the integrity of unseen parts of the transaction graph. Furthermore, state channel or sidechain is a technique for performing transactions and other state updates between different blockchains off-chain. Notably, things that happen "inside" of a state channel retain a very high degree of security and protection of off-chain data. Sidechain allows transactions of one blockchain/channel to be securely transferred and used in another blockchain/channel, while the integrity of blocks is still kept in the original chain or so-called main chain. Sidechains can be private chains which are linked to a public blockchain. Main chain can protect the transactions on the sidechains and prevent the forking issue. Sidechaining prevents overloading the main chain, reduces the latency, and increases the performance.

There are two ways of sidechaining, unilaterally and bilaterally linked. For a unilateral (or one-way) sidechain, the interaction is only from the main chain to the sidechain. For a bilateral sidechain, the communication is bidirectional. One mechanism to secure bilateral linked sidechains is essentially a voting system where a group of pre-specified peers vote to make decisions about a transaction [54,55]. While the private sidechain is pinned to the main chain, it only allows the permissioned members to interact with the data on the main chain. The pinning needs to be done in such a way that the list of participants in one sidechain is not revealed on the main chain as part of the pinning process. The rate of transactions needs to be masked such that participants on the main chain cannot infer the activity level on the sidechain [55].

2.2. Blockchain Performance Measures

Interaction of the abovementioned features affects the performance of a blockchain network, which can be measured in terms of throughput, latency, scalability, and transaction cost.

2.2.1. Throughput

Throughput is defined as the number of transactions that can be processed within a time period and depends on the decentralisation level, ledger, and block configuration [46].

2.2.2. Latency

Read and write latency is defined as the speed that the system responds to a request for reading or writing a transaction. Read and write latency is affected by demand, resource bottlenecks, smart contract, and architectural mechanisms used for scalability (e.g., load balancing) [46]. Read latency is often low in the blockchain platforms because peers can have a local copy of the blockchain. However, write latency is typically high because updates of transactions must be propagated across a global network. Validation latency is also defined as the time between the transaction submission and confirmation and is affected by the consensus protocol [46]. For example, latency in a public Ethereum network is around 3 min (consisting of 14 s block intervals with 12 block confirmation).

2.2.3. Scalability

Blockchain scalability also refers to the number of nodes and communication channels and is affected by the data storage and communication channels strategy.

2.2.4. Transaction Cost

Transaction cost is another critical concern in the design of a software system and particularly for the collaborative business processes. While the cost of the initial platform set up and on-going maintenance costs of private blockchains are high, these costs are very minimum for public blockchains [50]. Nevertheless, the cost of basic computation and storage on public blockchains has a different cost structure than conventional cloud infrastructure [56]. Public blockchain (e.g., Ethereum) costs orders of magnitude more than cloud services (e.g., Amazon Web Services) for practical uses for business process execution on a large-scale dataset [56]. This is basically the cost of distrust and distributed power that blockchain users have to pay. There is a cost (although not necessarily in private blockchains) for new transactions, computation, and data storage on blockchain platforms. The costs of running and hosting applications can also be high. For example, in Ethereum, there is a fixed cost of 21,000 gas—the fee, or pricing value, required to successfully conduct a transaction or execute a contract on the Ethereum blockchain platform—in addition to variable costs concerning the transaction's complexity. If the arbitrary data is stored in a smart contract, the cost of storing data depends on the number of operations, which starts at 20,000 gas. Alternatively, arbitrary data can be excluded from the smart contract, and instead a subsequent transaction can be executed to update the variables, which in that case, it incurs 5000 gas instead of 20,000 gas. The third option is storing arbitrary data as a log event which costs 375 gas and an extra 8 gas for every byte of data. Interested readers are referred to References [44,46], who reviewed the cost models of public blockchains and smart contracts.

2.3. Most Common Blockchain Platforms

There is a plethora of blockchain platforms, some of which are more popular such as Ethereum, Hyperledger, R3 Corda, Cardano, Parity, Quorum, and Ops Chain. A review of the blockchain-based supply chain projects suggested that the majority are built on top of Ethereum and Hyperledger Fabric (10 and 9 out of 30 projects, respectively), and others are platform agnostic [10,57]. This is expected since, among a plethora of platforms and projects, these enterprise blockchain platforms are the only ones that meet the business goals in supply chain use cases. In the port logistics, freight companies are collaborating to streamline shared business processes, such as data management, transactions, and asset tracking. Hence, the focus of this paper is also based upon these two platforms. It should be noted that there is no single product called "Enterprise Ethereum", and what this term basically covers is the modified Ethereum platforms such as Quorum, Parity, and Pantheon that provide permissioning on top of the public Ethereum network. The following subsections provide an overview of these two blockchain solutions.

2.3.1. Ethereum

Undoubtedly, Ethereum is currently the most common platform used by over 2000 Decentralised applications (Dapps). Ethereum is an open-source collaborative project, proposed by Vitalik Buterin in 2014, which supports a modified version of Nakamoto consensus (i.e., consensus mechanism used in Bitcoin) via transaction-based state transitions. Ethereum enables smart contracts via the Ethereum Virtual Machine (EVM) and deploys Solidity programming language. The amount of computational cost in Ethereum is expressed as 'gas' which is used to calculate the fees that need to be paid to the network in order to execute an operation, such as running a smart contract or executing a transaction. Ethereum can currently process roughly 15 transactions per second. The reason for this slow throughput is that Ethereum public blockchains require every transaction to be processed by every single node in the network.

Hence, several advances have been made to overcome the performance inefficiencies, as shown in Figure 4. In the so-called Layer 1 protocol, Sharding architecture has been deployed to increase throughput and reduce latency in the Layer one protocol by splitting the network into different sections called shards, each of which can independently process transactions. In this way, the throughput can be increased by orders of magnitude. These shards can be presented as separate blockchains that connect to each other to share consensus agreement.

So-called Layer 2 solutions address the specific needs of an enterprise such as increased privacy, performance, and scalability, as well as permission and governance controls. Despite the Layer 1 protocol, the Layer 2 solutions solve the scalability issue by better utilizing the current capacity instead of increasing it. Layer 2 solutions provide better throughput by creating off-chains (or child-chains) and adjusting gas limits and block sizes, making it competitive with other enterprise solutions. State channels [58], Plasma [59], and Raiden [60] are examples of such solutions in the permission-less public blockchain applications.

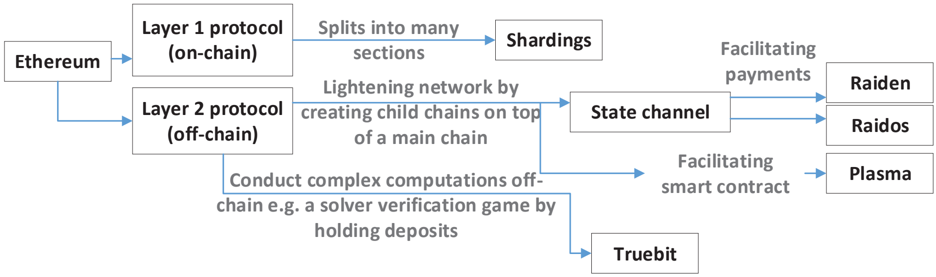

Figure 4. Public Ethereum protocols (developed by the author).

Notably, off-chains can also have their own consensus mechanism such as PoA or IBFT algorithm, while the main chain still deploys the PoW mechanism. Quorum (developed by JP Morgan) and Parity are examples of this solution. In these solutions, the capacity of the main chain remains the same, but many more transactions are performed in off-chains. In these Enterprise Ethereum solutions, nodes interact with various platforms through Application Programming Interfaces (APIs) and have full access to shared raw data, while also allowing for independent verifications.

In some of these solutions, however, the privacy settings are not suitable for an industry with high data confidentiality concerns. For example, while Quorum allows for transaction details to be made visible only to the parties specified in the contract, this feature is only available at the level of nodes, rather than between individual addresses. Consequently, in an industry with a high number of stakeholders, requiring each participant to run their own node is not feasible. Additionally, Quorum does not encrypt off-chain transactions [55]. Quorum has been used in supply chain applications such as AgriDigital, a food supply chain pilot project in Australia. Compared with the existing solutions, Quorum was evaluated as the best solution in 2016 based on throughput and privacy. The throughput of Quorum was sufficient for the AgriDigital use-case, producing sub-second transaction times for the exchange of digital currency and digital title. At a rate of four transactions per second, this settlement method was scalable to satisfy the throughput and latency requirements of the Australian grains industry. However, there were industry concerns in terms of transparency of transactions and scalability [46,61]. Newer Layer 2 solutions, such as Pantheon—the latest release of the Enterprise Ethereum collections—has addressed the privacy issue by encrypting the off-chain data, permissioning, and providing interoperability [62].

2.3.2. Hyperledger

Hyperledger is an open-source collaborative project, hosted by the Linux Foundation, which supports private and permissioned blockchain projects. Hyperledger developers have aimed to enable organisations to launch their own individual blockchain network. Hence, it has attracted over 200 organisations to develop their private or permissioned blockchain networks. In Hyperledger, all nodes of a network need to enrol through a trusted membership service provider. Despite Ethereum, nodes (users) of Hyperledger have known identities, and public keys are tied to the organisations and end-users. A channel allows a group of participants to create a separate ledger of transactions, shared only between themselves. The concept of a channel is similar to the off-chain in the Layer 2 solutions of the Ethereum, where the privacy and data confidentiality is guaranteed only between channel members, and no others can see the transactions on the associated ledger for that channel. Similar to traditional multi-layer database architectures, members in Hyperledger who are connected to one channel may be unaware of the existence of other channels.

Similar to the Ethereum Layer 2 solutions, nodes of the Hyperledger network have a pre-defined hierarchical role. There are three types of nodes within a Hyperledger system: client (end users), peer, and orderer (validators or miners). Peers commit transactions and maintain the state of the ledger.

Some of the peers can take a special role as the endorser. Each Chaincode might identify an endorsement policy to define the necessary and sufficient conditions for valid transaction endorsement. Such endorsement might involve single or multiple endorsers. Hyperledger deploys container technology for smart contracts (so-called Chaincode) execution. Container technology is a method to package an application so it can be run, with its dependencies, isolated from other processes.

The consensus mechanism used in Hyperledger is currently Practical Byzantine Fault Tolerance (PBFT), while it is claimed that various consensus mechanisms can be deployed in individual channels. In PBFT, each node in the network publishes a public key. Then, when messages come through a node, it is signed by the node to verify the message as being of the correct format. Once enough identical responses to the message are reached, a consensus that the message is a valid transaction is met. The PBFT consensus mechanism does not require any hashing power to validate transactions within a blockchain [63]. A transaction should be approved in three stages, including endorsement (done by peers), ordering (done by orderers), and validation. Validation checks the correctness of a set of ordered transactions within a block, considering the endorsement policy, and versioning checks for data integrity. Thakkar [64] provide six guidelines on configuring Hyperledger parameters (e.g., block size, endorsement policy, channels, resource allocation, and state database choices) based on an empirical study, and also identified three major performance bottlenecks and three simple optimisation methods to overcome those bottlenecks (for further details, see References [65,66]).

There are five major blockchain projects under the Hyperledger umbrella, namely Fabric, Sawtooth Lake, Iroha, Burrow, and Indy. Under modules, there are the Hyperledger Cello, Hyperledger Composer, Hyperledger Explorer, and Hyperledger Quilt. Fabric proposed by IBM is the most common project used by Hyperledger users. Fabric, developed by IBM, has addressed several problems of the public blockchain by providing permission, privacy, reduced read/write latency, and increased throughput. For the overview of Fabric architecture, interested readers are referred to a work by Bashir [44]. Table 3 summarises a comparative analysis of Ethereum and Hyperledger platforms.

Table 3. Comparative analysis of the two most common blockchain platforms (developed by author).

	Advantages	Limitations
Enterprise Ethereum solutions	Providing optional access to public Ethereum, which is the most used platform in the world so far. The capability of linking to a public network provides public enforcement for dispute resolution and arbitration while still maintains the full benefits of a privately controlled network. Tokenising or digitising of assets/transactions are enabled, which can be useful for incentivisation and removing international exchange rates. Negligible maintenance and deployment costs [50]. Encryption of the off-chain transactions is supported in the latest version. Adding a new participant is easier by merely executing a smart contract or so-called Ethereum Registration Authorities [67].	Lack of storage protocol since all private transactions need to be reprocessed each time an Enterprise Ethereum node restarted [55]. Lower performance measures compared to Hyperledger.
Hyperledger	Deployed by the dominant players in the maritime freight transportation and supply chain. Solving the performance scalability and privacy issues by permission mode of operation, using a IBFT algorithm and fine-grained access control. Supporting storage of data privately, by utilizing communication channels to provide a separation between different supply chain actors. Maintaining the existing business process and relationships by pre-specifying the roles of participants. Such as Access Control Lists (ACL) and data access rights. Encrypting of the off-chain transactions is supported in the latest version.	Hyperledger's assumption that all nodes (participants) are trusted cannot be fully supported in many applications, such as PCS. Ledgers are split in channels and even may lead to scalability issues because it becomes complicated to maintain a large number of encrypted channels at the same time and also maintaining a unified ledger structure on the entire network. The lack of bootstrapping method, which means adding new participants (e.g., a new importer, exporter, transport company, etc.) to a network is a complex and time-consuming process [55]. High initial setup costs, deployment costs, and maintenance costs [50].

3. Port Supply Chain

Maritime transportation is an example of a fragmented supply chain market where multiple parties interact with each other over one shipment, as shown in Figure 5. The interactions are in two layers of physical and administrative. Four types of transaction are identified within and across these two layers, namely information, financial, physical, and liability transaction [68]. Transaction cost is defined as the coordination cost incurred in a transaction, which consists of the costs of searching for agents or information, establishing a contract, governing, monitoring, settling disputes, or enforcing the implementation of contract. Coordination failures in transactions lead to higher logistics costs and losses of efficiency and productivity. In the context of port logistics, transaction costs include contract establishment costs (e.g., freight forwarder or customs broker fees), administrative fees (e.g., pre-receival permit and booking fees), transport service rates (e.g., terminal handling, storage and inland transport charges), governance costs (e.g., customs and auditing fees), and other costs for settling disputes and uncertainties.

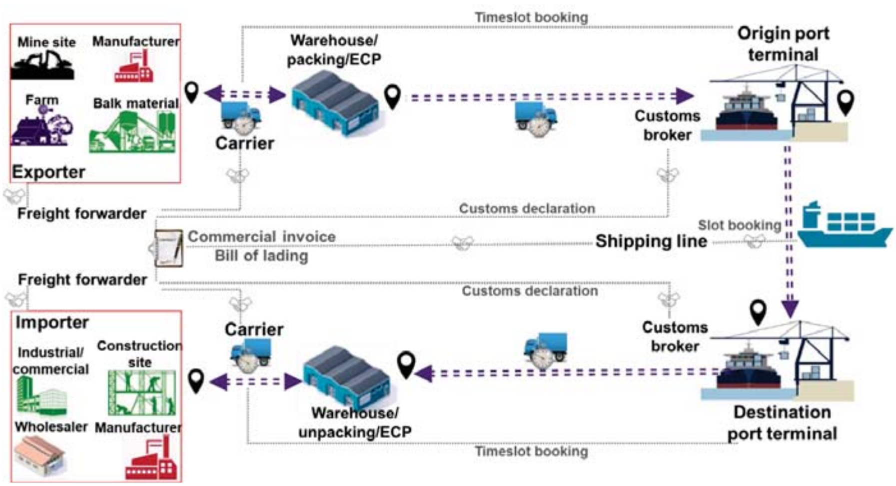

Figure 5. The fragmented market of international freight transportation.

Import/export trade starts with a bill of lading, which is a trade contract between consignor (seller or exporter) and consignee (buyer or importer) where the terms of sale and payments are identified. Importers and exporters may have in-house freight forwarder and customs broker, or they may contract these agents separately. Freight forwarders negotiate and contract with shipping lines and in-land carriers to manage the carriage stage. It is estimated that of total freight forwarder fee for administering of a container, 63% is the regular activities costs, 25% is the administrative costs related to customs checks, and 12% is the logistics preparation for scanning and inspections [69].

Customs brokers are responsible for submitting a summary document to the customs at least 3.5 days before the ship arrival, and releasing the container at maximum three days after the ship arrival [70]. The anecdotal evidence suggests that the freight forwarder should provide the customs broker with a list of relevant documents five days before the ship arrival. This suggests that all the necessary contracts and agreements should be finalised a few days in advance. Port terminals refer to businesses that engage in loading and unloading a ship's cargo. They are responsible for checking and releasing the discharged/charged cargo against manifest, customs declaration, and notifying the importer/exporter.

Shipping lines are responsible for carrying the containers and/or cargo, from the loading port to discharge at the destination port. Shipping lines may sign long-term contracts with in-land carriers and offer door-to-door service. They may also operate, own, or share vessels, and may own or rent containers. They are also responsible for notifying the importer/exporter about the estimated arrival/departure date and the name of port terminal to/from which the cargo is discharged/charged. Freight forwarders submit a booking order to a shipping line that includes an approximate volume/number of containers and the preferred time window for shipping. Freight booking order allows the shipping line to pre-plan the probable demands with respect to vessel capacities and schedules. Final booking is confirmed by the shipping line when the details of the cargo and the cut-off dates are finalised. The cut-off date is the deadline for the exporter that determines whether the full container should be in port terminal and is determined based on ship schedule. Final booking triggers assigning an empty container number which is simultaneously announced to the empty container park (ECP) and the freight forwarder.

Notably, only full containers generate revenue for shipping lines. Shipping lines impose restrictive time windows for importers and exporters in order to afford enough time in balancing the empty and full containers and optimise their revenue. Exceeding the time window incurs demurrage and detention fees which are borne by importers and exporters. Demurrage refers to the delay in picking up the full container, and detention is the delay in delivering an empty container. While these rates vary across shipping lines, they also have different demurrage and detention regimes across various customers, ports, and in-land carrier modes (rail or road). These regimes tend to favour trucking as the hinterland transport mode [69]. The time windows and fees are negotiable and are not transparent.

Port terminals also charge the importers and exporters if the storage exceeds the free days, and the daily storage rate increases exponentially the longer the container is left on the terminal's yard. The reasons causing storage include inconsistency between the documents, delay in customs release, missing the ship, unpaid duty and/or Goods and Services Tax (GST) invoice, and missing permits.

In export supply chain, freight forwarders are required to prepare a mandatory document called Export Receival Advice (ERA), or an electronic version called a Pre-Advice Export Receival Advice (PRA). The ERA/PRA includes details of the packed container such as the contents, booking number, container number, and booking timeslot at the stevedore. The valid ERA/PRAs are manifested to the truck registration number and are entered in the timeslot booking at the port terminals. If for any reason there is an inconsistency in the information in the ERA/PRA, the freight forwarder must submit an amendment and pay an amendment fee. Additionally, ERA/PRA adjustments often incur the 'missing timeslot fee', and/or 'truck waiting time fee', which is imposed when waiting more than 1–2 free hours at the wharf gate.

As shown in Tables 4 and 5, port logistics is subject to too many uncertainties, inefficiencies, and coordination failures. Direct costs are resulted from booking cancellations, timeslot missing, double-spending, re-packing costs, and penalty fees. Indirect costs are also incurred as a result of inefficient planning of resources, fleets, and drivers. For example, due to a lack of empty containers at ECP, invalid permits, or "re-direction", trucks are being turned away, causing futile truck trips, vastly inflated costs, and inefficient job allocation for truck drivers.

Table 4. Overview of transactions in pre-carriage logistics in the status quo (developed by the author).

Transaction	Main Actor	Documents/Key Events	Uncertainty/Inefficiency Causes
Freight forwarder contract	Exporter/Importer	Cargo information and transport instructions	Paper-based contracts, communications by email/phone, middleman involvement
Freight booking order	Freight forwarder	Negotiation with the shipping line, cargo information and instruction	Communications by email/phone between freight forwarder and shipping line.
Final booking	Shipping line	Vessel allocation, determining the cut-off date and empty container number issuance, notifying the freight forwarder and ECP operator	Missing cut-off dates and cancellation from the exporter side, since customer often books more container slots or book multiple times through various shipping lines to guarantee enough space for their cargo or just comparing the prices, hence lower ship utilisation and shipping line revenue loss. Unavailability of the released empty container leads to renting the container from a third-party.
Arrangements with warehouse, packing, unpacking	Freight forwarder	Cargo information and instructions	Paper-based contracts, communications by email/phone
Submission the documents to the customs broker	Exporter/Importer	Bill of Lading, commercial invoice, packing list, packing declaration, cargo manifest, other documents (e.g., phytosanitary certificate, manufacturer's declarations, lot codes and batch numbers, fumigation certificates, costings and assist sheets, permits, certificate of origin, certificate of Analysis)	Paper-based contract, communications by email/phone, middleman involvement
Pre-departure customs declaration/ Pre-arrival delivery order	Customs broker	Submission of a summary document to Customs	Manual data entry, lack of collaboration between freight forwarders and customs broker, double data entry
Customs release	Customs broker	Digital scanning, physical inspection (1–2% of containers)	Demurrages, detention fees, missing timeslots at the wharf, the futile trips to the wharf, ECP or depot storage, unpacking or packing areas
Inland haulage contract	Freight forwarder	Transport instruction, transport charge, liability	
Port call	Ship captain	Ship schedule, port charge payment including navigation, berth hire, and cargo charges, ship berthing permit including a list of personnel on board, all non-commercial goods on board, technical certificate	Surveillance, the increasing trend of port charges

Table 5. Overview of transactions in inland haulage logistics in the status quo (developed by the author).

Transaction	Main Actor	Documents/Key Events	Uncertainty/Inefficiency Causes
Terminal timeslot booking	Trucking company	PRA number for export, and pickup container number in import, truck registration number	Multiple-spending due to bulk bookings, costs of missing timeslots (A$100–250 per slot), due to unexpected congestion/delay in haulage, wrong container packing, PRA adjustments, or long queues at the terminal gates
ERA/PRA submission	Freight forwarder	Documents informing the container arrival at the port terminal including cargo information, container number, booking number, booking timeslot	Multiple adjustments (A$125 per each amendment)
Empty container pickup arrangement	ECP operator	Daily monitoring and notifying shipping lines about stocks, notifying forklift drivers, gate out receipt issuance and emailing to carrier	Cancellations, re-keying manual entries of the container number by the truck driver, no availability of container with the specified PIN, picking up the wrong container by the transport carrier
Container release at port terminals	Port terminal inspector	Checking the container against manifest and customs declaration, notifying importer and exporter	Delay which incurs truck waiting fee, storage fee (A$100–350 per container per day), and demurrage rates
Container pickup/delivery by carrier	Trucking company	Picking or delivering the container, entering the container number in the terminal system	Re-keying manual entry of container number at the terminal gate, wrong container pick-up or the wrong container number entered in the terminal system, counterfeiting container number data and risk of security breaches with container numbers being manipulated

This is mostly the result of incompatible interfaces between actors, reliance on manual transactions, and lack of interoperability between siloed systems. For example, bilateral communication between parties occurs mostly with email communication, and only on some occasions with dedicated user interfaces. These interfaces are privately owned and managed. Accordingly, data are not often shared with governments, let alone other businesses, due to data confidentiality issues and lack of data sharing protocols. While all parties are in favour of linking up one single interface to reduce their manual work and human errors, a new trusted third party is not a viable solution in many ports, particularly in landlord ports. Landlord ports suffer from a lack of authority over freight operators which is a big challenge for integration or perhaps reengineering the logistics business processes [9]. Accordingly, freight operators have no incentive or obligation in sharing information with the port authorities. As a result, there is no efficient monitoring mechanism over the whole supply chain and logistics operations. Where there is a lack of transparency, trust, and coordination, inefficiencies hardly can be quantified and be highlighted to the involved parties. For example, as suggested in Reference [71], while it is a general knowledge that ships often operate in 90% of their capacity due to container slot cancellations, and despite the industry attention to the slot cancellation, the factors leading to cancellations have not been investigated, mainly due to lack of real data.

The Transaction Cost Economics (TCE) theory explains the governance structure of agents to attain organisational efficiency, such as transaction cost minimisation through vertical integration [72]. In TCE, a transaction is defined as the ultimate unit of activity transferring across technologically separable interfaces, possessing three dimensions of uncertainty, frequency, and asset specificity [73]. Uncertainty is defined as an event that cannot be predicted. There are various types of uncertainty, including environmental, behavioural, relational, competitive, and strategic uncertainty [74]. The concept of asset specificity is also defined as the extent to which a party is tied in in a mutual business relationship. For example, physical asset specificity refers to the degree to which a specialised tool or IT equipment is designed for a single transaction, and human specificity refers to knowledge and experience that is required for a specific transaction. Clearly, the fragmented logistics processes and centralised IT platforms lead to higher specificity, and hence higher transaction cost. Williamson argued that asset specificity becomes an issue because of opportunism, and hence a high specificity leads to a higher transaction cost [73]. The intermediaries in the port supply chain such as customs brokers or freight forwarders increase the potential for opportunistic behaviour.

The unexpected costs such as demurrage/detention fee or terminal storage fees are often a source of many disputes over which party is ultimately liable since culpability for the delay is often unclear. Exporters and importers not only are liable for any of these unexpected costs but also must either invest in in-house specificity or contract with third parties such as freight forwarder or customs broker. Human specificity plays a vital role in the success of these industries. For example, the customs broker has a specialty in free trade agreements, concessions, duties, taxes, and GST. It is also a common knowledge that negotiation about the costs or free days is the key in this market. Hence, the information about arrangements and contracts are considered as an invaluable asset. The impact of a negotiable market and information asymmetry is ultimately borne by exporters, importers, and producers. For example, the infrastructure charges are levied by port terminals in Australia in order to recover their scaling costs, such as port rents, taxes, and council rates. However, the infrastructure charge has shown its impact to significant growth in towage rate (12.9% increase from 2018 to 2019), which is borne by exporters and importers, indicating the negotiation power of shipping lines [75].

Additionally, untruthful activities such as masquerading the information on the contracts or double spending incur extra costs of auditing and monitoring, resulting in higher transaction costs. Notably, the lack of visibility results in a lack of surveillance and compliance. On some occasions, the contents of containers are not declared correctly, either due to last-minute changes, to avoid duty, or to pay less insurance liability. For example, an accident investigation by the Marine Accident Investigation Branch in 2008 reported that about 20% of containers' manifests had less weight from the actual weight (in total 312 tonnes), and 7% had a wrong position than the declared position by the port terminals [69]. Another example is in excess of 31 million AUD of duty evasion in 2019 for smuggling tobacco and cigarettes in Australia [76].

4. The Value Proposition of Blockchain for Port Supply Chain

By and large, the issues above can be resolved by digitising, integration, and inter-organisational transaction governance. While digitalisation and integration via Electronic Data Interchange (EDI) protocols might be a solution for many of these issues, cyber-attacks always threaten the shipping and logistics industries given their vital and central role in the supply chain. Cyber-attacks to the centralised databases and IT systems paralyse the operations and cause irretrievable loss of sensitive information and financial damages to all supply chain actors. A cyber-attack on Maersk in 2017 crippled the IT infrastructures of this company for a few days, which led to 300 million USD costs to the company [76]. Another cyber-attack in 2018 on COSCO (China Ocean Shipping Company Limited) paralysed the communications between vessels, customers, and port terminals in the USA [76]. The comparison of costs and risks between blockchain, EDI, and service-oriented architectures is studied in Reference [18] for the food supply chain. The authors reiterated the advantage of blockchain in terms of reducing cyberattack threads, and the need for trust among parties and intermediaries. While in EDI, for example, one actor dominates the others and forces adoption, which ultimately leads to higher specificity and higher transaction cost.

Taking the discussions in the previous section into account, it was possible to summarise the following implications:

- Port logistics is a multi-party industry, where not all parties are trusted.
- Landlord port authorities are not trusted, and a new trusted third party is not viable.

- Several intermediaries are involved in the logistics process and hence incur higher specificity and results in higher transaction costs.
- Significant time and resources are spent in reconciling data that has been entered into multiple systems and databases.
- Tamper-proof digital recording of events and their evidences are required for monitoring, supervision, governance, and compliance analysis by the regulatory bodies.
- Transparency is partially required while immutability and encryption are essential for maintaining the confidentiality of businesses information.
- Supply chain actors are more likely geared towards technologies with lower entry barriers such as lower set up and maintaining costs.
- While the storage of data on the main network is not required, providing the visibility of transactions for all certified actors is crucial.
- Seamless administrative and financial transactions are required.
- A centralised platform not only creates another intermediary but also is subject to cybersecurity attacks.

The blockchain value proposition for port logistics is realised through the aforementioned unique specifications. Amongst many other potential drivers of value, blockchain resolves coordination failures that arise as a consequence of asymmetric information in such a fragmented and untrusted market. The distributed structure and the complex cryptographic verification make it nearly impossible to alter the state of the transaction fraudulently. Hence, some of the shortcomings of the current IT systems could be overcome by effectively digitising all transactions and providing sharing, accessibility, and readability protocols. For example, the Port of Antwerp tested a blockchain pilot project for the container release, whereby container PINs are generated and saved on a blockchain network, making it impossible to counterfeit.

Blockchain can also overcome disputes over unexpected costs and business complexities by achieving true tamper resistance of data, guaranteeing no collusion between business partners, no tampering with data or transactions, and no capacity to unilaterally alter business rules. As such, smart contracts can be securely executed if pre-specified conditions are met. Not only can a smart contract solve the inter-agent lack of trust, but it also reduces human error. Accordingly, operators see the advantages of an integrated marketplace, compared with dealing with multiple parties with different platforms and business structures. It not only removes the dependency on the other authorities and intermediaries by the disintermediation but also reduces the likelihood of hacking threats and cyberattacks [18].

Following the conceptualisation suggested in Reference [77], the value proposition of a blockchain-based PCS platform is assessed within four central dimensions: the Who, the What, the How, and the Value (Table 6). The first dimension 'Who' identifies the target customer or stakeholder. This dimension consists of all agents involved in the maritime supply chain either directly or indirectly. The 'What' dimension describes the value proposition, or in other words, what is offered via blockchain. The 'How' represents how several processes and activities must be mastered to generate and distribute the value proposition. The 'Value' dimension explains why blockchain is financially viable and how it relates to the revenue model.

Table 6. Implications of blockchain-based PCS business models, developed by the author based on the St. Gallen conceptual model [77].

What: Value Proposition	How: Potential Opportunity with Blockchain	Value: Implications
Track and traceability: Lack of traceability of contracts, carriers (trucks and containers), and shipments in the status quo results in manipulation and masquerading of crucial information, leading to higher monitoring and auditing costs.	Blockchain keeps track of all business events (transactions executed) and the associated details in the event's lifecycle such as timestamp, new asset creation, and asset state modification.	Provenance
Visibility and transparency: Lack of transparency adds complexity to the management where freight actors have no monitoring power over their resources when they are outside their premises. It is one of the key drivers of coordination failures and lower productivity due to lack of an accurate, real-time picture of container/truck, demand signals and supplier inventory levels (e.g., idle truck fleets, drivers, empty containers, storage capacity). Inefficiencies and uncertainties impose extra costs, and in the status quo, the supply chain actors consider these costs as "the cost of doing business" such as low truck utilisation, idle fleets, slots cancellation, and empty running of trucks.	The unimpeded flow of information provided by blockchain contributes to more efficient functionality and liability. All information on pricing and other aspects are continuously and instantaneously updated, hence facilitating pre-planning and creating a transparent market. The dynamic planning capabilities of the logistics service providers will be enhanced. Turnaround times, on-time delivery failures, and the costs of doing business will be reduced.	Efficiency and productivity at firm-level
Interoperability, coordination, and integration: In the status quo, every freight operator has its own management platform and dataset, with the limited interconnection capability. Freight operators are operating as silos with a limited sense of common purpose and impacts of each element on the overall performance of the supply chain. Container supply chain information is dispersed and needs to be able to be coalesced to facilitate planning and operations. Due to a lack of understanding of the capacity of the entire maritime supply chain, it is extremely difficult to know where the capacity constraints are likely to emerge and how they should be addressed.	Freight actors can securely share their information with their business partners across the supply chain to drive productivity through a trusted and possibly a multi-level data access architecture. Data on interoperability will enhance the ability of policymakers to coordinate across the system and relieve the points of highest friction in the system. The integration also enables providing optimised logistics solution (e.g., truck-sharing, back-loading, and empty container repositioning).	Efficiency and productivity at the system level
Disintermediation and reduced payment reconciliation time and cost: The majority of transactions in the port logistics are performed manually either by email or phone calls, resulting in human errors, double-booking, double-spending or pick up/delivery of a wrong shipment. There are several intermediaries (e.g., customs broker and freight forwarding company) involved in the process which incur extra costs.	The validation mechanism of blockchain prevents data discrepancies because transaction metadata should match to the previous linked block when passing through multiple supply chain actors. Smart contracts, instantaneous settlement and real-time processing reduce settlement, penalty fees, and human mistakes. History of immutable transactions removes the cost of settling disputes over co-ordination failures and unexpected delays and expenses. By tokenising, payments can be seamlessly transferred across the international trade parties without incurring an exchange rate.	Lowering business costs

Table 6. *Cont.*

What: Value Proposition	How: Potential Opportunity with Blockchain	Value: Implications
Risk mitigation in contractual, legal, and regulatory aspects of the trade: In the status quo, lack of information sharing protocol is the main barrier for compliance directives related to trade practices, environmental mandates, customs, legal and regulatory purposes. Cybersecurity attacks to granular IT infrastructure, data manipulation, masquerading the real information on the contracts, bill of lading, and customs declaration documents are common problems in the status quo.	The blockchain contains a complete history of every data manipulation and transactions. The transactions also contain metadata essential for compliance analysis and audit such as the identity of node, the identity of validator, the timestamp and exchanged monetary values. The distributed structure of database minimises the risk of cyberattacks.	Compliance, governance, and increasing security
Enabling trust: In the status quo, revealing sensitive business information is the main barrier for data sharing. Additionally, lack of a trustable and unique source of proof often leads to disputes over the accountability of freight actors for unexpected costs, losses, and delays.	Distributed confidentiality mechanism of blockchain enables data integration without a need for trust. Timely detection of any attempt to manipulate or compromise the booking system will reinforce trust in the platforms. Encryption of transaction metadata and secure identity management protocols remove entry barriers and lead to a greater willingness to use, compared to centralised systems.	Lowering auditing and monitoring costs Creating Co-innovation (Co-innovation refers to activities to build new knowledge and create opportunities for cooperation among participants [8]).

5. Architectural Design Requirements of a Blockchain-Based PCS Platform

An industry stakeholder consultation, involving various trade parties, was undertaken to outline the most important platform requirements, including minimum performance requirements for a PCS in terms of read/write latency and throughput. The results of the industry stakeholder engagement and the review of blockchain design components in Section 2 outlined five suggestive architectural design requirements in the context of PCS architecture, as follows:

5.1. Requirement 1: Lowering Entry Barrier, Creating Trust among Fragmented and Untrusted Actors

The supply chain actors are more likely geared towards technologies with lower entry barriers such as lower set up and maintaining costs. Using a private blockchain instead of a public blockchain may allow greater control over the admittance of processing nodes and transactions into the system but also increases entry barriers and thus partly reduces some of the benefits of using a blockchain. Particularly, it is risky when it is predicted that the public blockchains will provide connectivity in the future similar to the internet these days. It is believed that the future of public blockchain is similar to the Internet where all blockchain applications will be connected. Accordingly, the capability of public chain compatibility will be of utmost importance.

It seems that a permissioned public blockchain is preferred in the PCS architecture, where better performance is required while the core functionality of blockchains is also maintained, including creating trust among untrusted parties, less asset specificity, and removing middlemen. Accordingly, data in the platform will be deemed to be owned by its creator and the data owner can define who will be able to access to their data, but simultaneously, users should have access to proof that the base data they are relying on has not been altered since its source.

➢ Suggestion 1: Deploying permissioned public blockchain, in which transactions are fully transparent to the pre-specified parties and partially transparent to all involved actors, yet fully traceable on the public network.

5.2. Requirement 2: Enabling Interoperability

The inter-chain interoperability is a key criterion for PCS platforms. Interoperability relates to communication between various blockchain platforms, or between two instances of the same platform, or between two sidechains within the same platform. The interoperability is an important specification for ensuring the viability of the product, mainly because it is expected that some freight actors develop their own blockchain.

Private sidechain channels are also foreseen in the architecture of the platform to provide privacy for specific subsets of network members. In a private sidechain, the data for transactions on that channel is invisible to members that are not granted access. Due to the dynamic nature of the international trade market, there is also a need to provide a flexible platform that provides easy access for the new trade participants. The bootstrapping method, such as the mechanism suggested in Reference [67], enables adding a new participant to the network without a need for setting up a new channel by a third-party. A blockchain-based PCS should augment (via APIs) rather than replace the existing operational systems developed by different supply chain actors.

➢ Suggestion 2: Enabling private sidechain interoperability, employing bootstrapping method and API interaction with the existing non-blockchain operating systems to lower the entry barrier (e.g., Ethereum Layer 2 protocols).

5.3. Requirement 3: Near Seamless Administrative and Financial Transactions and Validation

Undoubtedly, a PCS architecture should be capable of handling thousands of concurrent transactions per hour, which are submitted from multiple participants. The preliminary consultation with different trade parties outlined 10 s and 30 min for read and write latency on the public network, respectively. In the private sidechains, these values are expected to be 1 and 5 s for the read and write latency, respectively.

In order to increase the throughput and read and write latency, computationally heavy validation algorithms will not be applicable for this specific use-case. The initial assessment of consensus mechanisms suggests that the ZPK and IBFT seem to be the most preferred protocols. However, no inevitable conclusion can be made until there is a more detailed comparative analysis, at least in a simulation setting.

➢ Suggestion 3: Permissioned public blockchain with an IBFT or ZPK consensus mechanism can support the latency and throughput requirements of a PCS.

5.4. Requirement 4: Vast Range of Roles and Responsibilities

In the envisaged platform, any organisation with a verifiable role in the maritime transportation and supply chain should be able to participate. However, transactions and participants could be treated differently. For example, an account which is permitted to submit a transaction to update the state of a contract should not necessarily be able to submit a transaction which deploys a new contract.

➢ Suggestion 4: Pre-identified roles of each node.

5.5. Requirement 5: Large-Scale Nature of Transaction Data

Currently, in most public blockchain protocols, each node stores all states (i.e., account balances or contract code) and processes all transactions. This mechanism provides a high level of security but greatly limits scalability. Considering the massive number of transactions for supply chain and logistics application, and the fact that transactions in blockchain will stay forever, after a while, the network will experience congestion at times, and the scaling problem may arise. This necessitates deploying new methods to overcome the scalability limitations, such as artificially aborting transactions by superseding them with an idempotent or counteracting transaction [78]. Clearly, due to the limited size of the data store provided by blockchain, an off-chain data storage is necessary for a PCS platform.

Furthermore, encrypting data before storing it on a blockchain may increase confidentiality, but will reduce performance, and may harm transparency or independent auditing processes. On the other hand, storing only a hash of data on-chain and keeping the contents off-chain will improve confidentiality and may improve performance, but partly undermines the distinctive benefit of blockchains in providing distributed trust. This may create a single point of failure, reducing system availability and reliability. Hence, support for the level of encryption must be specifically investigated ahead of time.

➢ Suggestion 5: *Enabling off-chain data storage and off-chain data encryption*.

6. Future Research Agenda

In this paper, many of the research questions raised by Tönnissen and Teuteberg [36] were answered in the context of port logistics. There are a few other studies that have outlined a number of research propositions. Saberi et al. [25] identified seven post-implementation research agenda focusing on the potential outcomes from blockchain implementation in the supply chain, which are still understudied. Wang et al. [10] suggested six future research agenda, some of which are still unexplored. Our survey of existing research on blockchain application and maritime supply chain also identifies a research agenda in six primary directions, as follows.

6.1. Model-Driven Engineering

Model-driven engineering is translating the business process into the design and testing the platform at various abstraction levels and different stages of platform development. Model-driven engineering is not only independent of a specified platform but is also easier to understand and verify than codes. This can be particularly useful for communicating with industry partners about smart contracts and strengthening confidence in that code from all stakeholders. Many studies have presented model-driven engineering for blockchain platforms in general [78–82]. To the best of the author's knowledge, there are only two qualitative studies looking at the reengineering of the business process of blockchain in the supply chain [17,19]. Hence, a more detailed analysis is required to identify and define the corresponding limitations and trade-offs. A simulation would need to be set up at the real-size scale taking the nature of freight actors, the database, and market structure into account. This simulation will cast light upon specification requirements, including throughput (of transactions), scalability, transaction cost, and interoperability. The outcome can progress the assessment of new and improved platforms and be tailored to meet the identified requirements of the PCS.

6.2. Benchmarking the Blockchain Performance

Generally, an inability to predict overall performance is one of the main challenges of blockchain technology [46]. However, architectural models can be employed to benchmark the performance of blockchain before and during development stages. The majority of performance metrics presented in the academic literature are limited to running laboratory experiments on proof of concept projects [57]. Future research is required to focus on the performance benchmarking of port logistics by developing architectural models.

Architectural models are either developed by analytical solvers or simulation engines. These models are two-fold including analytical performance models (e.g., Petri Nets Queueing networks and layered queueing networks), and architecture-level performance models that can be either simulated or converted to analytical models (e.g., Palladio Component model, UML profile, and Descartes modelling language). Virtual machines such as go-Ethereum (Geth) can also be deployed to mimic practical deployment to some degree. The importance of testing read/write latency is that a wide range of architectural alternatives can be analysed. Some of these decisions are about blockchain-specific issues, such as inter-block time or the number of confirmation blocks. Other design decisions, such as possible business process changes, are system-level design options but are impacted by latency arising from the blockchain-related factors [46].

6.3. Building Standards and Interoperability Protocols

A protocol is a standard language that lets a group of people work together on a specific problem. The first IT protocol was created in 1973 when different intranet networks realised that they could adopt a unified internetwork protocol to expand their service. Later, other protocols were developed such as Hypertext Transfer Protocol (HTTP) (i.e., protocol defining how information is transmitted over the web), Simple Mail Transfer Protocol (SMTP) (i.e., protocol for email app for sending and receiving email), and Secure Sockets Layer (SSL) (i.e., protocol of a browser for a secure data transfer). Interoperability is a protocol's capacity to interact and cooperate with different blockchains and to facilitate smart contracts between one protocol and another. Currently, blockchain suffers from a lack of standard protocols to link different blockchains, instead of creating a new larger blockchain. This lack of open standards and protocols may encourage companies to develop their own blockchain system without being designed for interoperability and positioning it among a myriad of systems involved in the port supply chain. Currently, various ports, shipping lines, and container terminals are currently developing their own blockchain platforms. Hence, it is expected that standards and interoperability protocols are required to leave everyone on their blockchain and just connect them to the rest of the ecosystem. These standards and protocols allow supply chain actors to minimise the disclosure of proprietary information while providing interoperability among other blockchain-based systems, such as another international ports. A combined desktop and interview study in Reference [83] revealed the importance of standardisation and regulations. Another area to investigate is the indicative level of standardisation needed to support the use of blockchain in port logistics. Consideration could be made of work underway in the international context to enabling interoperability among various blockchain platforms.

6.4. Blockchain Technology Adoption in the Port Supply Chain Industry

The adoption of new technology is often curtailed by a lack of appropriate IT capabilities within the traditional freight companies, and also lack of interoperability between supply chain actors. The literature is not devoid of technology adoption studies. There are a few studies reporting the expert opinions and providing first-hand insights into the blockchain adoption in the port logistics industry (see, e.g., References [35,37]). These studies indicate some of the barriers of blockchain adoption, such as privacy of information, lack of digitalisation in logistics companies, and lack of blockchain technology readiness [35].

There are also a handful of papers experimenting the technology adoption theories on case studies. Johnson [38] studied the theoretical relationship between organisational learning and blockchain through a qualitative case study approach and semi-structured interviews. Francisco and Swanson [37] used the technology innovation adoption concept or so-called the Unified Theory of Acceptance and Use of Technology to study the application of blockchain for supply chain traceability. Dobrovnik et al. [16] categorised blockchain applications based on multiple transformation phases and identified the potential blockchain applications in logistics based on the Diffusion of Innovation theory and the associated attributes of innovation framework which comprises relative advantage, compatibility, complexity, trialability, and observability. Verhoeven et al. [31] undertook a multiple case study approach on five applications selected based on five organisation objectives, namely smart contracts, business-to-business traceability, business-to-customer traceability, data transfer, and payment. Each selected case was reviewed according to five technology adoption principles, namely 'engagement with the technology', 'technological novelty-seeking', 'awareness of local context', 'cognisance of alternative technologies', and 'anticipation of technology alteration'.

Nevertheless, one future research inquiry concerns investigating the duration of the adoption cycle, and the degree to which blockchain is effectively integrated into the freight operator's systems.

These are dependent upon the experience gained from the adoption of like technologies such as Electronic Data Interchange (EDI) with particular reference to the frequency of these experiences and the complexity of the technology—indicating their technology readiness. As blockchain seeks to communicate and integrate across organisational boundaries, the complexity of the adoption process and the associated coordination costs and potential for opportunistic behaviour that can damage the adoption process are heightened.

6.5. Usability

Usability is defined as the ability of the platform to be easily usable by end-users as well as developers. Ease-of-use is extremely important for freight actors who do not necessarily possess IT skills. If properly designed, the end-users might not even get to know that they are using blockchain. Usability is supplied by a few other components working alongside the blockchain network, as depicted in Figure 6.

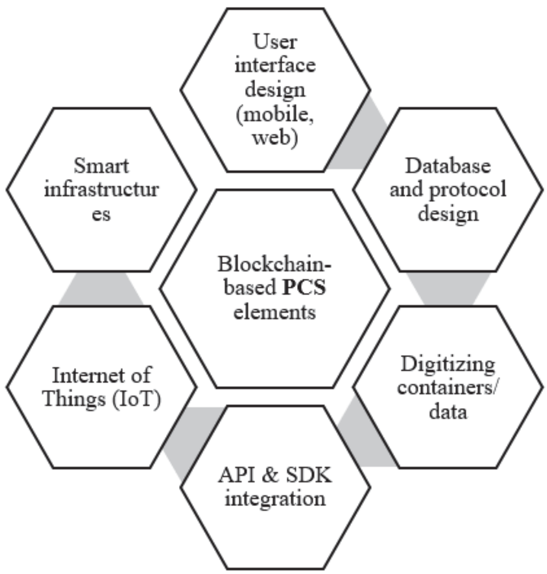

Figure 6. Blockchain-based PCS design components.

User interface design includes designing a mobile app or web portal to enable freight agents to transact and track their asset and data. Database design, similar to any Enterprise Resource Planning (ERP) system, allows interacting with APIs and smart contracts of external organisations. IoT design concerns automatic tracking of the physical movements of assets and containers across the supply chain and updating the chain of custody and other complementary decisions based on real-time sensor data (e.g., tracking shipment conditions such as geospatial data, temperature, humidity, etc.). APIs allow clients and applications to interact with the blockchain, and Software Development Kits (SDKs) provide mechanisms to deploy and execute transactions, query blocks, and monitor events on the blockchain. As the blockchain technology progress, platform providers develop data visualisation and analytics tools for on-chain data [84,85]. Nevertheless, usability and the ability to use analytic tools on blockchain transactions are understudied in the literature.

6.6. Regulatory Challenges

The emergence and application of blockchain technology clearly challenge existing public regulatory frameworks [10]. Future research should examine how blockchain minimises transactional legal risk in both national and international shipping law. It is particularly important to investigate how shipping law could be made amenable to incorporation into smart contracts. Since blockchain is codifying already extant rules and norms, it should be capable of working with different rule-based systems. However, there are debates on how smart contracts are interpreted by arbitrators and courts. Most blockchain legal activity has taken place around the cryptocurrency aspects, rather than contracts themselves. Immutable and unchangeable smart contracts could create problems where there is mistake, fraud, negligence, misrepresentation, and the like. Could smart contracts be made voidable, how would rescission operate? As yet, these questions are relatively untested in maritime logistics.

7. Conclusions

Blockchain characteristics are believed to assist a business structure such as port supply chain that involves many parties requiring trust, transparency, as well as efficiency in inter-party transactions, contracting, and data management. The emergence of this technology as the next generation of PCS platforms is predicted to transform business operations dramatically. Therefore, it is important to consider the rationale for embracing it as there are many questions that need to be answered as this technology progresses. Most importantly, while most articles are talking solely in favour of this technology, the barriers and challenges, either financial or technical, should not be underestimated.

In this paper, the value propositions of blockchain technology were assessed. The results of this assessment reconfirmed the potential of blockchain to lower the transaction costs, boost the service quality and transaction governance, and consequently improve the organisation and the entire supply chain competitiveness. The distributed and encrypted data structure of blockchain, provision of smart contract without human intervention, and no need for a central authority as the controlling agent are advantages of a blockchain-based PCS in landlord ports.

An essential aspect of this research was to investigate the existing blockchain platforms at a technical level and to cut through the 'marketing hype' which often makes unrealistic and unsubstantiated claims regarding the features and functionality of some of the available and emerging blockchain platforms. Confirmed also by the previous studies [2,83], despite the importance of blockchain on the maritime shipping and port logistics, the published papers are limited to discussing generalities of this technology, and the practical details are far from being clarified. The literature in the domain of logistics is also devoid of technical review of the architectural design of blockchain-based platforms. As suggested in Reference [83], the industry sources also suffer from a polarizing issue, where Tradelens—a Maersk–IBM joint venture—is introduced as the industry leader.

This paper addresses this gap by taking the first step to analyse the extant currently available blockchain platforms against the identified requirements for the port logistics use-case by answering two salient research questions. A detailed survey was conducted among currently available blockchain platforms suitable for the port logistics to address these research questions.

This paper offered a thorough survey of the advantages and limitations of a wide range of available consensus algorithms and various architectural choices. The results of this technical review highlight that there are considerations that should be taken into account to custom design a platform to PCS specifications. Availability—the readiness for correct service, and reliability—the continuity of correct service, are heavily reliant on the right choice being made for blockchain design for such a complex use case. A preliminary comparative analysis among different decentralisation level in this paper suggested that a permissioned public blockchain offers the best trade-off in performance measures for this use-case.

As a result of this survey, a number of necessary platform requirements were outlined for a blockchain-based PCS, including private sidechains, modular design with inter-chain interoperability, and encrypted off-chain data storage mechanisms. The results of this critical review reiterate that these properties are not summed up in one platform [48]. Hence, an uncritical adoption of an existing platform is not advised. This conclusion highlights the importance of close collaboration between the port authorities, freight operators, and blockchain platform developers to drive forward standards and protocols which will, in turn, maximise value propositions of this technology for this specific use-case.

Notably, the performance measures of various blockchain pilot projects in port supply chain have not been officially reported yet. Hence, it imposes a limitation on comparing the performance of these different platforms. This research can be extended by simulating and benchmarking the key performance measures, as well as a multi-disciplinary perspective in the design of a platform. Accordingly, a few research agenda were outlined for the future extension of this work. More importantly, there remained several unanswered critical questions that may even change the suggestive design requirements proposed in this paper. The author suspects these questions are fundamental barriers that have lagged the development of a blockchain-based PCS in practice, and perhaps should be answered in designing national and international roadmaps. These questions are as follows:

- Should a blockchain-based PCS be developed from bottom-up by individual ports or from the top by a multinational and a third-party entity?
- How will the costs of developing a platform be incurred by ports or companies?
- If each port has its PCS with a specific architecture, will this not constitute a barrier of costs to the entry of new companies in the supply chain and to free competition?
- Each PCS and public entity in port logistics has different information requirements in the ship and cargo processes. How will the integration task take place at the international level, to allow a true integration of the PCS in blockchain logistics chains, without losing the independence of each country and the possibility of requiring the documentation they want?
- Given that the future of integrated trade market is envisaged via interoperable blockchain-based PCSs, how can each individual solution be accepted by multinational companies?

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Appendix A

Using the notations of Ethereum [45], this appendix explains the PoW consensus mechanism and clarifies the reasons that this algorithm is computationally heavy. PoW involves choosing pseudo-random slices of the dataset, d, and cryptographically hashing them together, or so-called mix-hash, H_m. These slices, however, are selected only based on the block header, H, and the number of transactions (without the mix-hash). Accordingly, PoW evaluates to an array of (n, m) = PoW (H, d). The block finalisation, therefore, should satisfy the following conditions:

$$n \leq \frac{2^{256}}{H_d} \quad \wedge \quad m = H_m \quad \wedge \quad H_s > P(H)_{H_s} \quad \wedge \quad H_i = P(H)_{H_i} + 1 \tag{A1}$$

where H_s is a scalar value corresponding to the timestamp, $P(H)_{H_s}$ is a scalar value corresponding to the timestamp of parent's block, H_i is the number of ancestor blocks (for the genesis block $H_i = 0$), and n is the number of transactions sent from a given address, or so-called nonce, and is increasing by one at every time the sender sends a transaction. The nonce is used to enforce the valid transactions and therefore is dependent on block header difficulty, H_d.

This mechanism of block validity is the foundation of security and integrity of a public blockchain, because the nonce, n, must meet the conditions and conditions depend on the block's contents, which itself is made from a collated list of transactions. In PoW, the difficulty of finding a solution to

Equation (A1) is proportional to the difficulty of block H_d. Accordingly, the difficulty of a block header, H_d, is defined as:

$$H_d \equiv \max\left(H_{d_0}, \left(P(H)_{H_d} + \left[\frac{P(H)_{H_d}}{2048}\right] \times \varsigma + \varepsilon\right)\right) \tag{A2}$$

where H_{d_0} is the difficulty of the genesis block, defined as 131,072. $P(H)_{H_d}$ is a scalar value corresponding to the difficulty of the parent's block. The parameter ς is used to affect dynamic homeostasis of time between blocks, as shown in Equation (A3):

$$\varsigma \equiv \max\left(\left[y - \frac{H_s - P(H)_{H_s}}{9}\right], -99\right) \text{ where } y \equiv \begin{cases} 1 & \text{for the second block} \\ 2 & \text{otherwise} \end{cases} \tag{A3}$$

The difficulty exponentially increases by adding the parameter ε and as a result, the block time difference will be increased, as shown in Equation (A4). However, to avoid freezing up the network, the difficulty is scaled down by subtracting a big number (e.g., three million) from the ancestor block number H_i. As ε decreases, the time differences between blocks are reduced.

$$\varepsilon \equiv 2^{[\max(H_i - 3{,}000{,}000,\ \ 0)/100{,}000] - 2} \tag{A4}$$

This mechanism enforces an increase in the difficulty level for the smaller period between the last two blocks, which avoid forking of blocks.

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logistics

Article

Blockchain Solutions for International Logistics Networks along the New Silk Road between Europe and Asia

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Abstract: The primary research that underpins this paper seeks to explore the applications of blockchain technology on a specific international corridor and to draw policy implications for decision makers. To analyze the bottlenecks of operating on the New Silk Road and to identify opportunities for applying the blockchain technology on this corridor, a survey was conducted among main train operators and experts working on this route. These responses provide insight into the issues related to the adoption of blockchain technology from front-line actors. The top three challenges are lack of capacities, congestion at transshipment terminals, and slow border crossing. Through the application of blockchain technology, the operators are presented with opportunities for improved accuracy in the processing of data and information, higher reliability of information flows through failure-free transfer of information, and improved traceability of supply chains through irrevocable input of status information. Currently, 50% of the respondents have started to implement blockchain applications or have an actual interest to apply blockchain solutions. For a wider implementation of blockchain solutions, business models need to be developed allowing private and permissioned access that is accepted and open for parties involved. Policy makers should facilitate these digital innovations through flexible and harmonized legal regulations on an international level.

Keywords: New Silk Road; blockchain; international logistics networks; supply chains

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1. Introduction

The concept of Industry 4.0, and especially the application of digital transactions, data platforms, sensor technologies, and artificial intelligence, distributed ledger technologies (DLT) and blockchain solutions which can then create new opportunities to control and facilitate trade and transport services along the New Silk Road. DLT is used as an "umbrella term for technologies that store, distribute or exchange, publicly or privately, value between entities/users/peers based on shared transaction ledgers [1] (p. 7)." It is "frequently described as an 'authoritative shared truth'" ... in a peer-to-peer fashion without needing to rely on a single, centralized, or fully trusted party [2] (p. 10)."

Blockchain is "a specific type of DLT which distributes the storage, organization, and verification of hash pointers to a group of computers as opposed to storing them in a central database of an enterprise resource planning (ERP) system [3]."

"Blockchain is one type of DLT in which each piece of new data (a block) added to the shared ledger is attached in a sequential order to all the previous blocks (the chain) [4] (p. 6)." The registered users of a blockchain jointly have the permissions to write, read, and store data and information. This distinguishes it from a conventional database, which is usually maintained by one central authority. With blockchain technology, transactions between companies, individuals, or public institutions can be carried out and verified almost in real time without an intermediary.

The objectives of the research which underpins this paper were to identify challenges for the traffic on the New Silk Road and to explore the motivation of market players to use blockchain technology and their expectations of the possibility of blockchain technology applications to increase efficiency and security of the trade and transportation. The paper aims to derive recommendations for entrepreneurs and policy makers for implementing blockchain technology on this specific international corridor.

The research questions were: (1) which challenges exist for operating on the New Silk Road?; (2) which opportunities do front line actors see for blockchain technology to meet these challenges?; and (3) what should be done to facilitate implementation of blockchain on the New Silk Road?

The scope of this paper is limited to blockchain technology in its application to the New Silk Road and focuses on economic and institutional problems, primarily.

The methodology applied for the purpose of this paper consists of a literature review, analyzing benchmark cases and practical examples (TradeLens, DB Schenker, Essen, Germany) as well as a survey among market players who are active on this corridor. The survey which was based on the stated preference method consisted of three closed multiple choice and two open questions. The survey was conducted online in one round with follow-up during the period from September 2020 to March 2021.

A total of 23 questionnaires were sent to major train operators, terminal operators, shippers, and researchers active in this field, such as train operators or terminal operators offering transport services along the New Silk Road. Out of 23 questionnaires the survey received 14 responses, all from senior managers or executive-level decision makers. Although this number might be considered as comparably low, it can be seen as significantly representative survey on the very narrow niche market of the New Silk Road with a small number of operators.

Blockchain technology makes it possible to track different transactions along the whole supply chain in a secure and traceable manner. The documented transactions and data are irrevocably stored in the blockchain and cannot be used or read without consensus. Every time a consignment is being transported or handled, the transaction can be documented, creating a permanent history from the manufacturer to the trader or consumer. If the parties agree to use a certain blockchain platform, time delays because of missing or incomplete information could be reduced and incorrect data can be detected easily. Through automated data processing and auto-executing algorithms (if > then)—so called "smart contracts"—the manual processing of data (e.g., checking and confirming) can be eliminated which saves costs and time.

Although the practical applications of blockchain solutions in logistics are still in their nascent phase, there have been several papers and studies on blockchain in supply chains [5] (p. 884). For the maritime transport, a comprehensive literature review of positive impacts and challenges/barriers was performed in [6]. The authors identified and described 20 positive impacts and 20 challenges [6] (pp. 6, 7, 11, 12).

A review of blockchain projects in all industry sectors showed that food supply chains is the most represented area for application with 22 solutions out of 43 identified applications. Concerning the transport sector, the review identified two applications [7] (p. 728).

Nevertheless, what is missing and urgently needed is a body of knowledge and experience related to the application of blockchain technology to actual logistics systems.

Especially for very complex and global supply chains, blockchain technology can offer the unique advantages of guaranteeing consensus, immutability, and highest levels of security. Moreover, blockchain plays a potential role in enabling autonomous supply chains (Arun Samuga, cited in [8]). This is especially relevant for regulated supply chains of highly sensitive commodities where blockchain technology is seen as a preferred solution for secure traceability, e.g., for pharmaceutical products (see [9]).

Much of today's international trade transactions are still documented using traditional paper documents, such as Bill of Lading (B/L) in seaborne trade. The submission of a clean, original paper B/L to the bank is still a precondition for the approval of delivery and release of payment according to trade contracts including Letter of Credits (L/C). In the current traditional system, a “clean” B/L means that there are no remarks on this paper document in relation to damages or incompleteness of the delivery. With application of a smart contract using blockchain technology, the proof of delivery (including condition of the consignment) and the corresponding release of payment can be realized automatically and in a secure manner.

The potential savings in cost and time through the replacement of paper documents by digital information is enormous as largely paper-based processes slow down almost all steps and are also susceptible to a high error rate due to the iterative, manual transmission of information. It is estimated that the present analogue system costs about one trillion dollars or 5–10% of the value of the goods traded internationally each year [10] (p. 20).

Blockchain technology can be applied to assist managing cargo flows as well as assets such as containers, trailers, pallets, handling equipment, and rail and road infrastructure. [11].

Of course, blockchain solutions are not a panacea. The disadvantages are well documented and include relatively higher costs, time-consuming information transfers, and the required capacity to handle big data [4] (pp. 14–17). Another disadvantage of blockchain indicated in the literature is the high consumption of energy used for data storage and processing. One of the first publications to pay attention to these issues was work carried out by O’Dwyer & Malone. These researchers analyzed the energy consumption by Bitcoin [12]. Estimating the amount of energy used to implement blockchain is made more difficult due to the fact that data can be stored in many places on various devices. The lack of knowledge of their full specification excludes the possibility of estimating the amount of energy consumed by them [13] (p. 7). This is an evolving area of research and evidence.

According to another team of authors, the energy consumption needed for blockchain is significantly higher than in the case of centralized data storage and processing systems. The differences in energy consumption, however, are not so large that they could be perceived in the context of the entire economy. Additionally, these authors point out that the increase in the number of data and processing operations does not significantly increase energy consumption. Thus, the expansion of systems supported by blockchain should not cause a large increase in energy consumption [14] (p. 607).

Nevertheless, the advantages out way any drawbacks. The primary research that underpins this paper sought to explore the applications of blockchain technology on a specific international corridor and to draw policy implications for decision makers.

2. Blockchain Application in Supply Chains

Due to its characteristics, blockchain is widely used in supply chains. A bibliometric analysis of the subject entries was carried out in two popular databases of the scientific journals *Scopus* and *Web of Science Core Collection* (WoS CC). Two queries were developed for the analysis. In both queries the subject entries were searched in: title, abstract, and keywords. The first query searched for “Blockchain” and “case study” and “supply chain”. The second query searched for: “Blockchain” and “best practice” and “supply chain”. The analyses were conducted on 6 April 2021. The results of the analysis are presented in Figure 1.

The results presented in the above charts show that the number of scientific publications on using blockchain in supply chains is growing every year. Similarly, the number cited, although this relationship is not so obvious here, is clearly visible only in the *Web of Science Core Collection* database. It should be noted that the subject of blockchain is up-to-date and has been described for about four years. According to Fu and Zhu, blockchain technology will reduce the costs of the supply chain and logistics by 15%, which will affect the profits and profitability of enterprises [15]. Dujak & Sajter indicate the possibility of using blockchain in three areas in supply chains: traceability and visibility enhancements, improved demand forecasting, and open access [16] (p. 36). From the point of view of this publication, improved demand forecasting is of the least importance. The remaining areas will be described in more detail.

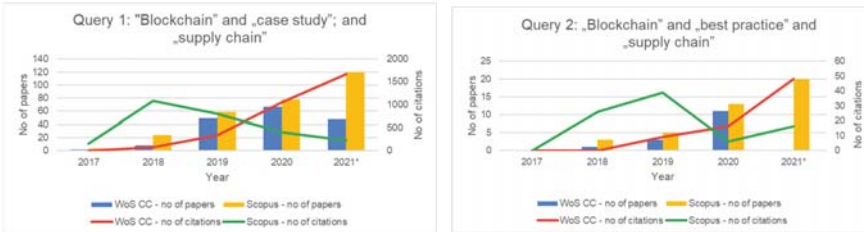

Figure 1. Results of the bibliometric analysis. (Source: own elaboration) (2021* The number of publications and citations in 2021 was estimated based on the numbers from the first quarter of 2021 (a linear model was used, the numbers from the first quarter was multiplied by 4)).

The use of blockchain to improve security and traceability is one of the basic areas of its application in supply chains. There are many examples of the use of this technology in literature. The widely known Walmart-IBM case study used blockchain technology for tracking mangoes from farm to store. By using blockchain, there was a reduced time of tracking the package of mangoes from the farm to the store, from several days to two seconds. [17]. A solution was also developed to increase the availability of information about food products, thanks to the consumers having full information about the products they buy [18]. In the area of open access, the greatest benefits for supply chains are obvious. Maersk and IBM have developed an open blockchain solution for container tracking. This solution is useful not only to partners in the supply chain, but also to insurance companies and banks. The use of blockchain to track cargo reduces risk and lowers insurance rate [19]. The IBM solution is delivered to a wider range of companies including General Motors, Procter and Gamble, Agility Logistics, Singapore Customs, Peruvian Customs, APM Terminals, PSA International, and Guangdong Inspection and Quarantine Bureau for trade corridors in and out of China [20].

Kumar et al. indicate the importance of blockchain in the implementation of smart contracts, i.e., those framed between the exporters and importers which record the quality, quantity, delivery date, and other clauses decided by the trading entities while agreeing. If the conditions are met, the payment is released automatically to the exporter. These authors also indicate the most important areas of blockchain application in the supply chain: data integrity, decentralized processing, and traceability [21].

Blockchain can also support the implementation of the concept of sustainable development. It supports sustainable development in aspects such as market disintermediation, operational efficiencies, cost efficiency, value creation opportunities (economic sustainability), empowering trust, food safety (social sustainability), and reducing the environmental logistic footprint (environmental sustainability) [22] (p. 366). Blockchain also allows for the constant tracking of material and commodity flows on trade routes, supply chains, and supply networks. It is therefore possible to identify the origin of raw materials and products. Thus, blockchain technology has potential to support ethical sourcing strategies [23].

Venkatesh et al. present the concept of blockchain-based supply chain social sustainability management (BSCSSM) system. The system consists of main modules such as production and logistics traceability, supply chain transparency, labor and human rights, and workplace health and safety. Thanks to it, it is possible to comprehensively manage aspects of sustainable development throughout the entire supply chain. According to the authors, such a solution can also be successfully used in the case of trade routes, such as the New Silk Road [24].

Shoaib et al. explored blockchain-based supply chain success factors. As a result of literature, research, and surveys on a sample of 64 people (from 22 countries), the authors determined the leading success factors as trackability, traceability, simplification of current paradigms, data access control in SCM, human safety, auditability in SCM, problem solution, quality fairness, environmentally friendly, and automation [25] (p. 2127).

It should also be noted that the results of the conducted research also indicate the concerns of enterprises related to the use of blockchain and the resource requirements in this solution [26].

To sum up, the use of blockchain in supply chains is very broad and is becoming increasingly popular. The identified applications and good practices which are potentially applicable on the New Silk Road include traceability and visibility enhancements, supporting open access, smart contracts, and supporting sustainable logistics development.

3. The New Silk Road as an International Intermodal Logistics Network

The New Silk Road or the "Iron Silk Road" consists of several rail corridors connecting China and Europe. The four major corridors run from China directly via Russia, Mongolia/Russia, Kazakhstan/Russia, or Central Asia/Caucasus/Turkey to Europe (see Figure 2).

Figure 2. China Express Railway Plan. (Source China Rail Express Plan, cited in [27] (p. 163)).

Although the vast majority of trade between China and Europe uses the sea connection ("One Road"), the Iron Silk Road ("One Belt") has been developing dynamically since the early 1970s. Nonetheless, real progress has been recorded over the last ten years. The rail links between Europe and Asia have proved as efficient and resilient connections within an international logistics network, as shown in Figure 3.

A peculiar characteristic of the land-based Silk Road is the relatively higher number of parties and infrastructure involved, compared to that in sea transport. The network consists of a variety of structural elements (parties, infra- and supra-structure) and complex information and physical flow processes. Major reasons for this complexity are the involvement of different national administrations and railway organizations with different technical and regulatory standards, border crossings, and parties involved.

This high complexity often results in a lack of traceability and delays due to different IT systems and platforms, partly still paper-based procedures and bottlenecks at border crossings. This results in often non-transparent, slow and consecutive workflows of the parties involved.

Therefore, expanding the New Silk Road from a niche market to "mainstream" would require, among others, the establishment of highly efficient and reliable processes and control of the interactions between all interlinked partners.

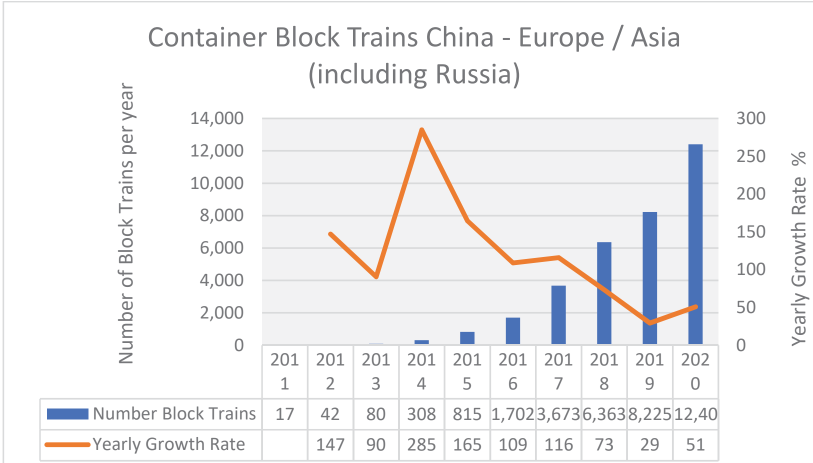

Figure 3. Container block trains between China and Europe/Asia (compiled from China Railways, Belt and Road Portal).

4. Challenges and Opportunities for Blockchain Solutions along the New Silk Road

To analyze the bottlenecks of operating on the New Silk Road and to identify opportunities for applying the blockchain technology on this corridor, a survey was conducted among main train operators and experts working on this route. Out of 23 requests, the survey received 14 responses (feedback rate of 61%). Detailed characteristics of the respondents are presented in Table 1.

Table 1. Detailed characteristics of the respondents (source: own elaboration).

Country/Company Type	Forwarding	Research	Shipper	Terminal Operator	Train Operator	Total
China				1	2	**3**
Germany		1		1	1	**3**
Croatia	1					**1**
Lithuania		1			1	**2**
Netherlands		1				**1**
Poland	2		1			**3**
Russia			1			**1**
Total	**3**	**3**	**2**	**2**	**4**	**14**

These responses provide insight into the issues related to the adoption of blockchain technology from front-line actors.

Figure 4 shows a high concentration of answers received in the median range with a high proportion of respondents claiming to have knowledge and experience with blockchain technology i.e., rating 3 (experienced) with 64.3%. An equal number indicated high or low experience i.e., 14.3% each. Only 21.4% of the participants rate themselves with low experience and little knowledge considering blockchain and smart contracts topics, cumulating rating 1 (low experience) with 7.1% and rating 2 with 14.3%.

Overall, a high percentage share of 78.6% of the participants assess themselves as having gained significant experience and knowledge in this area. Moreover, neither the extremes, 0 = no experience available or 5 = highly experienced, were chosen by the participants. Both arguments being presented could underline that, on the one hand, profound content will be reflected upon when looking to the other questions due to the high percentage share of professionals answering the survey, but also that some potential in terms of gaining experience and knowledge in blockchain and smart contracts can still be achieved.

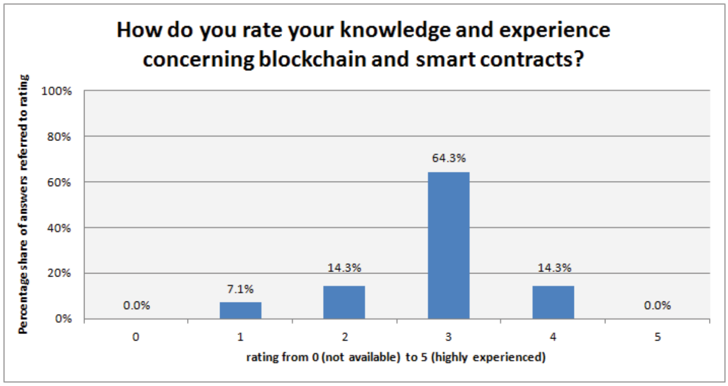

Figure 4. Knowledge and experience concerning blockchain and smart contracts (source: own elaboration).

Considering the challenges on the New Silk Road, the survey reveals that slow operation at border crossings is seen as the highest risk with a 36% share of received answers with the rating "high". (see Figure 5) The congestion at transshipment terminals is second when looking to possible challenges with rating "high". In this survey, 29% of participants rate this challenge as high. The third place is shared by five other challenges, namely lack of capacities, unpunctual or unreliable rail operation, the lack of information on the actual status of the container, the low capacity utilization, and damages and pilferage, which each score a 1% share of answers received.

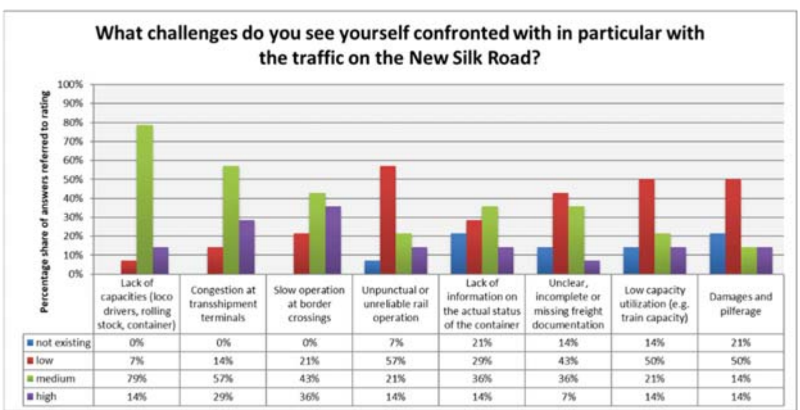

Figure 5. Challenge for the traffic on the New Silk Road (source: own elaboration).

When considering challenges with "high" or "medium" ratings, the top three are lack of capacities (93% of all ratings), congestion at transshipment terminals (86% of all ratings), and slow border crossing (79% of all ratings). Interestingly, these top three as medium- and high-rated challenges share the same answer possibilities which one could argue reflects the common orientation of realistic challenges being confronted with the traffic on the New Silk Road. The high importance of these challenges reflects the present, and often problematic, situation at border crossings and terminals, which is mostly caused by insufficient capacities but also by slow commercial procedures. It is remarkable that 43% of all respondents stated that unclear, incomplete, or missing freight documentation is a medium or high challenge for the traffic.

Looking to the lowest ratings, unpunctual or unreliable rail operation is rated lowest by 57% of respondents, followed with 50% each to the challenges of low capacity utilization and damages and pilferage. Interestingly, 21% of the participants highlighted the latter challenge as a non-existing challenge when focusing on security and safety along the New Silk Road. When considering challenges ratings with "not existing" or "low", the top three are damages and pilferage (71% of all ratings), low capacity utilization (64% of all ratings), and unpunctual or unreliable rail operation (64% of all ratings). This is remarkable because, in the early years of rail traffic along these routes, unreliability, damages, and lack of security were seen as major problems. Obviously, these former challenges seem to have been solved by modern block train concepts and operations.

Figure 6 presents the ratings of the participants referring to whether the possible area could have a low, medium or high impact on efficiency and security of trade and transport when considering blockchain solutions. By far "*improved accuracy for processing of data and information*" with a 79% share of received answers in this area reflects the highest rating, followed by *"higher reliability of information flows through failure free transfer of information*" with 64%, and, as third place, "*traceability of supply chains through irrevocable input of status information*" with a 57% share of answers received. In total, five out of seven possible areas have a higher rating in "high" than in "medium" or "low", thus reflecting the significant impact on efficiency and security of trade and transport when focusing on blockchain solutions.

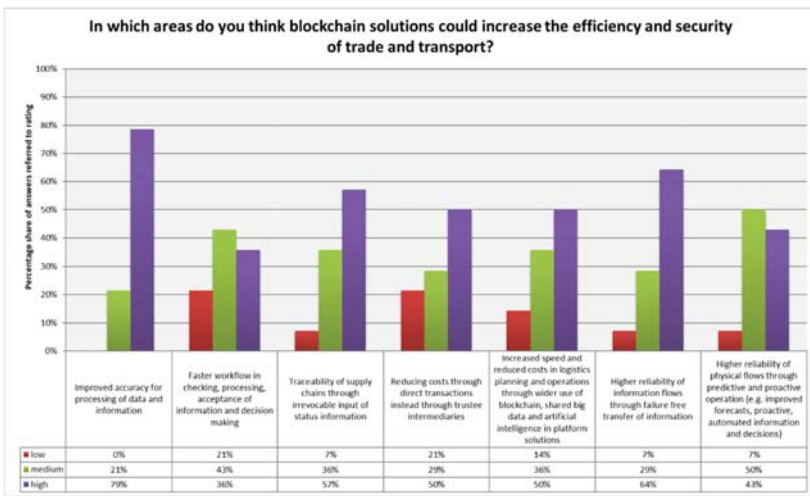

Figure 6. Opportunities for trade and transport through blockchain (source: own elaboration).

Furthermore, two areas can be highlighted where the "medium" rating outweighs the other ratings within the same area. These are "*higher reliability of physical flows through predictive and proactive operation*" with 50% and "*faster workflow in checking, processing, acceptance of information and decision making*" with 43%. However, the latter area is closely followed with a 36% share of answers received in the rating of "high" and 21% of participants reflecting this area with a "low" impact on the other side, thus turning this area into an arguable discussion point with no clear consensus compared to the other six areas of this question. This shows that some respondents doubt that blockchain will facilitate the workflows.

Concerning the question "Have you already tested blockchain solutions in your own company? If so, for which application?", seven respondents answered "No", three answered "No, but we want to try", and four with "Yes". That shows that the actual interest to apply blockchain solutions is 50/50. Companies which already tested blockchain include German Railways, Russian Railways, and a Chinese platform operator using an own designed Smart Container Global Tracing System. All the systems are in a testing or upgrading phase.

Finally, the open question "What would have to be done so that blockchain technology can also facilitate trade and transport on the New Silk Route?" was raised in the survey. As fields of actions, the following aspects were recommended by the respondents of the survey (wording in italic):

Governance and Business Model

- *"Co-operation*
- *Organizational structure which can be agreed with all the participants and strong IT platform.*
- *Push trust and compliance*
- *Finding champions (shippers, railway companies, logistics service providers and freight forwarders) to introduce/develop blockchain solutions on the New Silk Route.*
- *It's a wide topic with several scenarios, linked to trading company, logistics, customs, CIQ China Inspection and Quarantine, insurance company, bank, etc.*
- *Enterprises must learn to share data for better end-to-end supply chain performance."*

Knowledge and Competencies

- *"Improvement of competencies for blockchain technologies Incorporation at companies and government level (customs and border services, tax administration, sanitary control and etc.)*
- *Knowledge about Blockchain technology and its use has to be improved"*

Standardization

- *"Standardization*
- *Harmonization/standardization of dataflows of involved parties"*

Regulatory Framework

- *"Legal implications must be considered*
- *Bureaucracy should be cut and customs law liberalized."*

> *"Blockchain technology is still being developed. The more applications there are, the more trust this technology will gain. Using blockchain technology is not only a simple implementation of the tool but changes the communication and co-operation model in supply chain–and therefore it requires more time."* (one respondent of the survey)

Due to the used ordinal scales, it is not possible to test hypotheses. However, it is possible to apply the basic methods of descriptive statistics and the study of the Spearman's rho correlation. It should be stated that the most frequent answer in the questions regarding the challenges related to the implementation of blockchain solutions on the New Silk Road was the answer "Medium". The median for the responses was also the same (assuming that the responses could be ranked in ascending order: "Not Existing", "Low", "Medium", "High"). In questions about the opportunities brought by the implementation of blockchain solutions, the most common answer was "High", and the median was also the same (assuming the same ranking of answers as in the case of questions related to challenges). An important observation is also the relationship between knowledge and experience concerning blockchain of responders and their assessment of the challenges and opportunities offered by the implementation of blockchain solutions on the New Silk Road. The analysis with the Spearman's rho showed that there is a statistically significant negative correlation (rho = -0.66, p-Value = 0.009 assuming $\alpha = 0.05$) between the self-assessment of the respondent's knowledge, experience, and challenges posed by the implementation of blockchain solutions on the New Silk Road. This means that respondents with more knowledge and experience see fewer challenges and consider the implementation of Blockchain solutions on the New Silk Road more realistic. No other statistically significant relationships were found.

It can be summarized that blockchain solutions are seen as a potential tool for improving the conditions for trading along the New Silk Road through more secure and efficient documentation and transaction processes, especially because of the high complexity of countries and parties involved. For the success of blockchain, some essential preconditions must be ensured.

5. Platform Governance and Business Models

Concerning the type of access to the DLT, one can distinguish between "open" and "closed" networks (For a detailed explanation of DLT's see [28–30]). Publicly available and permissionless DLT's are the most decentralized form with the least control by one actor. This kind of DLT is considered as the most secure format, but requires highest computing power and is comparably slow (for example, Bitcoin). Another type of public DLT's are those that are public but permissioned. They are still open as everybody can view the content, but writing transactions are allowed for authorized users only. An example in the application of transport could be the registration and monitoring of transport vehicles and equipment (automobiles, wagons, containers, etc.) in the future (see also [4]) (p. 12).

In supply chains the stakeholders have a vital interest to protect their commercial data and to keep competitive advantages. This is an argument to prefer a closed type of blockchain. On the other hand, the benefits from blockchain can only be disclosed if the platform is open for possibly all parties involved in a certain supply chain. On the New Silk Road, a variety and high number of different private and administrative parties are involved. This calls for an authorization scheme to read and write, namely a closed, permissioned blockchain. These blockchain solutions are private systems in which only authorized users are granted access to join, view, and publish data. Permissioned users can securely record transactions and exchange information between one another.

It is obvious that the installation and maintenance of a blockchain platform needs administration. This administration can be assured by a single organization (private permissioned type) or by a set of parties (consortium type).

The experiences with "TradeLens" (See https://www.tradelens.com/, accessed on 25 March 2021) as one of the first operating blockchain platforms in overseas trade show that successful operation is possible only if acceptance and participation of a wider market share can be achieved. Strict neutrality and a non-discriminatory practice are preconditions. TradeLens is a closed, permissioned blockchain platform. Permissioned blockchains are private ecosystems whereby only authorized users are granted access to join, view, and publish data. Permissionless blockchains are open ecosystems that let any user access and interact with the network. Cryptocurrencies typically run on permissionless blockchains so they are distributed, transparent, and able to offer nearly total anonymity [31]. Having started as a partnership between Maersk and IBM, TradeLens was confronted with a great deal of hesitance from other shipping lines to use the platform. Only after revision of the partnership model, so that Maersk had no more control than other ocean carrier members over the platform governance, could the platform experience more acceptance by other industry leaders to join (see [4] (p. 25)).

For trades along the New Silk Road, permissioned blockchains should be the preferred solution since trade data are sensitive and need to be accessible by authorized users only. For the platform administration, several options are feasible.

In principle blockchain solutions can be managed by:

- IT-infrastructure providers and application developers
  open, user neutral platforms
  "Blockchain as a Service"
  Example: Hyperledger (See https://www.hyperledger.org/use/fabric, accessed on 25 March 2021), VeChain (See https://www.vechain.com/product/toolchain, accessed on 25 March 2021)
- Financial institutions, banks
  example: Corda (See https://www.corda.net/, accessed on 25 March 2021)
- Transportation and logistics systems providers
  Shipping Lines, Railway companies, Intermodal operators
  Example: TradeLens (See https://www.tradelens.com/, accessed on 25 March 2021)

- Logistics platform operators
  (ports, logistics parks)

To ensure neutrality, the IT-infrastructure providers and application developers are widely accepted by market participants. Nevertheless, transport operators are the main beneficiaries and drivers of the process.

Concerning the New Silk Road, a consortium of participating railway companies seems to be the most feasible solution to "order" a blockchain platform which is implemented by an IT company. First initiatives to establish blockchain technology exist:

Example DB Cargo Eurasia

The Deutsche Bahn DB (German railways) has been operating on the New Silk Road for more than 12 years. Since 2018, DB Cargo Eurasia GmbH is the DB-owned operator on the Trans-Eurasian corridor. It offers up to nine train departures every week connecting Germany with Russia and China.

Within the Seven Railways Agreement, the partners Chinese Railways (CR), Kazakh Railways (KTZ), Mongolian Railways (UBTZ), Russian Railways (RZD), White Russian Railways (BC), Polish Railways (PKP), and German Railways (DB) have been meeting and discussing joint blockchain solutions for the trade and traffic concerning this route since 2016. The main objectives are the improved tracking and tracing of containers, safer and easier exchange of data, and organizing paperless international rail transportation (see [32,33]).

The innovative IT-solution DB Cargo Eurasia is working together with DB Systel which developed the digital platform, known as joint enabling network (JEN). This platform connects customers, rail operators, customs, and other parties involved in the trade and allows for an accelerated digitalization of processes. It can be intelligently linked with innovations such as blockchain technology and artificial intelligence (AI). It provides a forgery prove, reliable, traceable, and immutable transfer and storage of information and transactions, as well as auditing proof archiving. As the single point of truth, the platform JEN forms the basis for horizontally and vertically integrated value-adding chains. The ecosystem of this platform offers microservices and intuitive micro user interfaces, which can be customized [34]. The principal configuration is shown in Figure 7.

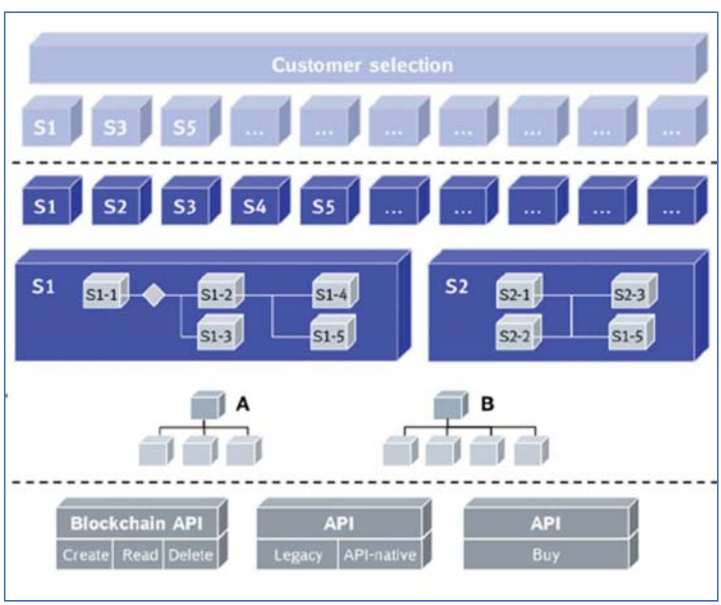

Figure 7. Scheme of joined enabling network (JEN). (Source: [34]).

The challenge is how to integrate trade-focused platforms (e.g., the IBM Food Trust Blockchain Platform) with logistics-focused platforms (e.g., railway or shipping platforms). Interfaces and common standards are needed.

Another challenge is cost recovery for the installation and administration of the blockchain platform on the one hand and to keep costs user-friendly on the other hand. The platform operator shall establish a scheme for generating income, for instance through registration ("entrance fee") and participation fees ("pay as you use"), and eventually also additional fees for premium services and consultancy.

6. Policy Implications

Unlike many innovations in technology, which are often incremental and transform the way activities are organized at the margins, blockchains challenge the notion of a central entity that controls the process and is a repository of all the main data. It also questions the way the fundamental role of the regulator is positioned within the supply chain. As demonstrated in this article, the early pilots indicate ways in which the traditional teething problems of transboundary logistics can be addressed. By offering a mechanism to track all transactions, a new type of contract mechanism is introduced which enables the entire system to be more resilient to human and natural shocks in the supply chain. The challenge for policy makers is how to introduce the appropriate regulation that does not suffocate innovation.

A recent study gives the following recommendations for policy makers concerning regulations on the use of the distributed ledger technology:

- Make regulations more flexible to accommodate the use of blockchain and other distributed ledger technologies
- Use regulatory sandboxes to promote innovation while minimizing risks
- Actively engage with transport industry initiatives around distributed ledger technologies
- Require some level of open data access for transport applications of distributed ledger technology
- Make transport policies machine-readable
- Run pilot projects to identify use cases for distributed ledger technologies in the public sector [4] (pp. 7–8)

Insofar, as blockchain technology is used in international trade, international trade agreements are applicable, either through bilateral or multilateral free trade agreements (FTAs) and/or by WTO agreements. Even if slowly, international cooperation on digital trade is deepening. Under the framework of the World Trade Organization, countries have reached agreements on electronic signatures, paperless trading, transparency, electronic transmission, tax exemptions, and other related issues. The member states of the WTO are working on new agreements on digital trade and e-commerce. For different models and outlook see [35].

By the end of 2019, 199 cooperation documents have been signed between 137 countries and 30 international organizations with China under the framework of the Belt and Road Initiative [36]. The New Silk Road covering many different states with different political and economic systems is a vivid field of international co-operation which should include harmonized rules on e-commerce and digital services.

7. Conclusions and Future Outlook

The New Silk Road has proved to be a reliable and dynamic alternative intermodal transport connection between Asia and Europe within international supply chains, especially for time sensitive and higher value goods. Due to the complexity of partners and countries, different railways systems and regulations involved a call for an efficient and secure transfer and processing of data. A survey among main transport operations working on this market shows that slow operation at interfaces as border crossings and terminals is the main challenge along this route. The most important reasons for that are the lack of capacities and slow commercial procedures. Among the operators, blockchain is seen as an opportunity to improve accuracy for processing data and information, to increase reliability of information flows through failure-free transfer of information, and to improve traceability of supply chains. Up to now. there is no blockchain application implemented on this trade route (New Silk Road). One result of the survey is that 50% of the respondents are interested in, or are in the process of testing/implementing, blockchain solutions. For a wider application of blockchain solutions, business models are required which are preferably private and permissioned but accepted widely by the various partners along this route. Standardization and harmonized rules and regulations are needed which call for increased co-operation and concerted actions of policy makers in the different countries in the future.

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Data Availability Statement: The data are not publicly available but can be obtained from the authors on request for scientific purposes.

Conflicts of Interest: The authors declare no conflict of interest.

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Article

Blockchain for Ecologically Embedded Coffee Supply Chains

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Abstract: *Background*: This research aims to identify how blockchain technology could support the ecological embeddedness of the coffee supply chain. Ecological embeddedness is a subset of the circular economy (CE) that demands legitimacy through design changes to product, production and/or packaging for benefits to economic actors and the environment. This is in contrast with legitimacy as a public relations exercise. Blockchain is a digital transformation technology that is not fully conceptualized with respect to supply chain implementation and the related strategy formulation, particularly in the context of sustainability. Furthermore, the integration of consumers into the CE remains not well understood or researched, with the main focus of CE being the cycling of resources. *Methods*: This research employs a qualitative case study methodology of the first coffee business in the USA to use blockchain technology as an exemplar. Gap analysis is then applied to identify how blockchain could be used to advance from the current state to a more sustainable one. *Results*: Findings indicate that the implementation of blockchain is not ecologically embedded in the example studied. *Conclusions*: The extension of blockchain technology to consider the by-products of production and valorizable waste throughout the supply chain as assets would support ecologically embedded CE for coffee.

Keywords: blockchain; circular economy; coffee; ecological embeddedness; supply chain; sustainability

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1. Introduction

Coffee is one of the world's most valuable traded commodities, making it a driving factor in the global economy. There are many sustainability concerns related to coffee production, including coffee farmers unable to earn a living income, child labour, ecological degradation, resource use, pollution and waste. Consequently, the sustainability of coffee production is of concern to conscientious consumers [1,2], the coffee industry, governments [3] and sustainability researchers [4].

Blockchain is a "shared, cryptographically unaltered distributed ledger" for recording and maintaining digital transaction history [5]. Blockchain has been recognized as a digital technology capable of adding an aspect of sustainability to supply chains that is correlated with the circular economy (CE) [6]. The notion of Blockchain for Good (B4G) yields innovative applications that may support socially and environmentally beneficial outcomes in terms of the UN's Sustainable Development Goals [7]. This has led some coffee producers and associated businesses to apply blockchain in their supply chains, and recent research encourages a wider adoption of this technology [8,9]. However, blockchain projects in the food sector are at a nascent stage, with a majority of applications limited to food traceability and safety [10,11]. With the consideration of B4G also come concerns about uses of blockchain that are not ecologically embedded or that lack legitimacy [12].

In this study, the perspective of ecological embeddedness is adopted to better understand the sustainability relationships in the coffee supply chain. Institutional theory is used to analyse the vertical relationships among smallholders, suppliers, the large buyer and consumers to identify where blockchain may intervene to improve CE and sustainability practices. Literature that considers multiple stages in the supply chain is relatively recent (e.g., [13–17]). Luo and Choi [18] advocate the use of real case studies for informing blockchain systems for practical business operations and sustainability whilst identifying critical success factors.

The theoretical lens of this study is the consumer experience, and the aim is to provide a nuanced understanding of the consumer aspects of legitimacy with respect to the ecological embeddedness of the case product [19]. Supply chain adoption of blockchain technology has as a first consideration the traceability awareness of consumers, which can be determined by investigating consumers' level of concern about product quality and safety as well as their willingness to pay for a traceable product [20]. The theoretical lens of consumer experience is combined with a qualitative (theory-building) approach that guides the investigation [21]. Consequently, this research focusses on the identification of unrealized benefits of blockchain adoption as part of the investigation of 'social' relations within the context of embeddedness [22]. As stated by Morris and Kirwan [22] "... to be understood as ecologically embedded ... a conscious or deliberate effort on the part of producers to communicate information about on-farm ecological relations must occur, either in person or through packaging or other promotional materials." Where information is not accessible from the consumer perspective, ecological embeddedness is lacking.

The first comprehensive study of the ecological embeddedness of supply chains was at a national level and in a regional case study for the Austrian food system with two conventional bread chains [23]. Subsequent research has predominantly focused on alternative, local and green supply chains which continue to be of interest (e.g., [24–27]). Globalization is increasingly considered along with the restructuring of agricultural value chains to reconnect supply chains and ecosystems at territory level, identifying a gap for reaching operational effectiveness in the lack of integration between biophysical and socioeconomic approaches [28,29]. Empirical findings indicate that perceived fairness has a highly positive link with embeddedness and that both embeddedness and knowledge sharing is significant to green innovation in sustainable supply chains [30]. However, the importance of technology in enabling ecological embeddedness is rarely considered or analyzed [31] and how blockchain could specifically support the ecological embeddedness of supply chains has yet to be fully considered [32]. There is a general lack of published case studies and concrete examples of the use of blockchain technology [33]. This study addresses this gap by investigating the potential contributions of blockchain to the ecological embeddedness of global supply chains using a case exemplar. The unique contribution of this work is the identification of blockchain as a technological enabler of ecologically embedded coffee supply chains.

The aim of this research is to study the blockchain application in a coffee supply chain to investigate how well sustainability and CE issues are addressed by the addition of this technology. Gap analysis and case knowledge are then employed to make recommendations for improvement.

The remainder of this paper is structured as follows. The first section presents a brief review of the literature related to CE, ecological embeddedness, and blockchain. This is followed by the methodology, that highlights why the case was selected and the approach to data analysis. Next, the results of the study are presented followed by a discussion of the results and their implications.

2. Literature Review

2.1. CE Theory Applied to Coffee

CE is distinguished from the linear economy by its inclusion of biological and technical loops that aim to slow, close or narrow the cycling of resources [34]. Slowing is achieved through the design of longer-lasting products and extending product life through maintenance and repair. Narrowing loops are a form of resource efficiency that reduce the cost of production. Closing loops implement recycling between post-use and production for a circular flow of resources. By extension, CE may be similarly applied to the packaging of a product, although the complex assessment of packaging in relation to particular products is only beginning to be investigated [35].

Coffee is grown in over 70 countries with ideal conditions along the equatorial zone between latitudes 25 degrees north and 30 degrees south. This means that delivery to many countries requires long transports of the beans for further processing (narrowing CE loops) and ideally reusable and/or recyclable packaging (slowing/closing loops). Coffee production generates considerable amounts of solid waste (by-products) such as defective green coffee beans, coffee tree leaves and coffee cherry husks as well as wastewater [36], uses resources in terms of energy and water principally, and generates consumer waste as spent coffee grounds. Many applications of coffee waste have been proposed as part of a CE including substrate for agricultural production, conversion into fuel, use as biosorbent for removal of pollutants from wastewater, and the extraction of value-added compounds such as antioxidants and dietary fibres [36–38].

2.2. Blockchain Capabilities in Support of CE

Blockchain is a combination of technologies with components such as public/private key cryptography [39], cryptographic hash functions [40], database technologies (distributed databases), consensus algorithms [41], and decentralized processing. These relate to the technical choices of implementing a blockchain, including permission design, choice of consensus algorithm, use of smart contracts, and use of cryptocurrency. The proper management of information throughout the blockchain may benefit strategic decisions related to natural resources and raw materials in support of CE [42]. Innovation in blockchain architectures, applications and business concepts is ongoing.

However, the implementation of blockchain needs to be technically supported and the benefits clearly identified [5,43]. The main challenge for blockchain is trust: ensuring that counterfeit blocks or counterfeit data do not permeate transactions that may then corrupt the digital ecosystem [44].

Blockchain features such as transparency, traceability, smart contracts, decentralization, data immutability and data privacy together with consensus mechanisms make blockchain suitable for complex supply chains with the potential to improve sustainability and resilience [6,45,46]. The tracking and sharing of data related to the environmental and social aspects of sustainability may reduce the related issues around food safety, intermediaries and transaction costs while building trust between producers and consumers [7,47].

2.3. Ecological Embeddedness Theory and Blockchain

Ecological embeddedness is a subset of the circular economy that demands legitimacy through design changes to product, production and/or packaging [12]. Ecological embeddedness is more comprehensible for companies when compared to the discursive paradigms that are "sustainability" and "sustainable development" and related concepts such as "embedding sustainability" [48]: ecological embeddedness simply requires that both the economic actors and the environment benefit [22]. Benefits may take the form of cost savings, health benefits or customer loyalty benefits (related to trust) [12]. For example, reducing waste in the supply chain benefits the environment as less waste needs to be absorbed, and the economic actors also benefit from the decrease in costs associated with losses due to waste as long as these savings are shared throughout the supply chain. Sharing benefits among all supply chain actors has been linked to significant supernormal profit (when total revenue exceeds total cost) and suggests that manufacturers centrally positioned in triadic supply chains should deliberately shape relational embeddedness with suppliers and customers [49].

Ecological embeddedness enforces a holistic perspective on sustainability-related changes including the implementation of digital transformational technology such as blockchain through the necessary consideration of impacts on both economic actors and the environment. Blockchain has been examined as a dynamic capability that is perceived to improve both external (suppliers and customers) competencies and internal integration; however, the focus was only on the economic component with further studies recommended for environmental and social sustainable supply chain performance [50]. Ecological embeddedness relates to blockchain technology through economic, social and environmental considerations: Among the most basic questions to ask when investigating implementation is "Who benefits?", alongside "What problems does blockchain solve?" and "What problems does blockchain create?" [51].

Such questions are more likely to be realistically addressed when real-world applications are investigated. Having built the theoretical structure for this study, there is evident value in investigating the hypothesis that ecologically embedded blockchain enables CE and sustainability in the coffee supply chain as described in the following section.

2.4. Blockchain Impacts on Business Performance

One specific focus of blockchain research has been supply chains as the "most promising non-finance application of blockchain" believed "to deliver real Return on Investment at an early state of blockchain development" [52]. Blockchain technology aids the authentication of products, facilitates disintermediation and improves operational efficiency [53]. Blockchain technology reduces risks, which could negatively affect company performance related to the clarity of supply sources, counterfeit and poor-quality products and fraud in contract fulfilment while providing the flexibility of capacity and sensitivity to demand change [54]. However, blockchain companies are not delivering the promised business value precipitated by a lack of understanding of how blockchain technology may benefit their respective business models [55,56].

The performance of a supply chain needs to be driven by management initiatives. The value placed on an initiative such as blockchain may originate with stakeholders and retailers to create added value for customers and improve company and supply chain performance [57–60]. Masudin et al. [61] demonstrated that implementing green supply chain management practices has positive and significant impacts on performance. Managerial initiatives have been found to support traceability system adoption, which significantly and positively affects food cold chain performance [62]. Consequently, the investigation of blockchain implementation for supporting ecologically embedded coffee supply chains in this research is justified.

3. Methodology

A qualitative case-study approach has been chosen to explore the relevant relations of ecological embeddedness and hence an in-depth approach is required [63,64]. Case-study research is a suitable research strategy for the food sector as it enables investigations of ecological embeddedness [23,30,65]. Ecological embeddedness remains under-investigated in sustainable supply chains [66], and the case study method fits the exploration of this complex phenomenon. A case study enables the capture of both situational and context-specific factors regarding the connectedness and embeddedness of relationships that may then be related to the role of blockchain as an exploratory investigation [67]. The research process flow is based on a case study approach [68] as shown in Figure 1.

A single-case design may be conducted if an extreme or unusual case is chosen and if rarely observed phenomena are investigated to better understand the underlying relationships [69]. The selected case research design aims to understand the meaning-making behind the legitimacy of technology application under institutional theory. The intrinsic case shapes the direction of the case study by offering thick descriptions (observation, description, interpretation and analysis of the situation) [70].

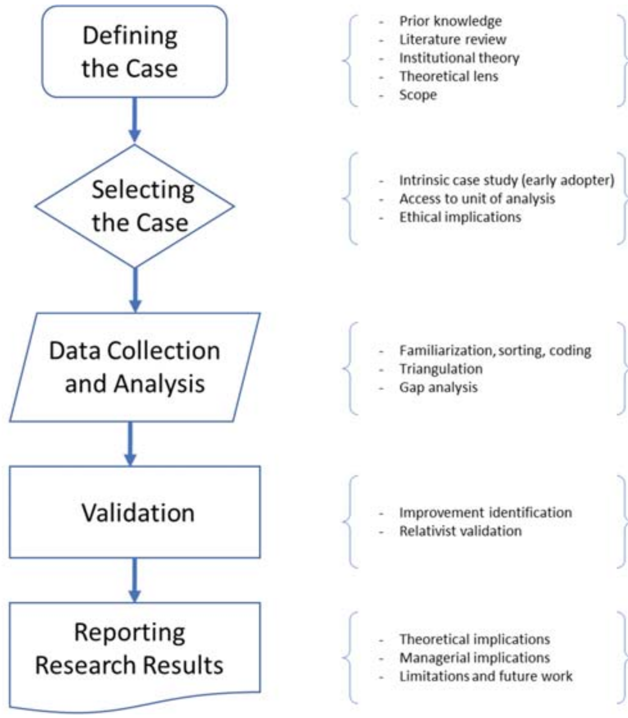

Figure 1. The process flow of this research.

This research relies on relativist validation as opposed to logical empiricist validation. This means that a semiformal and communicative process is employed in which validation is a gradual process of building confidence in the usefulness of new knowledge. Such an approach is appropriate for open problems connected with heuristics and non-precise representations. Literature is used to build confidence in the validity of individual constructs, and confidence in consistency is in the demonstration of adequate input for each step of the research process flow, in the fact that the anticipated output from the step is likely to occur based on the input, and in the fact that the anticipated output is an adequate input to another step. Confidence is built in the appropriateness of the exemplar by relating the exemplar to similar cases. This is followed by accepting the outcome of the chosen exemplar with respect to the initial purpose, linking the achieved usefulness to the method and extending the usefulness beyond the exemplar. The aforementioned validation procedure (the 'Validation Square') has been proposed for engineering design to provide a relativist/holistic/social view [71].

3.1. Case Selection

The selection of a single-case exemplar was appropriate and in accordance with the theoretical sampling approach of the case-study methodology [72]. There are obvious limitations to generalizability with single case studies [67]; however, studying a leading company often leads to useful insights for the purpose of benchmarking and yields deeper observations necessary for underexplored phenomena [73,74]. To support triangulation, multiple investigators were involved to better process the rich contextual data and increase confidence in the research findings [74,75].

The Folgers Coffee Company is part of The J.M. Smucker Company, whose products lead the 10 billion USD at-home retail coffee category. Folgers 1850 coffee was selected as a single-case exemplar for the following reasons:

1. In the 52 weeks that ended 17 May 2020, Folgers was the leading ground coffee brand in the U.S. with over 25% of the market, an increase of about 3% since 2008 [76].
2. The Folgers Coffee Company aims to improve the lives of the farmers who grow their coffee and to purchase green coffee in a responsible manner. Folgers works with UTZ (part of the Rainforest Alliance) to make green-coffee purchases and introduce sustainable coffee practices (UTZ certified as The J.M. Smucker Company, Member ID ME01_7585), and with World Coffee Research (WCR) to protect natural resources ($250,000 to $500,000 category for annual support as J.M. Smucker Co./Folgers Coffee).
3. Folgers 1850 coffee is 100% Colombian. Folgers has partnered with Farmer Connect, a tech start-up building farm-to-fork consumer traceability solutions, to connect consumers of Folgers 1850 coffee with farmers in Colombia.

3.2. Research Setting

The Folgers Coffee Company currently exists in an environment in which other businesses are starting to introduce blockchain given greater concern about compensation for farmers. Examples include Trabocca, a green coffee importer employing Trace by Fairfood to show consumers how coffee from Ethiopia reaches Amsterdam, and Starbucks, which uses blockchain technology so that customers can trace the journey of their coffee beans using a QR code or number on the back of bags of coffee bought in US stores.

3.3. Unit of Analysis

The unit of analysis was a bag of Folgers 1850 coffee. Coffee cherries may be processed using one of three different methods, known as dry, wet, or semi-dry processing [36]. This research focuses on dry processing, as this is the production method of the selected product.

The main by-product of the dry method is the dried skin, pulp and parchment, representing about 12% of the berry on a dry-weight basis [36]. Rotta et al. [77] found that on average, 100 kg of harvested coffee cherries yields 2.6 kg of mass consumed by humans as exported coffee. These by-products, mainly located in the production countries, are often treated as waste that adds to the cost of production [78,79]; however, there exist alternative economic uses such as energy production, chemical compound extraction, and the production of industrial products [80].

Coffee silverskin, also known as chaff, may be the first coffee industry residue produced in consuming countries as it is released during roasting if polishing did not occur before shipping. Spent coffee grounds are the waste produced by brewing coffee. Consequently, the potential feedstock for CE spans agricultural production, industry and consumers starting from origin in Colombia.

3.4. Data Collection

Data collection consisted of four main steps:

1. The lead researcher ordered a bag of Folgers 1850 coffee from amazon.co.uk.
2. The blockchain was investigated using the QR code on the coffee bag.
3. The company (Folgers) was investigated using information available online (sustainability reports, website).
4. Colombian coffee production was investigated using online resources.

The reason for using these steps was to provide a holistic perspective on the production of Folgers 1850 coffee in the context of Colombian coffee production for subsequent thematic analysis [81,82]. The researchers were unsuccessful in attempts to interview supply chain actors including the J.M. Smucker Company, Orrville, OH, USA; Albertsons (retailer, USA); Food Lion (retailer, USA); Harris Teeter (retailer, USA); and Meijer (retailer, USA).

3.5. Data Analysis

As suggested by Kristoffersen et al. [83], the following steps were followed to analyse Folgers 1850 coffee:

1. Determine framework elements and strategies present–are they ecologically embedded?
2. Perform business analytics gap analysis.
3. Identify improvements to circular-oriented innovation that can be enabled with blockchain.

The gap analysis consisted of the following steps [84]:

1. Define the future state as informed by the literature review: The desired future state is ecological embeddedness with farm-to-fork traceability enabling product quality and safety (consumer health benefits), waste identification and location for the inclusion of by-products and waste in CE activities to reduce or recover value and decrease costs (to be shared throughout the supply chain as benefits), and a digital ledger for efficient economic transactions and adequate compensation upstream of the customer and a fair price for the customer (benefits throughout the supply chain).
2. Identify needs: The current state is identified for Folgers 1850 coffee using the physical product and grey literature through the lens of consumer experience. Needs are identified for supply chain actors.
3. Describe the Gap: The gap between the current and future states and contributing factors are described.
4. Bridging the Gap: Solutions are suggested to advance from the current to future state within the context of blockchain.

4. Results

4.1. Data Collection

(1) The Product

A 12 oz (340 g) bag of Folgers 1850 coffee was delivered to the United Kingdom as shown in Figure 2. The bag was printed with the "Juan Valdez and donkey" registered trademark of the Colombian Coffee Growers Federation (FNC). The coffee bag had three stick-on labels attached: a barcode with the description "New–1850 by Folgers Coffee 100% Colombian Light Roast Ground Coffee, 340 g"; a date "20 July 2021" and a QR code with "Learn More 88309001", which was easily removed intact for better scanning of the QR code. The barcode sticker was covering a barcode originally printed on the package, and the date sticker covered a "best if used by" notification printed on the package with the same date as on the sticker and a 13-digit number. The QR code sticker had nothing printed underneath. No UTZ label was found on the package.

(2) The Blockchain

The scanned QR code led to a website (www.thankmyfarmer.com, accessed on 23 January 2022). The products on the website are "traceable" without having to purchase the product. The pop-up titled "Blockchain & farmer connect" read "Farmer Connect uses blockchain to empower the different actors in the ecosystem to share their data in a secure and verifiable manner. The data visualized on this map comes directly from the Farmer Connect platform, uploaded by the different actors." The zoomable map titled "Your product's journey" identified the supply chain starting with two collection centers (Sevilla, Colombia and Manizales, Colombia) as leading to a dry mill (La Variante Sitio La y Salida a Pereira, Pereira, Colombia) and then going to the exporting port in Cartagena. The importing port was identified as New Orleans, LA, USA. From the importing port, two warehouses were identified (Smucker Coffee Silo Operations, 5242 Coffee Drive, New Orleans, Louisiana (LA), USA and Smucker Coffee Almonaster Warehouse, 5050 Almonaster Avenue, New Orleans, Louisiana (LA), USA). From the warehouses, the next identified destination was the roasting facility (The Folgers Coffee Company, 5500 Chef Menteur Highway, New Orleans, Louisiana (LA), USA), and the last location identified was another warehouse (Smuckers Lacombe Distribution Center, 64490 Louisiana-434, Lacombe, LA, USA). Figure 3 is a visualization of the Folgers coffee supply chain.

Figure 2. The product delivered to the United Kingdom.

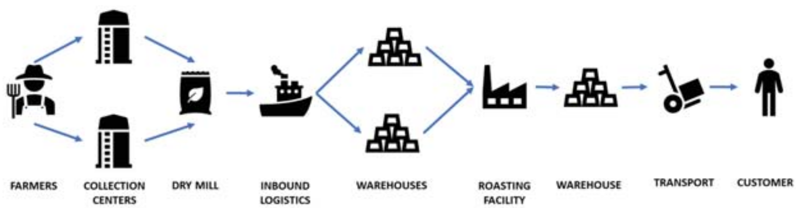

Figure 3. Visualization of the Folgers coffee supply chain.

The following processes of the supply chain can be improved using blockchain technology:

(1) The process of collecting, analysing and making forecasts from supply chain data.
(2) The process of ensuring the security and accuracy of data across the supply chain.
(3) The process of sharing data for improved collaboration across the supply chain.
(4) The process of facilitating and recording financial transactions for greater accuracy and efficiency.
(5) The process of tracing products.
(6) The processes of ensuring product safety and quality.
(7) The process of delivering products more quickly and efficiently.
(8) The process of enabling global supply chain compatibility.
(9) The process of managing and valorising waste (supported by IoT technology).
(10) The marketing process in relation to customer engagement with sustainability.

(3) The Company

Folgers 1850 coffee is a premium brand launched in 2018. The J.M. Smucker Company sources coffee from nearly two dozen countries at any given time. Employees of the J.M. Smucker Company are claimed to be located within major coffee producing regions for the purpose of supporting quality through relationships and transparency. The J.M. Smucker Company has two coffee manufacturing facilities: New Orleans and Suffolk (both USA).

Folgers uses the Farmer Connect website to offer the following:

- The Thank My Farmer™ app for consumers to use to scan a QR code on packaging of a finished good to access the story behind it and donate to sustainability projects in the farmers' communities.
- A farmer connect platform for enterprise clients.

- Farmer ID with a Self-Sovereign Identity (SSI) to allow producers to store and manage digital versions of identification documents, transaction receipts or (agricultural) certifications in one place.

Farmer Connect has been asked by consumers if, using their transparency function, brand owners would share the price paid to farmers in origin countries. Showing farm-gate prices on traced coffee is possible, but Farmer Connect indicates that the industry chooses how to use their tool.

(4) Colombian Coffee Production

The FNC is one of the world's largest nongovernmental agricultural organizations. The mission of the FNC is to ensure the well-being of more than 500,000 coffee growers, with about 95% being small farmers with less than 3 hectares. The organization holds a number of certifications.

The collective savings of the coffee growers gives them access to public funds. One of the most important benefits of the public funds is the guaranteed purchase of the coffee harvest based on market prices and transparency indicators.

The FNC promotes the use of the Smart Coffee ID Card and Smart Coffee Card among the certified coffee growers for financial transactions for the following purposes:

- To receive payment for the sale of their coffee at the Coffee Growers Cooperative.
- To have access to bank operations and purchases at more than 260,000 points: agricultural provision warehouses, cooperative purchase points, ATMs of any network, bank correspondents, Aval Group offices, and commercial establishments, in addition to transactions online and under the ACH (automated clearing house) system.
- To withdraw and send money and for deposits and savings in their bank account.

Colombia also has a Coffee Information System (SICA) containing the descriptions of 1,800,000 lots and socioeconomic data about producers featuring information that is updated by the FNC extension service with over 1500 technicians.

4.2. Data Analysis

(1) Framework Elements and Strategies

From the data collected, no circular strategies were evident related to Folgers 1850 coffee as outlined in the Circular Strategies Scanner [83]. The only apparent strategy was the overarching strategy of supporting farmers to make a financially viable living in which the contribution of the blockchain effort is to externalize this support to consumers.

(2) Gap Analysis

In the context of the ecological embeddedness of the product, production, packaging and the supply chain actors for Folgers 1850 coffee, the blockchain may yield a benefit to farmers arising from the final product packaging if the customer decides to donate money through the Thank My Farmer™ app. However, this is not a direct financial benefit to any specific farmer but rather a potential benefit through the support of projects such as Coffee Seedlings for Smallholder Farmers or Clean Drinking Water and Infrastructure for Schools.

Table 1 summarizes the current needs, desired future state, contributing factors to the gap between the desired future state and current needs and solutions for advancement within the context of blockchain.

(3) Identification of improvements to circular-oriented innovation that can be enabled with blockchain

Opportunities for innovation may be found in examples of best practices or by rethinking and reconfiguring strategic initiatives and the business model including operational processes [83].

Best practices in the case of blockchain may be found outside of the coffee industry: For instance, the pharmaceutical industry is being driven by legislation (the Falsified Medicines Directive in the European Union and the Drug Supply Chain Security Act in the USA) that stipulates that there must be tracking of pharmaceutical products. This (theoretical) best practice demonstrates that end-to-end supply chain actor involvement is viable and could be used to improve the blockchain application in the coffee sector. However, legislation may need to act as a driver.

Table 1. Gap analysis of Folgers 1850 coffee.

	Supply Chain Actor	Current Needs	Desired Future State (Ecological Embeddedness)	Contributing Factors	Bridging the Gap
Columbia/New Orleans, USA	Farmer	Living income	Fair and efficient financial transactions Waste minimization and valorisation	Lack of power	Inclusion in blockchain financial transactions Blockchain for waste
	Collection	Supply of coffee	Waste minimization and valorisation	Lack of advanced waste management	Blockchain for waste
	Dry Mill				
	Exporting Port				
	Importing Port				
J.M. Smucker Company	Warehouse	Supply of coffee Good public relations	Quality and safety of product Waste minimization and valorisation	Lack of incentive	Regulation and legislation for blockchain Full product blockchain traceability and visibility Blockchain for waste
	Roasting Facility				
	Warehouse				
Amazon	Delivery	Good public relations	Quality and safety of product	Lack of integrated technology (e.g., IoT)	Introduction of IoT information into blockchain and integration with upstream supply chain
United Kingdom	Customer	Safe supply of coffee Conscientious consumption (enabled by a connection with the farmer & redirection of coffee grounds from landfill)	Fair price Quality and safety of product	Lack of farm-to-fork transparency Lack of awareness around spent coffee grounds use Lack of access to spent coffee grounds recycling	Increased blockchain transparency Education and participation in blockchain for waste

Waste and blockchain are being considered in the context of CE mainly with regard to plastic waste and electronic waste (e.g., [85,86]). A proposed model for electronic waste considers both forward and reverse supply chains [86]. Blockchain has the added advantage that waste may be tracked across borders [87]. With regard to the collection of waste, a blockchain-based approach using smart contracts has been proposed [88].

Nevertheless, there are wider opportunities to optimise the circularity of the management of non-packaging waste and by-products from the coffee supply chain. The main materials to consider in this regard are coffee husks, pulp, immature or defective beans, coffee silverskin, spent coffee grounds [89] and parts of the plant, such as the flowers, leaves, stems and twigs [90]. Although most of them are currently unused, thermally recycled or used as animal feed, they can be used within the food sector for human consumption [90], which is the ideal solution from a CE point of view, since materials from the food sector remain in it. Furthermore, some of these materials can be used in a wider range of applications, such as to produce biofuel, remove heavy metals and dyes from aqueous solution and extract value-added compounds such as antioxidants and dietary fibres, which can be used in new foods [36].

If such coffee waste and by-products were valorised instead of simply being disposed of, new supply chains would be generated to account for the management of these feedstocks up to the point they are used. This would significantly complicate the overall coffee supply chain, adding new stakeholders and activities. Alves et al. [89] recommended more integrated strategies with the involvement of coffee producers, industries, academic institutions and governmental and nongovernmental organizations to further valorise coffee by-products. Blockchain can support this by making more data available to stakeholders while guaranteeing the data's security and strengthening the accountability of the new products. Taylor et al. [91] argued that blockchain could incentivise sustainable waste management and offer clarity in the property rights related to products and wastes, while maintaining anonymity and privacy for institutions and individuals.

There is also evidence that blockchain can help reduce food waste [92,93], for example by informing stakeholders when abnormal conditions occur [94]. In general, blockchain can help by sharing data about growth conditions, expiry dates, product quality, cultivation methods and processing technology [95]. All this helps with managing inventory, forecasting and planning purchases to suppliers, so there is less need to overbuy, and consequently less food waste is generated. Furthermore, food recalls can be optimised, since it is much easier and faster to identify defective batches. Further opportunities can be realised by co-locating food and biorefining industries to share feedstocks and processing equipment. Sheppard et al. [96] modelled coffee bean roasting co-located with lignocellulosic biorefining of spent coffee grounds, concluding that financial and environmental gains can be achieved. Again, blockchain can support data sharing and therefore strengthen synergies between different industries or even sectors.

IoT can support blockchain by sensing and collecting data to send to the blockchain to create tamperproof records of shared transactions [97]. IoT enables the acquisition of data related to the actual environmental conditions (temperature, humidity, appearance, location, etc.) in which the food product is produced, processed and stored. Data are collected using various sensors (humidity and temperature), cameras (images) and global positioning system (location and movement), and these data may be communicated through technologies such as ZigBee, Bluetooth and WiFi. These technologies collect real-time product data affecting shelf life from farm to fork to minimise food waste [11], predict product shelf life [98] and identify the reasons for food waste [99].

Since the aforementioned considerations of blockchain fail to consider the valorisation of the by-products of production and biological-loop waste at end of life in support of ecologically embedded CE as identified by the gap analysis, best practices are not applicable, and a rethinking and reconfiguring of strategic initiatives and the business model including operational processes are required.

5. Discussion

The aim of this research was to identify how blockchain technology could support ecological embeddedness of the coffee supply chain. The results of the data collection and gap analysis show that blockchain could contribute to ecological relationships among the supply chain actors and the environment by facilitating the sharing of information for a safer supply chain (health benefits for consumers), valorising waste throughout the supply chain in support of CE by highlighting its location and quality with the aid of the IoT to create environmental and economic benefits (cost savings) and improving supply chain relations with greater transparency for the economic and environmental issues of the supply chain (customer loyalty benefits, benefits related to efficiency).

This research indicates via the product marketing of a single-case exemplar under institutional theory that coffee companies may be experiencing decoupling in that organizations superficially accommodate institutional pressures and adopt new technological solutions without necessarily implementing the related practices [100]. The original contribution of this work to the body of knowledge is that blockchain technology has the potential to support the ecological embeddedness of coffee supply chains. The application of the proposed methodology for determining ecological embeddedness yields results that are consistent with previous research yet also enables the identification of means of bridging gaps to achieving ecological embeddedness. Ecological embeddedness supports benefits to all supply chain actors and the natural environment as part of a legitimate approach to CE which is intrinsically important to helping business address modern challenges related to the Sustainable Development Goals, specifically in relation to corporate sustainability, Principle 9 of the UN Global Compact, which states "Encourage the development and diffusion of environmentally friendly technologies".

This single-case exemplar of Folgers 1850 coffee reveals that for ecologically embedded CE as part of the supply chain, there needs to be a consideration of the relationships among supply chain actors and the environment (both natural and business). Relationships are supported both by financial considerations (economic sustainability) through the sharing of benefits among all supply chain actors [49] and for sustainable consumption behaviour through the creation of connections between consumers and producers [101]. Blockchain enabled these relationships, but the single-case exemplar demonstrates that blockchain has not been utilized to its fullest potential. The use of cryptocurrency was not identified as a necessary enabler of these relationships. These findings align with social sustainability and the minimization of risk in the supply chain through user-friendly applications, secure digital payment systems, support for suppliers and farmers and adapting to local conditions [32,102].

The relationships among the supply chain actors are not fully realized in the sense of blockchain farm-to-fork traceability for the Folgers 1850 supply chain. Individual farmers are not visible to consumers even though this would be technically feasible. Consumers may thus be less likely to engage with supporting them. Furthermore, any donations are not linked to a blockchain, so there is little accountability as to how much of the money reaches a specific destination. The supply chain that is visible to consumers does not account for the majority of food miles that the product may have travelled (the USA to the United Kingdom for the single-case exemplar), thereby limiting considerations related to sustainability. The delivering organization also lacks integration with the producer through the blockchain, and this integration could be important for the safety of the consumer and quality of the product with repercussions throughout the supply chain.

Furthermore, the Folgers 1850 supply chain inadequately considers the relationships that are possible within the existing business environment that could enable a more effective blockchain. The FNC has already implemented a number of digital solutions related to farmers that could be integrated into the supply chain. The FNC also supports farmers through fair coffee prices and with the implementation of sustainable agricultural practices. A relationship between Folgers and the FNC would appear to be beneficial, but it does not appear to have been realized. Similarly, although Folgers works with UTZ, which has MultiTrace, a platform supporting traceability of coffee among other products, there is no UTZ certification on the 1850 coffee.

The relationship of the supply chain single-case exemplar with the end user in terms of health and safety is lacking in terms of establishing consumer trust for the delivery of an unadulterated product. Literature has noted that supply chain participants, especially the end customers, need to be able to appreciate the advantages of blockchain technology [33]. There is no direct connection between the blockchain and product quality from the consumer perspective. Coffee has been found to be adulterated using legumes, cereal, nuts and other vegetables, which may be a source of dangerous allergens for some people. However, these forms of adulteration lack caffeine [103]. Although not formally recognized, there is emerging evidence for the impacts of caffeine use disorder (CUD) [104]. When arabica coffee is substituted with cheaper robusta coffee, the caffeine content may increase significantly, which may have implications for CUD. Colombia grows mostly arabica.

Finally, the supply chain analysed in this single-case exemplar was been conceived for environmental sustainability. Waste is present throughout the supply chain in the form of by-products and resources, although there are many potential applications of this waste in support of a CE, many of which could lead to additional revenue. A barrier in the valorisation of this waste is not knowing the quality, quantity and location. Blockchain has the potential to provide the necessary visibility by describing waste as an asset in an associated digital ledger when combined with IoT technology [99].

6. Theoretical Implications

The overarching theoretical contribution of this work is to extend the consideration of ecological embeddedness as defined for individual manufacturers [48] to the supply chain. In this context, the supply chain should be considered in terms of benefits for all of the actors and the environment.

The second contribution of this research is to methodologically extend the theoretical framework [83] to the application of blockchain by detailing the gap analysis. Investigations of ecological embeddedness for other digital technologies may employ the gap analysis steps demonstrated in this research by identifying current needs, the desired future state, contributing factors to the gap between the desired future state and solutions for advancement.

The third theoretical contribution of this work is extending the consideration of blockchain to by-products and waste throughout the supply chain that may be valorised in support of an ecologically embedded CE. Previous research on blockchains has focussed on waste in terms of products at the end of life. This research needs to be extended for greater transparency and therefore access to valuable by-products and waste along the entire supply chain.

7. Managerial Implications

The main managerial implication of this study's findings is that a consumer experience perspective (the theoretical lens used in this research) should not lead to questions about the legitimacy of the implementation of digital technology. Consumer trust is a notable feature meant to be enabled by blockchain [105]. Contradictions that are evident from the investigation of online content regarding the actors in a supply chain may lead to reduced trust and erode perceptions of the brand. An easily removeable QR label which links to an essentially static website showing a supply chain with duplicated nodes not specific to the actual product purchased may not be conducive to increasing consumer trust. Trust is also unlikely to be built on a lack of transparency, whereas disclosure (e.g., prices paid to farmers) would enable equity throughout the supply chain.

A related implication is that for ecological embeddedness, the implementation of digital technology needs to demonstrate mutual benefits through the adaptation of outputs, goals and methods of operation. Establishing a relationship through communicating identification with institutions which have a strong base of legitimacy is a public relations exercise which is not ecologically embedded [12].

8. Limitations and Future Research

The main limitation of this research is the reliance on a single-case exemplar: not all of the findings are generalizable. In particular, not all supply chains will have valorisable waste in sufficient quantity and quality to justify efforts to implement supporting blockchain solutions. Similarly, the supply chain that was studied is not decentralized (third-party platform by Farmer Connect) and avoids most of the typical issues of data immutability and privacy (trust) along with consensus mechanisms. Such implementation may act as a barrier to ecological embeddedness and the extent to which this could be the case would be important future work.

Future research could also focus on the technical aspects of blockchain implementation for ecological embeddedness arising from the Folgers exemplar:

(1) How to resolve traceability issues when the supply chain branches and then reunites commodities (two collection centres leading to one dry mill, two warehouses leading to one roasting facility) both among supply chain actors and within the processes of individual supply chain actors.

(2) How to implement new business models supported by blockchain technology for the valorisation of by-products of production and biological-loop waste at the end of life.

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Value Proposition Assessment of Blockchain Technology for Luxury, Food, and Healthcare Supply Chains

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Abstract: *Background*: In relevant research, blockchain technology (BCT) is credited with great potential for supply chain management (SCM). However, even after more than 10 years of the technology's existence, it is barely used for any self-sustaining applications. This raises the question of why BC cannot prevail against its alternatives. With this paper we want to identify criteria by which the added value of BCT can be measured. Furthermore, we want to evaluate how well the different supply chains (SC) exploit the added values of BCT. *Methods*: For this, we identified real-world examples and case studies for luxury, food, and healthcare SCs. These examples are described in detail and then analyzed for their added value compared to possible alternatives. *Results*: The results show that in the clusters of food and healthcare SCs, no general added value of BC over current best-practice solutions could be verified. Luxury SCs manage valuable products that are typically traded in small quantities. It is within this cluster that the implementation of BC can be justified best. *Conclusions*: In conclusion, this study shows that the application of BCT is especially beneficial for goods with a high value and low trade volume. In addition, the interface between reality and the digital twin should be as secure as the database or BC solution itself. Furthermore, the demand for transparency and immutability of data should be more important than the need to protect sensitive data. Finally, SC participants, especially the end customer, must also be able to appreciate the advantages of BCT.

Keywords: blockchain technology; Smart Contracts; logistics; supply chain management; value proposition assessment

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1. Introduction

In 2021, the most successful application of blockchain technology (BCT) is still in the field of cryptocurrencies, but researchers have recognized the potential of BCT and are trying to apply it to other areas of research, such as supply chain management (SCM). Many different areas of academia have explored BCT in terms of the distributed storage of data, peer-to-peer networks, cryptography, Smart Contracts, and consensus algorithms [1] (p. 1). By design, BC is a very secure database structure where information, such as transactions or programs, is stored in chained blocks [2] (p. 5). BC is designed to be storable in a decentralized manner while functioning without a central controlling system. Moreover, BC is transparent, in order to allow decentralized storage so that older blocks become unchangeable and a high level of trust in the data set can be established.

Supply chain management is defined as the cross-company coordination and optimization of the flow of materials, information, and value along the entire value chain, from resource extraction to the end customer. The aim is to optimize SC holistically in terms of costs and time. SCM must contend with several challenges, such as globalization, increasing customer demand, shortened product life cycles, and developing information technology. To maintain or gain competitive advantages, Supply Chain (SC) companies must face these challenges. Thus, increasingly complex systems must be coordinated. As a result of globalization, the SC of many products extends across different countries of the world, each with different currencies and laws. From the source to the delivery to the end consumer, goods pass through different companies in different countries, such as manufacturing plants, warehouses, wholesalers, or retailers. SCM could benefit from a transparent, tamper-proof database and automated contracts, which is why Xu et al. (2019) recommend that any SCM company should consider BCT [1] (p. 11).

Current research on BCT, especially in the context of cryptocurrencies, is available in abundance, but published case studies and concrete examples in an industrial context are lacking at present. There are still only a few applications of BCT in SCM with commercial success and the chances of a successful implementation are currently low. According to Browne (2017), on average, only 8% of BC projects were still active within one year of starting [3]. Moreover, there is little research on the actual added value of BCT. This paper therefore aims to fill this gap. Our achievement is to classify and evaluate the value proposition of BCT for the three clusters on the basis of preliminary work. In doing so, we aim to answer the following two questions: (a) What criteria can be used to measure the added value of BCT? (b) How do different SCs exploit the properties of BCT?

Therefore, this paper aims to identify possible reasons for the few real implementations of BCT in the industrial context. For this purpose, the three clusters of Luxury, Food and Healthcare SC are analyzed in detail for the potential application of BCT to each. In a previous systematic literature review, we found that these three clusters are credited the greatest potential for BC adoption [4]. Therefore, it is evaluated whether the technology is currently mature enough for practical use in some areas.

2. Blockchain Technology in Supply Chain Management

2.1. Fundamentals of BCT in SCM

BCT is a form of data storage in the so-called blocks of the BC. These blocks are arranged chronologically and are inseparably connected to each other, hence the name BC. The data within the blocks cannot be changed without destroying the BC. A desired change, e.g., a transfer from A to B, is executed in the form of a transaction in a new block. Thus, a BC is a constantly growing chain of data blocks that are cryptographically linked to each other.

BCT was developed for the secure, worldwide transfer of virtual values without intermediaries; BCT fulfills this functionality very effectively and successfully [2] (p. 49). However, other functions of BCT, for which it was not originally designed, are needed in SCM. The practical applications of BCT go far beyond cryptocurrencies, as any type of valuable information can be digitized and tracked and traced via a BC [5]. Customers are demanding more and more origin-related data. In 2016, for example, an *E. coli* virus outbreak at Chipotle Mexican Grill led to 55 cases of infection, shutdowns, and investigations. As a result, the company's reputation was damaged, sales dropped, and there was a 42% drop in the value of its stock [6]. The desire of many consumers was to be able to track food with confidence, which BCT can principally enable.

Hinckeldeyn (2019) states that BC is always worthwhile when high levels of trust between multiple actors are needed. The exploration of BCT in the field of food SC is an attempt to gain the trust of customers through greater transparency. BCT can generate or secure a competitive advantage for companies if customers trust the BC solution and if this trust is of value to the customer [2] (p. 47). For this reason, after this event at Chipotle Mexican Grill, several large food companies, such as Dole, Unilever, and Walmart, approached the problem by working together with IBM, since IBM already demonstrated competence in the use of BCT. Thus, food SCs in particular began to recognize the relevance of strategic partnerships, because only when SC works as an integrated whole can the confidence of consumers in the products of the SC be strengthened [7] (p. 5).

However, BCT can not only support SCM by means of reliable provenance knowledge. According to Roeck et al. (2020), BCT introduces transparency, trust, and disintermediation as key value propositions in SCM [8] (p. 2125). Colaka et al. (2020) cite the main value proposition of BCT in SCM as creating transparency for the customer, simplifying the tracking process, reducing costs and errors, minimizing inventory, minimizing transportation costs, reducing delays, and identifying problems faster [9] (p. 937). Ideally, SCM controls SCs by means of cross-company software systems. This software must enable SC activities to be planned, scheduled, coordinated, monitored, and validated. Al-Jaroodi and Mohamed (2019) state that with the help of BCT, this software could be enabled [10] (p. 36504).

Consequently, the possible applications of BCT are very diverse. However, for meaningful economic use, this technology must solve existing problems of SCs or lead to process improvements. In the literature review conducted in a previously published paper, two major clusters were identified. The first cluster presents an overview of BCT in SCM and the second cluster shows possible concrete applications of BCT. In that second cluster, six papers each on luxury and food SC were found, as well as five papers on health SC [4]. The conducted literature review [4] (p. 7) was able to identify two functionalities of BCT that are very promising for SCM. These are, firstly, the functionality as a secure, transparent database and, secondly, the application of Smart Contracts written on the BC.

2.2. Features of a BC That Are Beneficial for the SCM

One way to categorize the influence of BCT on SCM is provided by Litke et al. 2019, who identified the following possible positive influences of BCT on SCM: Scalability, Performance, Consensus, Privacy, Location and Cost. They state that SCs scale better and that the SC performance could increase due to BCT. This is because modern SCs are becoming more complex and a significant amount of data needs to be exchanged between many actors. The data from these SCs is currently managed very inefficiently, as each company uses its own solution and when necessary, data must be exchanged with another company that relies on a different approach. No common database has yet been implemented in an SC; BCT could unite all SC participants for such an endeavor. Furthermore, BCT can provide unity within the SC through consensus and protect privacy effectively through permissioned access and by making private transactions invisible but properly verified. A significant amount of money could be saved by payments with cryptocurrencies, as well as by better detection of potential savings. However, one of the most potentially important elements of BCT is the ability to document the location of products over time in a trustworthy manner [11] (p. 7).

BCT offers traceability, certifiability, trackability, and verifiability for determining the origin of a product. By improving knowledge about the origin of a product, the perceived risks of customers can be reduced (see Figure 1). Traceability leads to increased certainty about the origin. This reduces potential financial risk because the customer can verify that the source materials are those the manufacturer advertises. For example, the customer could trace source materials such as cashmere or high-value leather. The certainty about the authenticity strengthens the customer's confidence not to behave unethically and, for example, to purchase counterfeits or products with undignified production conditions. This reduces the customer's psychological risk and the social impact when other people find out about the purchase, known as the social risk. Trackability through the different stages of SC enables subsequent control and thus increases trust in the product. For example, in the case of a high-quality wine, the storage conditions, such as temperature and humidity, could be documented. This lowers the risk for the customer of the performance or function of the product being inadequate. Verifiability ensures data integrity. This can dramatically reduce the risk of counterfeit products, especially for critical products such as medicine. This security can in turn reduce the risk of physical damage to the customer [12] (pp. 286–291). An example of a BC provider is Provenance, which connects consumers and suppliers for different logistical activities to enable provenance knowledge [10] (p. 36504). The most important prerequisite for such a service is the unambiguous assignability of products with their image in the BC. Ideally, the products are inseparably linked with the BC. However, the BC solution can only be as secure as the link between the physical products and the BC [13] (p. 42).

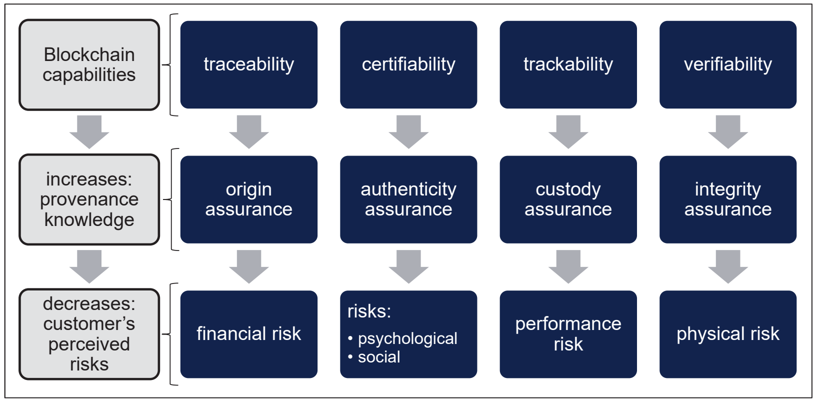

Figure 1. Impacts of Blockchain-activated origin knowledge on the customer [12].

3. Value Proposition Analysis

The authors of this paper conducted a systematic literature review on the applications of BCT in logistics and SCM. Three clusters were identified in which the application of BCT is particularly promising: Luxury, Food, and Healthcare SCs. In what remains of this paper, real-world examples are used to analyze the added value of BCT for each respective cluster. The examples identified in the conducted literature analysis serve as a basis [4] (pp. 10–13).

In this chapter, applications of BCT in SCM are introduced and validated. For the Luxury SC, the Food SC, and the Health SC, the value proposition of BCT is worked out in each case using the example of a specific application. Here, the BCT, with its limitations, must be measured against alternative solutions. The structure of the subchapters starts with a summary of the actual problem of that cluster, followed by a description of how BCT can help, i.e., what its value is. Subsequently, the limitations and challenges of the BC solution are considered, before being compared with alternatives. Finally, a summary and assessment are provided.

3.1. Luxury Supply Chain

3.1.1. Examples of Applications and Case Studies

In the relevant research there are various possibilities as to how BCT can support Luxury SC. A current application is the authentication and certification of diamonds. On the one hand, this is important in order to prevent "blood" diamonds; on the other hand, conventional certificates can be faked, or a real certificate can be used for a fake diamond. Furthermore, BC certificates are permanent [14] (p. 17).

Two major providers have established themselves for BCT in SCM: Everledger and the open source project Hyperledger, which has been supported by IBM, SAP, and Intel, among others [5]. The platform Everledger offers a unique digital thumbprint for high value and hard-to-replace goods, such as diamonds, wine, etc. [15] (p. 9). This thumbprint is unalterably stored in the BC and consists "of 40 metadata points, the laser inscription on the girdle, and the stone's four Cs—color, clarity, cut, and carat weight" [16]. Since the diamond is uniquely digitally assignable, Everledger can create a digital twin for each diamond. The website states: "By combining blockchain technology with AI, IoT and nanotechnology, we create a digital twin of every diamond, enabling traceability in a secure, unalterable and private platform" [17].

In addition to the already existing BC-certificates [14] (p. 27), the transport of the diamond can be documented completely by means of the BCT (tracked and traced). As soon as the recipient of the package confirms that the package has been delivered, a transaction can be triggered by means of a Smart Contract. The advantage of using the BCT is that it is suitable for use across different companies, which means that the transportation means of different companies can be used, if they agree to use this BC. No one can change the data in the BC retrospectively. As the BC is law, the person currently responsible for the diamond is always visible to all parties; the person currently responsible is always liable for any damage or loss. The responsible persons can individually insure themselves. In the case of a public block certificate, there is a risk that criminals could gain access to the current location of the valuable diamond, which makes private, permissioned BCs more suitable [15] (p. 6). However, a residual risk remains because all companies along the SC have access to the BC.

Breitling was identified as another example within Luxury SC. Breitling includes a digital passport and a certificate of ownership with a QR code, with new watches. The data of the owner of a Breitling watch and the certificate can be stored in the BC using an app. Each Breitling watch features a serial number on the back of its case, and as of 2021, older watches can also be registered. Breitling cites traceability, transparency, and tradability as its advantages [18].

In terms of traceability, information such as the warranty or the full history of the watch can be viewed. It is easier to engage in anonymous conversations with Breitling customer services; for example, ordering an additional bracelet can become easier. Breitling tries to motivate its customers to use its service by offering an extended warranty. A significant advantage, however, is that the current owner of a Breitling is stored in the BC. In the event of a sale, ownership can be proven and transferred very easily using the app. For this purpose, a transaction is stored in the BC in a new block. This has a potentially positive effect on the resale value of the watch. On the one hand, the buyer can be sure that it is an original and that the seller is the rightful owner. On the other hand, general information, such as the number of previous owners or whether maintenance has been complied with, can be retrieved.

It is very likely that the BC used by Breitling is a private BC; whether Breitling developed the BC solution itself, or uses a vendor is not known (note: an inquiry to Breitling on this matter was not answered).

3.1.2. Current Problems of the Respective Area

In the following section, the value creation of BCs will be examined primarily using the example of the digital twin of a diamond. However, most of this also applies to the Breitling example or goods of other Luxury SCs. In the example, clearly marked diamonds were linked to the BC. Since the diamonds are very valuable, there is a trust problem.

On the one hand, the diamond should be traceable to be able to determine its origin with certainty and to ensure that it is not a "blood" diamond. Many consumers actively try to avoid illegally mined elements [2] (p. 47). Consumers thereby try to avoid the social and psychological risks described in Section 2.2. On the other hand, with such an expensive commodity, there is always the risk of counterfeiting. The customer wants to be sure that the information about the diamond is correct. This is important because non-professionals find it difficult to determine the value of a diamond.

3.1.3. Possible Value BCT Could Provide (+)—Pros of Implementing a BC

Everledger states that the origin of a diamond is stored thanks to AI, nanotechnology, and BCT. Thanks to nanotechnology, the diamonds can be clearly assigned and a digital twin can be created. Should the technology with the marking of diamonds become accepted worldwide, the resale value of stolen diamonds would be reduced. This digital twin must be stored as securely as possible, as diamonds are often very valuable; trust must be established.

The BCT is designed to create trust. In a public BC with many participants, the BC can provide trust very effectively. However, the data around the diamond is too sensitive for a public BC. Everledger therefore relies on a private BC. Everledger's website states: "The lifetime story of a diamond, colored gemstone or fine bottle of wine is valuable information. It's a story you must increasingly be able to tell with clarity and confidence, to meet your customer's call for responsible and verifiable sourcing" [19]. In the case of Everledger, the life history of the diamond consists of entries in different blocks of Everledger's own BC. When a change is made, the old record is not overwritten; instead, the change is recorded in a new block. This ensures maximum transparency. The benefit of the BCT is that changes to the data set are made transparent and traceable, and therefore unchangeable.

3.1.4. Limitations and Challenges of BCT (−)—Cons of Implementing a BC

Everledger uses a private BC, so the decentralized component of the BC is lost. With the private BC, old blocks could be changed. However, all the subsequent blocks would have to be recalculated. If no requirements are placed on the hash, in contrast to the PoW algorithm, recalculation is possible quickly. However, if the clients have access to the hash, they may notice that a previous block has been modified. Since Everledger is the main node, all new information must be verified by Everledger itself, which requires trust from all parties involved towards Everledger. It comes down to this: the customer must trust Everledger. Therefore, it must be questioned what value proposition the BC has to offer over storing the data of the uniquely marked diamonds on a normal database of a trusted third party, which could also be Everledger.

3.1.5. Alternative Solutions without the Use of BCT

Since the customer must trust Everledger, Everledger could also store the data in a conventional database. Furthermore, in the conventional database, changes to the data set, such as the current location of the diamond, could be stored and made traceable. Everledger must guarantee that they do not manipulate old data, and that the data cannot be manipulated from the outside. However, Everledger must provide this guarantee independently of the database's structure, i.e., also when using a BC.

Conclusion and assessment—Compared with a conventional database structure, the BC can offer the advantage that customers could more easily check whether older data have been manipulated. The cost of storing data in a BC is also reasonable. Everledger only needs to keep the old data and, if it changes, it does not have to change the data but link a block with the change to the BC. In this case, the value proposition of BCT is relatively small. Storing digital twins in a BC is more of an incremental innovation than a revolution. Nevertheless, the value proposition could cover the low costs relative to the high value of the diamonds.

3.2. Food Supply Chain

3.2.1. Examples of Applications and Case Studies

Food SC were the largest cluster found in the literature analysis; nevertheless, no case was found in which a company actively uses the BCT to earn money and gain a competitive advantage [4] (p. 11). Many feasibility studies have been found, but only few have tested their prototypes in the real world; this finding matches the findings of Hinckeldeyn (2019) [2] (p. 32). Demestichas et al. (2020) also identified many ideas, models, and case studies in a recent comprehensive literature review, as well as a growing interest in research. However, they could not find this growth in commercial applications of BCT [20] (pp. 10–14). Instead, they found companies and websites promoting BC solutions in Food SCs (see Table 1). Below, some projects are briefly mentioned as examples, followed by more detailed descriptions of selected applications.

Table 1. Companies which promote BCT for the food SC [20] (p. 15).

Company	Website	Description
agrichain	https://agrichain.com accessed on 15 November 2021	Platform to manage agricultural products
agridigital	https://www.agridigital.io accessed on 15 November 2021	Digitizing and growing grain SC
agriledger	http://www.agriledger.io accessed on 15 November 2021	Tools for participants of agricultural SC
arc-net	https://arc-net.io accessed on 15 November 2021	Brand protection through security and transparency
down stream	www.down-stream.io accessed on 15 November 2021	Beer brewing project for tracing the beer's ingredients
Fishcoin	https://fishcoin.co accessed on 15 November 2021	Incentivizes SC members to share harvest data
Ripe.io	https://www.ripe.io accessed on 15 November 2021	Platform for transparent and reliable information on the origin and journey of their food
TE-FOOD	https://te-food.com/ accessed on 15 November 2021	End-to-end food traceability solution on blockchain

Firstly, there is the cooperation of Walmart and Hyperledger Fabric, a BC platform for companies, which is intensively supported by IBM [2] (p. 24) and has been found numerous times [21]. In a field test, Walmart and IBM were able to demonstrate that the origin of mangoes and pork could be determined via BC within a short time [2] (p. 32). The IBM Trustchain can track tomatoes *from the farm to the pot, to the jar, to the table*, but is not yet in use, instead is a working prototype [22]. Bumble Bee Foods cooperates with SAP to document tuna fish products from Indonesia. The size of the fish, fishing location and time, freshness during its processing, and the company's certificate of production are stored within the BC [23]. Other examples deal with the traceability and certification of Extra Virgin Olive Oil [24] (p. 173) or describe how eggs could be traced in the USA using BCT [25].

On the one hand, these examples demonstrate the increased interest of food manufacturers in the trustworthy documentation of their products in the BC. Many companies are already trying to gain the trust of consumers with the help of seals, such as the Fairtrade label, which is awarded by a Fairtrade organization under certain conditions. On the other hand, the examples also show the interest of large IT groups. Whether the interest comes from the Research and Development department or the Marketing department is not always identifiable. Food scandals have led to manufacturers generating competitive advantages by providing reliable proof of the origin and processing of goods. The BCT might be able to strengthen the confidence of the consumer [2] (p. 32).

Below, a prototype that has been tested in the field is discussed. Zhang et al. (2020) developed a new system architecture along the entire Grain SC based on the BCT. Compared to traditional methods of the SCM, their system is characterized by high data security, real-time exchange of relevant information, such as hazardous material information, and trustworthy grain tracing along the entire SC [26] (p. 36398). The Grain SC starts with grain cultivation and production, primary grain processing, grain product cycles, and deep grain processing, and ends with transport to the consumer. Zhang et al. (2020) identified five typical links in the traditional Grain SC: the link of grain production, the link of grain storage, the link of grain processing, the link of grain logistics and transport, and the link of grain marketing [26] (p. 36400).

Smart Contracts define the conditions for the execution of transactions in advance. The system collects data on the grain, which is then stored within the BC. The data is collected mainly by electronic tags and various sensors, such as code-scan guns, cameras, smoke detectors, humidity sensors, light sensors, etc. When the parameters of the grain meet the requirements and, in addition, all other requirements are met, the transaction is automatically triggered [26] (p. 36404). A special use case was applied to validate the proposed system: an Information Management System for the Grain SC was established with grain companies in the province of Shandong. This field test was conducted on the BC platform, Hyperledger Fabric with the cloud database, MySQL. The system was able to provide reliable information in the SC for participants, consumers and third parties, and the data provided a good basis for the assessment, prediction, and early warning of hazards [26] (p. 36407).

As mentioned briefly above, Walmart and IBM are working on a BC to increase the transparency of the SC by tracking goods efficiently. Walmart faces the challenge of tracking and identifying a large number of products through a complex SC. If there is a problem with a product, such as contamination, Walmart needs to be able to locate and remove affected products from the shelves or contact affected customers as quickly as possible. The solution from Walmart and IBM is based on a private BC and is intended to be used to identify products very quickly. At the time of writing, a localization takes 6 days, while new solution products should be identified and localized within 2 s [27] (p. 14). Although many papers have mentioned this example, no technical details are identified. Who verifies the data entered, how false data is handled, and who pays for the transactions remains unclear.

Three papers were found in the Food Cluster that addressed the tracking and tracing of meat (see: [12,28,29]). Barge et al. (2020) focus on methods to better mark and identify meat, as they identified the problem of the interface between the physical meat and the digital information. According to Barge et al. (2020), increased consumer confidence in food and producer reputation, especially for meat, have been shown to provide increased sales. In the area of meat, there have already been several food scandals, e.g., concerning diseases, which is why there are already laws regarding this in the EU. Manufacturers must keep traceability data on meat, but do not necessarily have to share this data with customers. In Italy, the consumer even has the right to view part of the stored information about the meat, via a website from which the information can be accessed. This information includes the date of birth, sex, breed, farm code and slaughter date of the meat source animal. For this purpose, the customer needs a 14 digit code, which is written on each package. This information is provided without the BCT [28].

In addition to these obligations, the SC can also store further tracking and tracing information. High-quality meat producers can provide customers with further information. To be able to assign a piece of meat to a cow, the meat and the cow must be clearly identifiable. In the EU, electronic tagging is mandatory for sheep, goats, and cattle. The unique ID of the animal is stored in a passive tag, which is also stored in the national animal register [28]. In summary, producers already possess the relevant information, but rarely share it with their customers.

Ferdousi et al. (2020) identified the problem that many farmers view data about their meat as confidential and its disclosure as a threat. As a solution to this problem, Ferdousi et al. (2020) propagate a Smart Contract-enabled private BC with the goal of preserving the anonymity of users. To establish consensus among the participants of the network, Proof of Authority (PoA) is used. This is an evolution of the Proof of Stake (PoS) consensus mechanism [29]. In PoA, unlike PoS, no assets in a cryptocurrency ensure trustworthiness; instead, participants with a good reputation ensure consensus by vouching for the correctness of the transaction with their name. However, this requires the identification of the user. Therefore, this system requires a central administration, which takes over the registration of the farm owners and assesses their trustworthiness and reputation. The main advantage of this method is that neither computing power is needed, nor a large amount of cryptocurrency.

Transactions or Smart Contracts are stored in the approved blocks, as before. This form of consensus building allows more data and more complex Smart Contracts to be stored in the BC. The propagated system can be hosted on any SQL DBMS (database management system) and the Smart Contracts can be executed using Ethereum. In the field of Smart Contracts, anonymity can be guaranteed in the proposed system. The special feature of the system is that data protection, data ownership, and security are guaranteed. Therefore, farmers can share data relevant to the customer anonymously [29] (p. 154841).

3.2.2. Current Problems of the Respective Area

Some applications of BCT in Food SCs were introduced. A model for grain SC, the cooperation of Walmart with IBM and the tracking and tracing of meat were presented in detail. Most approaches in food deal with improving traceability. The goal is either to offer the customer added value through trustworthy, in-depth information, so that the willingness to pay increases, or it is for companies to make recalls more efficient.

3.2.3. Possible Value BCT Could Provide (+)—Pros of Implementing a BC

The BC can function as a database and provide trustworthy traceability data. As described earlier, in meat and fish, traceability is mandatory in many countries. However, these data often do not have to be shared with the customer. Producers often do not want to share this data because the data is considered trustworthy. The BC could help to share the data in an anonymous but trustworthy manner with the customers.

3.2.4. Limitations and Challenges of BCT (−)—Cons of Implementing a BC

Food is produced in large quantities and there are many different types of food. Thus, it is a very high -volume productive process; by contrast BCT is not designed for high volumes, but rather for high values. Furthermore, BCT can provide trust, but it provides trust through transparency. Since this transparency is not desired by many manufacturers, approaches are being pursued in which transparency is widely restricted. In this case, much of the manufacturer's data is anonymous to the customer. The lower level of transparency automatically reduces the customer's trust in the data, meaning that a higher level of basic trust on the customers' side is assumed. Another critical point of BC solutions is that a secure interface between the food and the BC is often difficult to implement. Ideally, the interface and the BC itself should be similarly secure and ensure a well-balanced system without vulnerabilities. For example, Walmart's mangoes could simply be exchanged. The customer cannot be sure that the presented secure BC-based data also belong to the product at hand.

3.2.5. Alternative Solutions without the Use of BCT

Alternative solutions to BCT include a write-only database or a trusted third party. If food data must be stored according to the law, then these data are already trustworthy, since there is a threat of penalties in the case of false information. The trust in mandatory data is therefore comparatively high, which is why a BC is not required. In addition, companies usually do not want to hand over the data voluntarily and, therefore, they try to minimize the costs.

In the example of Walmart, there is already a great deal of trust between the SC participants due to often intensive cooperation. In the area of product recalls, there is often no trust problem in a data set. Rather, the problem is that the data are not available at all and must be investigated manually by employees. Accordingly, BCT is not necessarily needed for this use case from a technical point of view. However, customers may feel more secure if the traceability system is based on BCT.

In the case of fish, origin information is already mandatory in Europe. The company followfood or followfish has made the complete traceability of food, mainly fish, its business model [30]. Using a code, the traceability data for salmon, for example, can be retrieved, such as: "Bred by the Salmar company in Frøya, Norway, processed in Lithuania, packaged in Holland and stored in Bocholt, Germany" [31]. The company guarantees the correctness of the data and does not use BCT for this purpose. Other companies or SCs could follow the example of followfood and make transparent traceability of food a part of their business model.

In the food sector, however, the customer is often not provided with the option of traceability at all. Customers are often not provided with tracking data, which is why the problem of a lack of trust in tracking data cannot arise in the first place. The ability to track products without BCT offers a great value proposition. Should customers embrace tracking and tracing and increasingly access the data, then for exclusive products this tracking and tracing solution could be run on a BC. However, this is only worthwhile if customers can appreciate the benefits of BCT.

Conclusion and assessment—Verhoeven et al. (2018) critically discuss the cooperation between Walmart and IBM. According to them, Walmart's disclosures suggest relatively little engagement with BCT. Walmart does not specify how and where the BC is stored and seems to store the data centrally. Further, Walmart does not address the costs and procedure of writing on the BC, nor how secure and trusted data sources are created. As mentioned above, Walmart claims to have reduced the tracking time of the respective products from 6 days to 2 s. How Walmart arrives at these numbers is not known, especially in comparison to alternatives to BCT. According to Verhoeven et al. (2018), Walmart does not seem to validate the data written to the BC. With a central database with regulated write permissions, for example, a write-only database, even faster traceability times could be achieved. Walmart also does not address who has access to the data. Some companies do not want competitors to obtain access to such data. Based on all the identified requirements from Walmart and the manufacturers of the products, no need for a BC solution could be identified [27] (pp. 14–18). In conclusion, it remains unclear whether a BC is the best solution for Walmart; however, marketing strategies were not included in the analysis.

In the area of meat SCs, there could be a great value proposition to the customer in the form of traceability. The entire tracking is possible with a central data bank; the only advantage that BCT could offer to the customer is an increased trust in the data, provided that the customer values the BCT. However, this is only worth striving for if the interface between food and BC is improved. This is because, especially in the case of food, the interface between the food, such as a steak, and the BC is very difficult, since food is often processed in very high numbers [28] (p. 2). If the customer trusts the stored data because of the BCT, the problem remains that the customer must ensure that he has also received the steak that matches the data in the BC. For example, the same QR code from a high-quality steak could have been used on other steaks of poorer quality. The customer must also trust that the data entered is correct. Currently, BCT in the Food SC sector only seems to be worthwhile for those who do provide a high-quality service with a higher-priced product and want to prove this transparently to the customer. In this case, the benefits must outweigh the disadvantages of disclosing the information to the competition.

3.3. Healthcare Supply Chain

3.3.1. Examples of Applications and Case Studies

The SC in Healthcare was the second largest cluster found in the application of BCT. The company Modum, a Swiss start-up, is as an example for this category. Modum has initiated several studies and developed and tested prototypes and offers its services in the field of BCT in SCM. The goal of the company is the secure tracking and tracing of pharmaceutical products. To this end, the company relies on a public BC, the Ethereum BC. For tracking, IoT sensor devices, QR codes, and barcodes are used to clearly identify the items handled.

The Good Distribution Practice Regulation (GDP 2013/C 343/01) requires proof that the transport conditions (in particular the temperature) do not affect the quality of the pharmaceutical products transported [32]. Modum enables other companies to meet the GDP requirements with the help of the BCT. At the same time, it should be possible to generate significant cost savings for the transport of pharmaceuticals that do not require active cooling [33] (p. 5).

To monitor the temperature during the transport of medicines, a calibrated temperature sensor in the package stores a measured value every 10 min. When receiving the package, the customer can scan the ID number on the package and then request the temperature data via Bluetooth, without having to open the package [33] (p. 5). The customer then sends the data to the Smart Contract. The data is stored in PostgreSQL because the collected data is too large or too sensitive to be stored in the Ethereum BC [34] (p. 588).

Other suggestions we found in the relevant research h on how the cold chain of medicines can be monitored transparently, e.g., using RFID systems [35], and how the risk of counterfeit drugs [36] can be reduced. For this purpose, Singh et al. (2020) proposed an IoT- and BC-based model for SCM in healthcare, where consensus is established by the Raft algorithm. The Raft algorithm builds on the Paxos algorithm but is intended to be more comprehensible (see: https://raft.github.io—last accessed on 15 September 2021). In these algorithms, a changing leader is elected, and each node must agree to the changes. The algorithm is suitable for a network with few participants, allows high data throughput and does not require high computing power to do so. The authors refined their model to improve privacy, security and show a full implementation, including an analysis of the performance and security of the network [37] (p. 20).

Another way in which BCT can support SCM in healthcare is through process improvements. One example is IBM's Hyperledger Fabric, which can connect all parties to the vaccine SC, such as manufacturers, government agencies, participating companies, and others. Each of these participants can view relevant information about the vaccine, such as its production and storage conditions, and related data [38] (p. 16). In this context, a vaccine SC monitoring model was proposed by Yong et al. (2020). In the model, vaccine tracking data is based on Ethereum Smart Contracts, enabling functions such as the notification of soon-to-expire vaccines. By analyzing the available trusted data, for example, the need for vaccines can be predicted [39] (p. 10). BC could also support SCM in pharmacy; since more trustworthy data are available through a BC, better and more meaningful analyses could be performed, such as in the discovery of trends [10] (p. 36503). Jayaraman et al. (2018) are considering a BC-based drug recall system because product recalls have increased in recent years [40].

Another application of BCT in healthcare that we found several times is the storage of patient data, so-called Electronic Medical Record (EMR) in a BC. Only if the treating physician possesses all the relevant information about his patient can they make the best possible decision between all treatment options. Various models for implementation have been promoted in research, including MedRec by Azaria et al., Healthcare Data Gateway (HGD) by Yue et al., MediBchain by AlOmar et al., or MeDShare by Xia et al. All of these models deal with the storage of patient data in a BC, but differ in their implementation, such as the BC type [41] (p. 1420). The main advantage resulting from this is that all parties involved have the current version of the patient data stored. If the data changes, it is stored between the doctors, the insurance company, and the patients as a transaction [7] (p. 4).

3.3.2. Current Problems of the Respective Areas

In healthcare, most data are critical because, in the worst case, health or human lives depend on it. On the one hand, patient data must be stored and made available to all concerned, and on the other hand, data about medications or vaccines must be stored. For these critical goods, the storage of production data, tracking and tracing data or data on storage conditions such as temperature could lead to a new quality. Currently, patients' medical records are stored in multiple locations and are rarely merged, which in the worst case could lead to treatment errors due to missing information.

3.3.3. Possible Value BCT Could Provide (+)—Pros of Implementing a BC

BCT can support SCM through data immutability, storing critical data in a very secure and immutable way. Immutable datasets could enable automated payments via Smart Contracts by sharing data with the insurer. The insurer might have an interest in this to prevent various types of fraud by preventing the critical data from being manipulated [7] (p. 4).

Palas and Bunduchi (2020) investigated the value of BCT for SCM by conducting an extensive literature review and combining the findings with an expert survey. As a result, for the value proposition of BCT, they identified improvements in the following: privacy and security; value capture, especially cost savings; and the value network, especially in data accessibility and the reduction of intermediation [42] (p. 1). Furthermore, BCs should generate a value proposition for healthcare by "enhancing privacy and security, offering more efficient management of health data, and, to a lesser extent, enhancing accountability, thus offering better services to patients" [42] (p. 34).

As a result of their expert survey, Palas/Bunduchi (2020) add the following points to these value propositions of BCT for healthcare that are already often mentioned in other studies. First, BCT should improve the quality of healthcare service delivery. Second, patients could be granted the opportunity to earn money with their data, through data sharing with studies. Third, social value can also be generated by reducing opportunities for fraud and supporting honesty and ethical behavior when sharing data [42] (p. 35).

3.3.4. Limitations and Challenges of BCT (−)—Cons of Implementing a BC

The general limitations and challenges of BCT such as the conflict between transparency, security, and privacy, also apply to the healthcare sector. The data to be managed are not only critical in terms of their correctness, but also very sensitive and must not be made public. In addition to the general limitations, the main problem in the healthcare sector is that BC is still at a very early stage in this area. There are no commercial applications of BCT so far and very few large studies. The actual value proposition of BCT can only be predicted in theory, as well as the actual total costs and disadvantages [42] (p. 3). The expected value proposition of BCT is therefore based on the expectations of actors and not on experience [42] (p. 13).

In healthcare, there are few very large and powerful players that would need to collaborate for a secure BC. Most of the anticipated benefits will only come to bear with a full implementation. Errors the storage of patient data must be eliminated from an implementation because, in the worst case, patients could be harmed. In addition, all existing patient data would first have to be transferred to the BC securely and without the possibility of manipulation.

3.3.5. Alternative Solutions without the Use of BCT

Patients' medical records are often distributed across several systems provided by different players. Merging and digitizing all patient data offers significant value in itself, which should not be directly credited to BCT. However, the merged data must be viewed and processed by many different healthcare providers, physicians, hospitals, insurers, and others, which creates many problems, including security and privacy [10] (p. 36503). In this area, a large, trusted provider that can guarantee data correctness and be held liable for errors could establish itself. The large provider could also make changes to the data set traceable without the BCT.

In Germany, for example, the elektronische Patientenakte (*electronic patient file*) was introduced in 2021. Since a large volume of relevant data is currently only stored in one place and often not even digitally, such as in file folders in doctors' offices, examinations often must be repeated. All 70 million people with public health insurance will soon be able to store important data, such as their vaccination record or allergy report, in this secure database. The insured person can decide whether and which of his or her data he or she would like to have stored digitally and can then determine who may access this data and for how long [43].

The elektronische Patientenakte (*electronic patient file*) is not based on BCT but on a central database in which access rights are restricted and the data is encrypted. With 70 million insured people, very large amounts of data are generated, which cannot be stored in a reasonable way with BCT.

Conclusion and assessment—BCT could theoretically solve some of the problems of the healthcare system. However, no case could be identified in which BCT is without alternatives, so it must compete with alternative solutions that do not include a BC. Furthermore, some participants demonstrate no interest in implementing a BC and the greatest value only exists with a very broad implementation of BCT. For example, the very high level of information in the medical field, such as diagnoses or prescriptions, could lead to resistance from some physicians because they may feel controlled or threatened in their autonomy [44] (p. 49653). In Germany, doctors are bound by a duty of confidentiality, and any solution must comply with this legal requirement, which could pose a challenge to the implementation of transparent BCs. In the healthcare sector, there is already a high level of trust among most participants, which speaks against a BC solution in tracking and tracing. In addition, many drugs are monopolized due to patents and manufacturer guarantees of quality.

4. Implications on the Added Value of BCT for Respective SCs

Within the literature analysis, the following clusters were analyzed in possible applications of BCT in SCM: Food SC, Health SC, logistical process, Luxury SC and other applications. Within the cluster of food SCs, a model for grain SC, the cooperation of Walmart with IBM, and the traceability of meat were presented in detail. The main objective found in this area was a need for traceability, either by making this data available to customers or allowing companies to make recalls more efficient. The study showed that a BC solution can help this area by providing the traceability data of companies anonymously while allowing the customer to enjoy high confidence in the data. However, it was concluded that BC is only suitable for this area in exceptional cases, especially in comparison to alternatives, because the trading volumes are very large and the value of most items is comparatively low. In addition, the interface between BCs and physical foodstuffs was identified as a problem, as it is often difficult to produce this type of interface. As an ideal case, we suggest that the interface should be as secure as the database itself to create a well-balanced system. In conclusion, no general need for a BC solution could be identified in the field of food SCs, due to the interface problem, high volumes, and low values. On the other hand, the customer must be able to appreciate the advantages of BCT, which would require an understanding of the complex technology.

Healthcare SCs were the second largest cluster found; in this case, there is a lot of critical data to be stored. A major concern in this area is to ensure the immutability, completeness, and correctness of the stored data. For healthcare in particular, the paradox of the trade-off between security resulting from transparency and the resulting lower level of data protection found by this thesis applies. Since data protection is a high priority in healthcare, trade-offs in BC security must be accepted. A major problem of BCT in this cluster is that like the network effect, the benefits of BCT are not evident until it is fully implemented. Until then, the impact of BCT can only be predicted in theory. Since some participants are not interested in joining the network or would like to be the last to join, full implementation is very unlikely unless legislation introduces an obligation. Further, especially when storing patient data, the amount of data is simply too large for BCT. When storing tracking data to verify the authenticity of a drug, no need for a BC solution could be identified. In the case of drugs, trust in the manufacturer is already assumed, so creating trust does not generate any additional benefits here. The verification of authenticity via a central solution or the manufacturer's own solution has a similar effect to a BC solution. In summary, no general need for a BC could be verified in the healthcare sector.

Luxury SCs manage valuable products, which are usually traded in relatively small quantities; thus, the advantages of BCT can be exploited effectively, according to the guideline of high value, low volume. With valuable products, trust is often a challenge, and laymen cannot verify the authenticity of many products. BCT can store traceability data securely so that the end customer can enjoy a high level of confidence in the data. In the area of luxury goods, a certain level of privacy is desired, as tracking data must not fall into the wrong hands. For this reason, permissioned BCs are also suitable in this area, where access is strictly limited. In the case of luxury goods, a secure interface with the BC can usually be created by clearly marking the goods. The additional costs for the interface are relatively low compared to the often-high total costs. In this area, most BC solutions are implemented in-house or, alternatively, trusted third parties are established. Nevertheless, most of the value proposition comes from the storage of the data by a trusted third party and not from the BCT. However, the customer could enjoy the advantage of greater security with a BC solution because it would ensure that older data could not be manipulated.

The identified clusters, Luxury, Food, and Health SC, can be analyzed according to strategic considerations in order to compare them with other possible fields of application. The strategic trade-offs can be evaluated in terms of the following needs and strategies: immutability of data, Smart Contracts, digital currency, traceability, visibility and transparency, privacy, value to be transferred, volume to be transferred, trust level, and cost sensitivity (See Table 2).

Table 2. General determination of the value of BCT for selected SC [45] (p. 28) (greatly modified).

Strategic Considerations and Requirements for:	Luxury SC	Food SC	Health SC	Evaluation
Immutability of data	high	low	high	Only if immutability has a high relevance is BCT worthwhile.
Smart Contracts	medium	low	medium	If Smart Contracts are desired, a BC solution must be considered.
Digital currency	high	depends on	depends on	If values are to be stored and transferred, cryptocurrencies should be considered as an alternative.
Traceability	high	high	high	Traceability data can be stored in any database. However, the BC can strengthen the confidence in traceability data.
Visibility and transparency	high	medium	high	For maximum security, the data set must be transparent.
Privacy	medium	low	high	Maximum privacy can only be realized at the expense of security.
Value to be transferred	high	low	mostly high	BCT is very suitable for high values
Data volume to be transferred	low	high	medium	and low volumes.
Trust level	low	high	high	The BC can ensure trust.
Cost sensitivity	low	high	medium	The more secure the solution, the more expensive it becomes.

Although BCT offers a value proposition that could theoretically offset the costs in many examples, successful implementations still do not exist, apart from cryptocurrencies. Bitcoin has now existed for 12 years and has thus demonstrated a very successful application of BCT. Therefore, parts of the research material are very critical towards a transfer of BCT to areas other than Bitcoin. Ammous (2016) summarizes that the only commercially successful application of BCT is digital cash, specifically Bitcoin. According to him, other applications have not made it out of prototype status because they cannot compete with the best practices currently available. He concludes from this observation that the redundancies in storing transactions and the expense of consensus algorithms can only be justified with digital money. With digital money, no interface with the outside world is necessary, because the money cannot exist without the BCT and, on the other hand, the amounts of data are very small. There is no application that exploits BCT as well as digital money because BCT was developed specifically for this purpose, according to Ammous (2016) there is no reason to expect that this very specific technology can be successfully implemented in other areas [46] (p. 5).

However, the authors of this paper are not as critical about the BCT because some use cases exist in which a low-cost implementation could have a benefit. Nevertheless, some identified BC solutions are so far away from the actual concept of BCT that the term BC, in the sense of a proof of work-based BC, such as Bitcoin's BC, no longer applies. For example, if a Trusted Third Party stores a BC centrally and no other participant stores the BC for cost reasons, this system relies on trust towards the Trusted Third Party. Older blocks could be changed without any problems, so the advantages of BCT are omitted in this example. The following decision tree (see Figure 2) can be used to assess whether a BC could be a potential solution for a specific application, although cost and marketing effects are not considered. If there is the potential for a successful implementation of a BC solution, the lower part of the diagram can be used to estimate which type of BC might be the right choice.

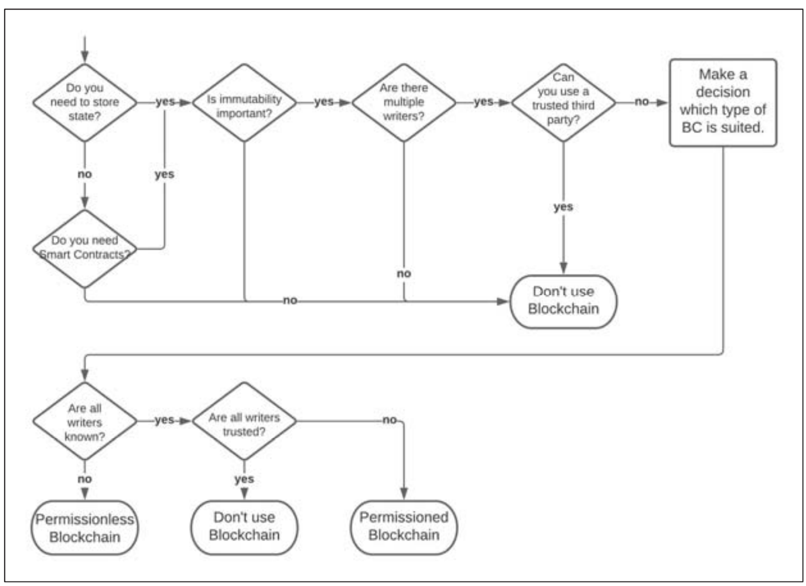

Figure 2. Decision tree on whether a BC is an appropriate technology for a use case [47] (p. 47) (greatly modified).

The implementation of a BC is a complex procedure, in which many individual aspects must be considered. The decision tree is intended to serve as a potential assessment, especially for companies that possess no expertise in BCT. The management of a SC should implement BCT not because the technology works in cryptocurrencies, is revolutionary and exerts a marketing effect but, rather, because it is more effective than its alternatives. According to Verhoeven et al. (2018), the best and most efficient technology should always be selected regarding a concrete problem, which requires a comprehensive understanding of the problem and the available technologies. In the case of BCT, however, it is often the other way around: some organizations seem to first choose a solution based on BCT and then to tune the problem with BC [27] (p. 18). This may be one reason for the low success rate of BC projects, as after one year, only 8% of started projects are still active [3].

5. Summary, Findings and Outlook

In summary, the study has shown that the application of BCT is especially beneficial for goods with a high value. The advantages of BCT are further augmented if, in addition, the trade volume of the goods is low. At the same time, SCs should be affected as little as possible by the following three key problems found with BCT. First, the interface between reality and the digital twin should be as secure as the database or BC solution. If a secure interface cannot be implemented with reasonable effort, a BC solution is not advisable, which is the case for many products. Second, the primary conflicting goals of BCT must not pose a significant problem; the demand for transparency and the immutability of data must be more important than the need to protect sensitive data. Third, SC participants must also be able to perceive and appreciate the benefits of BCT. Often, the end customer is the main beneficiary of an implemented BC. Understanding BCT is necessary for an increased willingness to pay, which must cover the increased costs. This knowledge cannot be taken for granted, especially in the mass market, and educating customers is often not profitable. In conclusion, the management of an SC should implement BCT not because the technology works in cryptocurrencies, is revolutionary, and exerts a marketing effect, but only if it is more effective than its alternatives.

No paper is without limitations. Due to space limitations, the much-described topic of BCT cannot be fully discussed, and this paper is no exception. Future research could follow up on the decision tree presented and add more decisions regarding the needs of the business, although this would be at the expense of clarity. In addition, further research could analyze how customers' knowledge of BCT affects the technology's value proposition, as only customers with a basic understanding of BCT can appreciate its benefits.

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From Traditional Product Lifecycle Management Systems to Blockchain-Based Platforms

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Abstract: *Background:* Several product lifecycle management systems (PLMs) have been implemented in the industrial sector for managing the data of the product from the design up to the disposal or recycling stage. However, these PLMs face certain challenges in managing the complex and decentralized product lifecycles. *Methods:* To this aim, this work investigates the currently implemented PLMs used in industries through the exploration of various software reviews and selection websites. Accordingly, these existing PLMs are quantitatively compared and analyzed. *Results:* The analysis shows that most of the existing PLMs do not contain all the required features; therefore, industries integrate different software to create a full-fledged PLM system. However, this practice results in reducing the overall system efficiency. In this context, this paper assesses and recommends a blockchain-based innovative solution that overcomes the challenges of existing PLMs, hence increasing the overall system efficiency. Furthermore, this work argues, in a logical way, that the recommended blockchain-based platform provides a secure and connected infrastructure for data handling, processing, and storage at different stages of the product lifecycle. *Conclusions:* This work can be considered among the first to compare the currently implemented PLMs with a novel blockchain-based method. Thus, the stakeholders can utilize the outputs of this research in their analysis and decision-making processes for implementing the blockchain in their organizations.

Keywords: product lifecycle management; blockchain technology; product development; decentralization; production system

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1. Introduction

Product lifecycle management (PLM) is the process of data management that directs the entire lifecycle of a product, from inception to its ultimate disposal or retirement. The core requirement for the PLM in the production industry is data storage and ensuring its fast, easy, and trouble-free processing for intelligent decision making in product development. PLM involves different stages of the product lifecycle, including design, production, distribution, operations, and maintenance, as well as disposal or recycling. In today's market, PLM has become a tactical solution for improving product competitiveness in the industry [1]. To compete successfully, the industries are constantly trying to implement a system that can efficiently collect and store the product data in real-time at a series of stages of the product lifecycle. The more data are collected from each phase of the product lifecycle, the greater the potential for product development. However, managing this large amount of data generated at various stages is not an easy task, and hence requires a proper management system.

To this aim, several PLM systems have been implemented and used in different industries. These systems are developed using a centralized and standalone framework and are usually responsible for data collection and management locally in their domain. However, in today's cyber-physical age, the aim in the industries is not just the data collection, but the ability to connect the collected data in a sophisticated way that can easily be used for training the intelligent learning models. Simultaneously, the objective is to convert the data managed by the concerned personnel into the industry's capital in an easily manageable and shareable form [2]. In other words, work that has once been performed on the product at any time and phase shall remain exploitable. However, the existing systems are unable to allocate the data to the individually customized product. Therefore, there is a need to holistically gather the data generated at different stages so that it can be allocated to each product and concerned customer.

Furthermore, currently, product lifecycles are usually complex and decentralized in nature. Hence, the data need to be transparent and auditable so that every stakeholder has access and can exchange the data with all the associated parties. A new data management system needs to be implemented that can address and solve the data transparency and auditability challenges. For this purpose, blockchain, a shared and immutable ledger, can be used to facilitate the process of recording transactions and tracking assets in a business network [3]. In a blockchain, the transactions are recorded, protected, proofed, stored, and shared with all the participants of the chain. Hence, all the stakeholders can permanently exchange the data that are important from their perspectives. In comparison to the traditional PLM approaches, a blockchain has distinct characteristics, i.e., it is a secure, decentralized, and distributed ledger. Each member of the chain can access it from anywhere in the world using an internet connection, which leads to greater transparency and auditability. A blockchain allows the data to be tracked in an inviolable way, making it possible to go back through the entire history of the product lifecycle [4].

In this work, we aim to explore the currently implemented PLMs. These existing PLMs are quantitatively compared and analyzed regarding certain basic features and characteristics that are the core requirements of any system. Then, problems associated with those PLMs are highlighted and an alternative solution is presented that can solve these problems. In other words, this work is a systematic review that highlights and emphasizes the specific issues with data management and recommends a novel solution for those issues. For this purpose, the research questions that this paper aims to answer are:

- What are the currently implemented PLMs, and what features do those PLMs contain?
- Do blockchains address the same purpose and functionalities as those of existing PLMs?
- Why are blockchain-based platforms better and hence, recommended over the traditional PLMs?
- How does the proposed solution enhance the efficiency of the production system?

The rest of the paper is organized as follows: The currently implemented PLMs are explored and evaluated in Section 2. Section 3 provides the conceptual background and basics of the blockchain technology. The recommended blockchain-based platform is presented in Section 4. Section 5 consists of the discussion and benefits of the recommended platform. Finally, this work is summarized in Section 6.

2. Exploration of Traditional PLMs

During the exploration of various software reviews and selection websites, a total of 135 PLM systems currently implemented in industries have been determined. All of these 135 systems are deployed on-cloud; however, 23 of them provide on-premises services as well. The features of the software using both systems are the same; however, the difference is in the data storage policy. The on-cloud database is hosted on the vendor's server and can only be accessed through the web browser. While in the on-premises scenario, the software is installed on the industry's databases and servers so that the generated data are managed locally by the industry itself. A detailed quantitative comparison of existing PLMs in the industries is carried out and is provided in Appendix A. Some considerations that have been implemented during the process of exploration can be pointed out as:

- Depending upon the vendor, features, and size, the PLM systems are available in different price ranges. However, this survey considered PLMs of all price ranges.
- Different systems are suitable for use in different sized industries. However, we considered all PLMs, irrespective of their implementation in the respective industry.

- The supported language in most of the PLMs is English; however, some systems support other languages as well. This study considered PLM in all languages.
- Only those PLMs that contains at least three basic features are considered in the comparison.
- The type of production system in which these PLM are implemented, i.e., mass, batch, or job shop production is also ignored in this comparison.

It is observed from the data presented in Appendix A that most of the PLMs do not include all the required features; therefore, the software vendors usually offer a list of applications that may be integrated with each other to form a complete PLM system. However, in this case, data exchange would be slow and time-consuming. The time required for data conversion from one system to another becomes high, reducing overall system efficiency. Table 1 summarize the number of currently implemented PLMs that are capable of supporting specific basic features. In the literature, the existing research publications consider only a limited number of existing PLMs in their analysis and are unable to take all the available PLMs into account. Therefore, searching using internet search engines could be considered a more sophisticated method, and hence is used in our exploration process. Therefore, the data of Appendix A and Table 1 are based on our search using various search engines, i.e., SelectHub [5], G2 Business software and services [6], Software TestingHelp [7], Capterra [8], PAT Research [9], and Adam Enfroy [10]. Furthermore, as these search engines are usually amended and updated on a regular basis, exploration via these websites leads to the latest list of existing PLMs.

Table 1. Number of PLMs targeting specific features.

Features	Number of Capable PLMs	Number of Incapable PLMs
Change Management	57	34
Design Management	54	44
Document Management	24	51
Project Management	29	42
Product Data Management	78	101
Requirements Management	81	91
Quality and Compliance Management	111	84
Supplier Management	106	93

It is quite clear from Table 1 that document management is the feature that most of the existing PLMs carry (a total of 111 PLMs), while change management is the most challenging feature and is carried by the least number of PLMs (a total of 78 PLMs). In addition to the basic features of PLMs, as described earlier, some software also carries additional capabilities. Enriquez et al. considered some of the top PLM systems and evaluated extra features in those systems at different stages, i.e., from "design" up to "after-sales management," as illustrated in Table 2 [11]. Furthermore, they also presented some of the applications that can be integrated into the respective PLM to achieve specific tasks.

In addition to the extra features mentioned in Table 2, these PLMs are also highly scalable. Hence, these systems have the ability to grow and manage the increasing needs and demands of the consumers. Furthermore, these top PLMs also focus on the appropriate use and governance of data that is being generated, collected, and shared by different stages.

Table 2. Extra features included in top PLMs [11] "Adopted with permission from Enriquez et al. (2018). Copyright © 2018 Elsevier".

Extra Features	Enovia	Teamcenter	Windchill	CATIA	ARAS	Oracle
Design						
Compliance, environment, health and safety management	Yes	Yes	Yes	Yes	Yes	Yes
Product analysis, validation, and simulation	Simulia	TecnoMatrix	PTC Creo	Yes	Yes	Yes
Authoring Tools: CAD, CAE, CAM, ECAD, CASE . . .	CATIA/SW	NX/Sedge	PTC Creo	Yes	Yes	Yes
Multi-CAD management	Yes	Yes	Yes	Yes	Yes	Yes
Software development	Partially	Partially	No	Yes	Yes	Yes
Technical documentation	Yes	Yes	Yes	Yes	Yes	Yes
Technology planning	Partially	Partially	No	No	No	No
Production						
Digital manufacturing	Simulia	TecnoMatrix	No	Yes	Yes	No
PLC programming	Delmia	TecnoMatrix	No	Yes	No	No
Support/Use						
After-sales management	Partially	Partially	Partially	No	Yes	No
Marketing	3D Excite Mar	No	No	No	No	No
General						
Intellectual property management	Yes	Yes	Yes	Yes	Yes	Yes
Quality lifecycle management	Yes	Yes	Yes	Yes	Yes	Yes
Communities of practice	Yes	Yes	Yes	Yes	Yes	Yes
Infrastructure management	Yes	Yes	Yes	Yes	Yes	Yes
Distribution	Partially	Partially	No	No	Yes	Yes

3. Fundamentals of a Blockchain

A blockchain is a digital, decentralized, and immutable ledger maintained by different computer nodes that facilitate the process of recording transactions and tracking assets in a business network [3]. The transactions are recorded in a data format called "block" and added to a shared database in chronological order to form a chain [12,13]. The transaction data in the block is validated by all the nodes in the network before its addition and storage on the chain [14–16]. A simple structure of a blockchain consisting of linked blocks is illustrated in Figure 1. The first block is usually referred to as a genesis block, followed by other blocks [17]. Each block mainly consists of three metadata, i.e., the pointer or hash that connects it to the previous block, the timestamp that certifies the time at which the transaction takes place, and the transaction data. Hashing of each block makes the complete chain an immutable ledger, so that the blocks can only be added and not removed from the chain [18]. In this way, the data is recorded, protected, proofed, stored, and shared with all the participants of the chain, which is the basic concept of a blockchain.

In general, there are three types of blockchain networks: public, private, and consortium blockchains. Public blockchains are permissionless in nature, and are therefore open for anyone in the world to access, perform transactions, and participate in the consensus process [19]. The blockchain concept presented by Satoshi Nakamoto in 2008 is an example of a public chain [20]. Private blockchains are permissioned blockchains controlled by a single central authority. The central authority permits the nodes who can join and perform the transaction. Hyperledger fabric, hosted by the Linux Foundation, is an example of a private blockchain [21]. Consortium blockchains are also permissioned blockchains, but instead of a single authority, they are controlled by a group of preselected nodes [22]. Consortium blockchains are more decentralized compared to fully private blockchains, and hence provide higher security. The global shipping business network (GSBN), developed by CargoSmart, is an example of a blockchain consortium that aims to digitalize the shipping industry, allowing maritime industry operators to work more collaboratively.

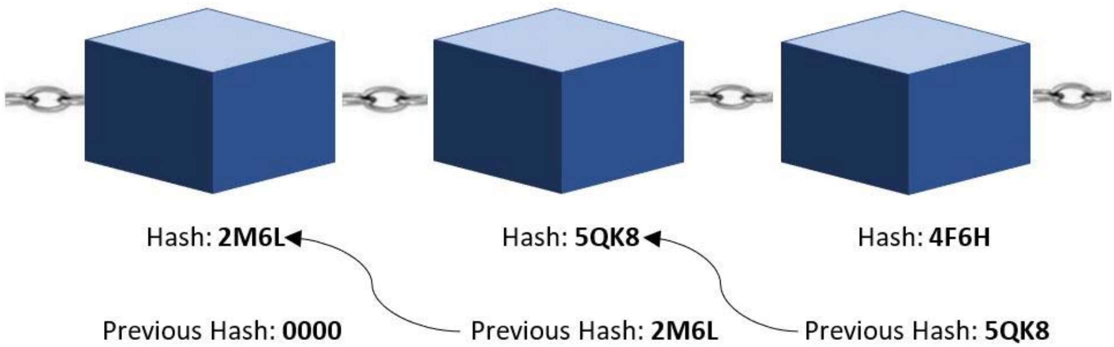

Figure 1. A structure of a blockchain consisting of linked blocks.

A blockchain is a digital platform that changes the way traditional databases store and record data and transactions [23]. In comparison to traditional ledgers, blockchains have distinct characteristics, i.e., they are secure, distributed, and decentralized in nature. Using an internet connection, each participant in the chain can access it from anywhere in the world, leading to greater transparency and auditability. A blockchain allows the data to be tracked in an inviolable way, making it possible to go back through the entire history of the product lifecycle. Hence, all the participants of the chain can permanently exchange information that is important from each perspective. Moreover, since all the permitted members of the network control each other, unlike in traditional ledgers, no intermediary or central point of account is needed [24]. A blockchain is more suitable to use in cases where the data requires clear identification and verifications. Furthermore, the use of blockchain technology is especially beneficial in the case of high value products with low trading volume [25].

Currently, an increasing number of initiatives in the blockchain are altering the traditional approaches in each sector. However, most of the research work available on blockchains focuses on cryptocurrency, i.e., over 80% of the research articles on blockchains are based on crypto, while less than 20% target other blockchain applications [26]. Moreover, most of the current work on the blockchain in the real business environment is still in an early stage, i.e., at the concept or idea phase [27]. However, it is strongly expected by the experts that the blockchain will target every industry and significantly change the existing approaches [12,15,28]. According to the report by the Statista research department, published on March 18, 2022, investment in blockchain-based solutions is expected to reach almost $19 billion by 2024 (https://www.statista.com/statistics/800426; accessed on 20 April 2022). Blockchains would be able to track $2 trillion worth of tangible and intangible goods in their supply across the globe by 2023, and accordingly, it will be an over $3 trillion business by 2030 [29].

4. Conceptualization of a Blockchain-Based Architecture

In this section, we present the concept of a blockchain-based platform that can be considered as a novel solution to the challenges faced by the existing PLMs. This platform contains all the basic and extra features of traditional PLMs. The conceptual framework for the proposed platform is shown in Figure 2. This platform connects all the phases of the product lifecycle from the design up to the disposal or recycling of any product; hence, the data can be visible and accessible to every stakeholder associated with the product throughout its lifecycle. Moreover, as the blockchain is an immutable ledger, the data in this presented platform would be secured and impossible to manipulate or forge. Hence, this can be considered a robust solution for safeguarding the data generated and shared among the stakeholders throughout the product lifecycle.

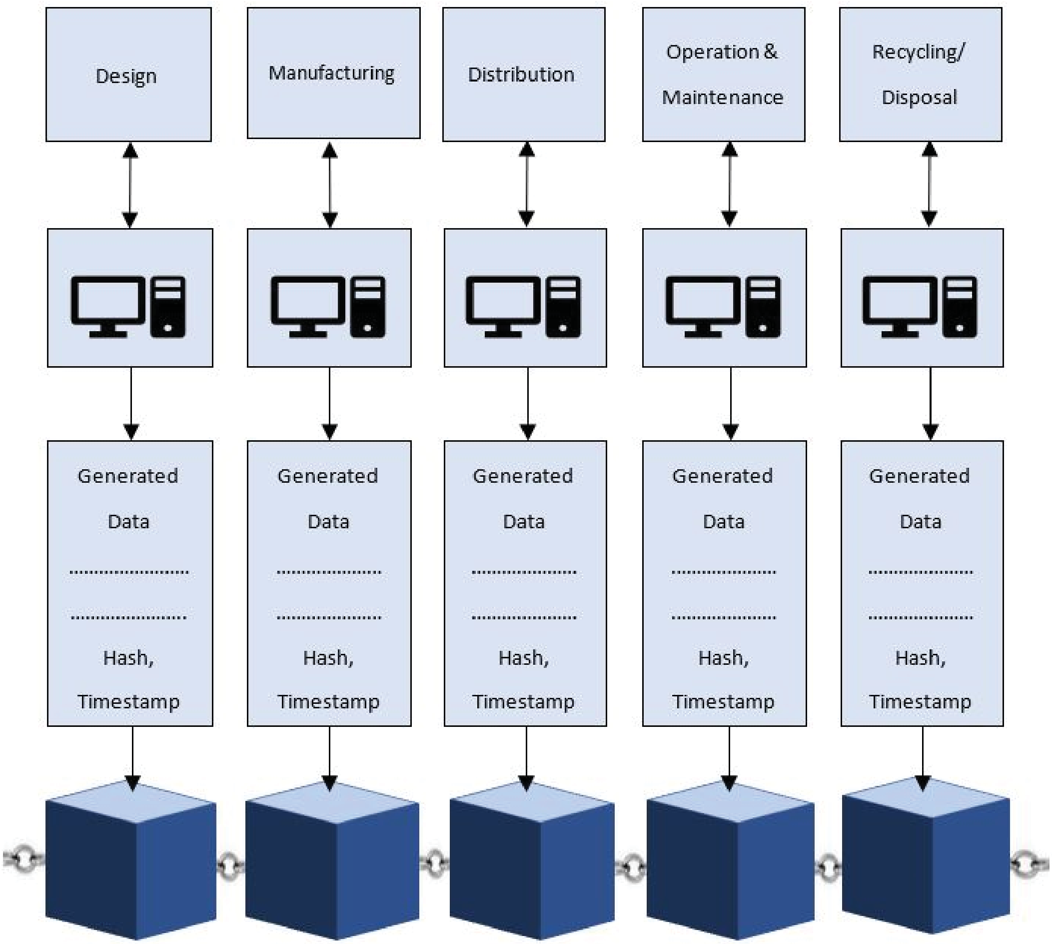

Figure 2. Conceptual Framework for a Blockchain-Based Platform.

The fundamental layers in this solution are similar to those of traditional PLMs, i.e., the physical and digital environment, digital data, and storage database. The physical environment consists of different stages of the product lifecycle where actual tasks are performed. The data generated through these tasks is converted to a digital form and stored in the database, which is blockchain-based, in this case. The data is validated by concerned nodes according to the defined protocols, and then it is stored and becomes part of the chain. This platform provides data access, along with advanced data analytics, to all stakeholders involved at different stages of the product lifecycle. Hence, all the stakeholders can permanently exchange the data from their perspectives.

Although the fundamental concepts in implementing blockchain technology in any industry are the same, as different industries may have different policies and working environments, every setup would require setting the basic strategies according to their own conditions. These strategies may be:

- Defining or choosing the suitable consensus protocols: A blockchain consensus protocol enables all the parties of the blockchain network to come to a common agreement on the present data state of the ledger. The business can define its own, or can choose from well-known available protocols. In case of the production industry, Byzantine fault tolerance, or crash fault tolerance, are the most commonly used consensus protocols.
- Selecting the suitable blockchain platform: Depending upon the chosen consensus protocols, industries can then select the most suitable blockchain platform. Many free and open-source blockchain platforms are available. In case of the production industry, the commonly used private blockchains are Hyperledger Fabric, Corda, and so on.
- Configurations of the blockchain instance: Blockchain platforms usually require very carefully planned configurations for different parameters. Some of these key parameters, i.e., permissions, hashes, block signatures, etc., can be configured and finalized by the individual businesses according to their own policies.

To clarify how the data generated at each stage is stored on the selected blockchain platform, we consider the manufacturing phase of the product lifecycle, as shown in Figure 3. In this stage, the raw material is processed through certain machines to create a finished product. The machines and processes in this stage depend on the type of manufacturing (conventional or additive), as well as on the type of product.

Initially, the data of raw material, i.e., its type, properties, suppliers, etc., are uploaded to the production database. During the manufacturing process at machine 1, all the information of the machine, materials, and process parameters are drawn up in a local database, digitally signed, and uploaded to the main production database by concerned personnel, such as the machine operator. The processed material is forwarded to the next machine as a work-in-process inventory for onward processing, and the same procedure of data generation, digital signature, and uploading is followed at machine 2, and so on. Once all the operations are performed and the production is completed, a complete production report is ready. The production manager checks to verify the data stored in the database and then hashes, timestamps, and shares them. Once the data are validated as per the consensus protocols, they then become part of the chain. The data of specific products and production processes in this specific phase of the product lifecycle are stored and become visible to all the stakeholders.

In this way, the block in this phase is created each time the production of a product is completed. In any blockchain platform, each block consists of two parts, i.e., the block header and the block body. In this phase, the block header has three elements, i.e., block version, timestamp, and a hash of the corresponding previous block. The block body in this phase caries the complete information of raw material, machines, processes parameters, as well as finished product data. The proposed blockchain-based platform is compared with the traditional PLMs, and the final results are given in Table 3.

The comparison in Table 3 summarizes that the blockchain-based platform contains all the features of the traditional PLMs. Moreover, the proposed platform also exhibits other unique characteristics that, in contrast, are challenges faced by traditional PLMs. Hence, we can use this blockchain-based platform to more securely and easily manage the data of products and create a bridge to link the data throughout its lifecycle.

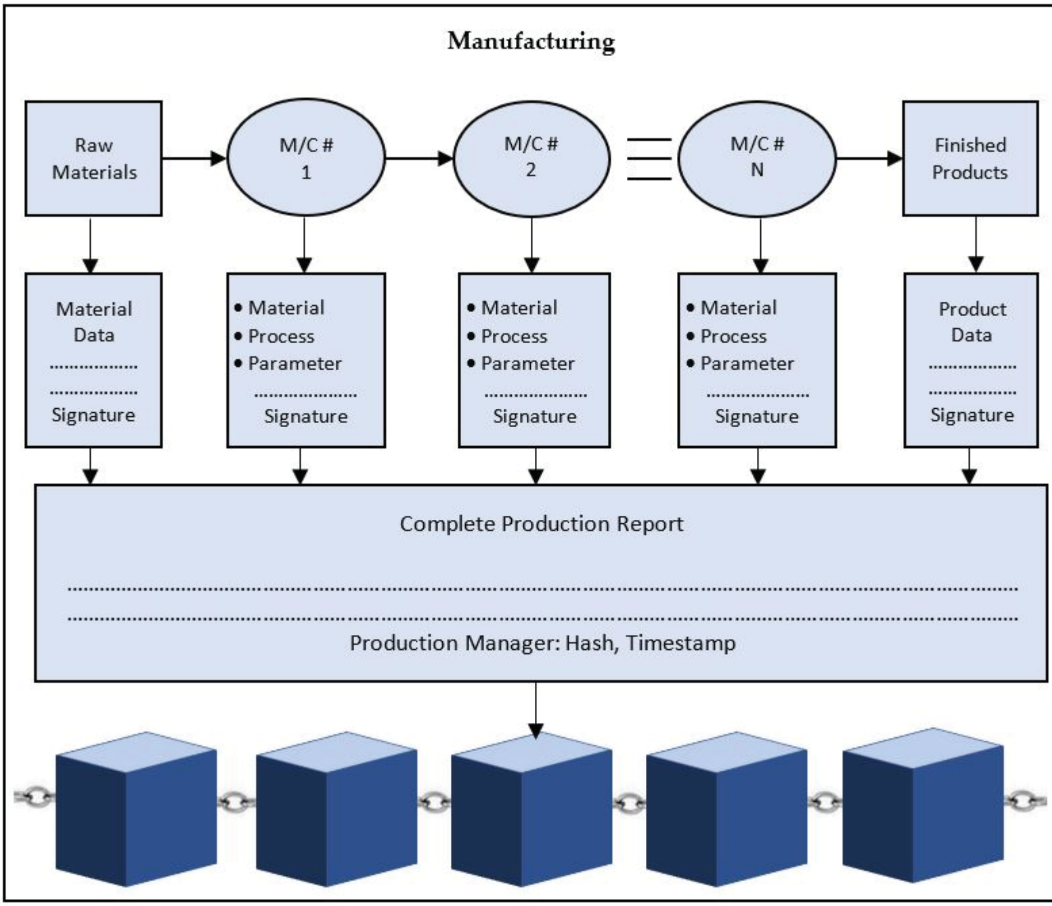

Figure 3. Data storage on the blockchain.

Table 3. Comparison between Traditional and Blockchain-Based PLMs.

Characteristics	On-Premises PLMs	On-Cloud PLMs	Blockchain-Based PLM
Basic Features (Table 1)	Yes	Yes	Yes
Extra Features (Table 2)	Yes	Yes	Yes
Interoperability	No	No	Yes
Data Transparency and Openness	No	No	Yes
Flexibility	No	Yes	Yes
Scalability	Yes	Yes	Yes
Decentralization	No	No	Yes
Software as a Service	No	Yes	Yes
Credibility	No	No	Yes
Big-Data Analytics	No	Yes	Yes
Ubiquitous Access	No	Yes	Yes
Collaborative Data Provision	No	No	Yes
Data Security	No	No	Yes

5. Discussion and Benefits of the Proposed Solution

Traditional PLMs, whether on-cloud or on-premises, offered by different vendors are centralized in nature and hence, face certain challenges in real-life production systems. Moreover, the quantitative comparison shows that most of these systems do not contain all the required features that a standard PLM tool should carry. Therefore, industries usually implement different PLMs and integrate them to create a complete PLM system. However, the data exchange between these different PLM tools is usually slow and time-consuming, reducing overall system efficiency. Additionally, due to the complex and decentralized nature of product lifecycles, the data needs to be transparent and auditable so that every stakeholder has access to and can exchange authentic data with all the other parties.

To meet all these requirements and features in a single system, we proposed a digital blockchain-based platform. This solution illustrates how various phases of the product lifecycle, from the design up to the disposal or recycling of any product, can be connected for data sharing. Through detailed elaboration, this paper determined that the proposed platform contains all the features of the traditional PLMs. Moreover, as illustrated in Table 3, this platform also has other distinct characteristics that the traditional PLMs lack. This study takes system-to-system shuffling into account and does not consider a specific blockchain-based platform. Therefore, in the near future, we can use any analytic technique, i.e., combined VIKOR-fuzzy AHP [30], to select among the available blockchain-based platforms. Once the specific blockchain-based platform is selected and implemented for PLM, we would then be able to compare the actual results with the previous studies, based on certain key performance indicators (KPIs). In addition to the features discussed in this paper, the KPIs could also be set for certain other dimensions, i.e., coercive and non-coercive drivers of sustainability [31], cleaner production [32], and so on.

Through the implementation of this platform, several benefits can be achieved in a real production environment. As the blockchain is an immutable ledger, the data in this presented platform would be secured and impossible to manipulate or forge. Hence, this model is considered to be a robust solution for safeguarding the data generated and shared among the stakeholders throughout the product lifecycle. This platform allows the data to be tracked in an inviolable way, making it possible to go back through the entire history of the product lifecycle. As the data is visible and accessible to every stakeholder associated with the product, it therefore provides an opportunity for a collaborative decision-making environment in product development. Hence, all the stakeholders can work continually on collaborative tasks throughout the product lifecycle. This collaborative environment results in:

- Better data management;
- Production agility and resiliency;
- Drive innovation;
- Improved production and performance;
- Continuity and traceability of information.

Real-time communication throughout different stages of the product lifecycle and data representation is of prime importance for planning and better decision making during product development. Therefore, this solution tends to reduce obstacles, creating an easy-to-communicate environment that is not possible through the use of centralized PLMs. All the blockchain platforms provide ubiquitous access, so they can be accessed from any device and any location with just an internet connection. This platform has specific attributes, i.e., availability, effectiveness, reliability, security, real-time, maintainability, and survivability, and hence it can be considered a highly credible system. Furthermore, large and intermittent data are usually generated in a complex and distributed product lifecycle, so the traditional PLMs sometimes face issues in handling such data. As the proposed solution is based on a distributed ledger, intermittent and large data can be easily handled and stored chronologically.

6. Conclusions and Future Directions

This work aims to explore and evaluate the currently implemented PLMs and accordingly recommends a novel platform to overcome the challenges faced by these PLMs. A total of 135 currently implemented PLMs and their associated features were identified through the exploration of various search engines, as given in Appendix A. Through the evaluation, it was observed that most of the existing systems do not contain all the required features; therefore, industries usually integrate different tools to create a full-fledged PLM system. However, this results in reducing overall system efficiency. Furthermore, we highlighted various challenges associated with these centralized PLMs in Table 3. Among these challenges, data security, transparency, and interoperability are the most important, since today's data management is not limited to a specific phase, but requires collaborative tasks. To succeed in these challenges, this paper emphasizes the need to adopt a novel technology for production industries.

Consequently, we present and recommend a blockchain-based platform that can solve all the challenges faced by the existing PLMs. The proposed blockchain-based platform addresses the same purpose as those of the existing PLMs. In addition to the basic features of traditional PLMs, this platform also contains other distinct characteristics, as illustrated in Table 3. Therefore, we strongly recommend it over traditional PLMs for more securely and easily managing product data. Industries can use this platform to more accurately assess their product use, performance, and product maintenance cycles, enabling more intelligent decisions. This may lead to improving the system efficiency in terms of flexibility, optimizing product design, and improving product functions. Moreover, with the ever-increasing need for connectedness and security, the proposed blockchain-based platform provides a framework for organizing and securing the data generated at different phases of the product lifecycle. This work also helps in clarifying how industries exploiting the blockchain method can build a secure and connected production infrastructure.

To conclude, this work highlights and emphasizes the specific challenges with the existing data management systems and recommends a novel blockchain-based solution to overcome those challenges. The recommended solution improves product lifecycle management, and hence plays a vital role in the collaboration process. Finally, the blockchain solution offers versatile capabilities and can be applied in any production industry.

Future work could explore of the existing blockchain-based platform that can be used for product lifecycle management. Moreover, defining the proper criterion and then selecting among the available alternative platforms, using any analytic technique, may be of interest for future contributions.

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Appendix A Quantitative Comparison of Existing PLMs

S. No	PLM Software	Change Mgmt	Design Mgmt	Document Mgmt	Project Mgmt	Product Data Mgmt	Requireme-nts Mgmt	Q and C Mgmt	Supplier Mgmt
1	* Coats Digital	No	Yes	Yes	No	Yes	No	No	Yes
2	* Jama Connect	Yes	No	Yes	Yes	Yes	Yes	Yes	No
3	* SpiraTeam	Yes	No	Yes	Yes	No	Yes	Yes	No
4	* Odoo	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5	* Jira	Yes	No	Yes	Yes	No	Yes	Yes	No
6	* Airtable	No	No	Yes	Yes	No	Yes	No	Yes
7	* Sage 100 Cloud	No	No	Yes	Yes	No	No	Yes	Yes
8	* Delteck Costpoint	No	No	Yes	Yes	No	No	Yes	Yes
9	* Quip	Yes	No	Yes	Yes	No	Yes	No	Yes
10	* Kinetic	No	No	Yes	Yes	Yes	No	Yes	Yes
11	* CATIA	No	Yes	No	Yes	No	Yes	No	No
12	* MasterControl QE	Yes	Yes	Yes	Yes	No	No	Yes	Yes
13	* Assembla	No	No	Yes	Yes	No	No	Yes	No
14	* Genius ERP	No	No	Yes	Yes	No	No	Yes	Yes
15	* Creo	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
16	* SyteLine	Yes	No	Yes	Yes	No	No	Yes	Yes
17	* Infor M3	Yes	No	Yes	Yes	No	No	Yes	Yes
18	* BlueCherry	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
19	* Momentis Fashion Sys	Yes	Yes	Yes	No	Yes	Yes	No	Yes
20	* ProdPad	No	Yes	Yes	Yes	No	Yes	No	No
21	* BlackBelt Fusion	No	Yes	No	No	Yes	No	Yes	Yes
22	* CodeScene	No	No	No	Yes	Yes	Yes	No	No
23	* Exenta	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
24	Arena PLM	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
25	Enovia	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
26	monday.com	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
27	Aha!	Yes	Yes	Yes	Yes	Yes	Yes	No	No
28	Wrike	Yes	No	Yes	Yes	No	Yes	No	Yes
29	Logility	No	Yes	Yes	Yes	No	Yes	Yes	Yes
30	Arbortext	No	Yes	Yes	Yes	Yes	Yes	No	Yes
31	Trello	No	No	Yes	Yes	No	Yes	No	No
32	beCPG PLM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
33	Space	Yes	No	Yes	Yes	Yes	Yes	No	No
34	PDXpert PLM	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
35	Canny	No	No	No	No	No	No	No	No
36	ClickUp	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
37	FusePLM	Yes	No	Yes	No	Yes	Yes	No	Yes
38	TARA	No	No	Yes	Yes	No	Yes	No	No
39	QM Software	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
40	Trace One PLM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
41	LaunchDarkly	Yes	No	No	No	Yes	Yes	No	No
42	Infor Visual	Yes	No	Yes	Yes	Yes	No	Yes	Yes
43	NetSuite WMS	Yes	No	Yes	Yes	Yes	No	Yes	Yes
44	Productboard	No	No	Yes	Yes	No	Yes	No	No

S. No	PLM Software	Change Mgmt	Design Mgmt	Document Mgmt	Project Mgmt	Product Data Mgmt	Requireme-nts Mgmt	Q and C Mgmt	Supplier Mgmt
45	Teamcenter	Yes	Yes	No	Yes	No	Yes	Yes	Yes
46	UserVoice	No	No	No	Yes	Yes	Yes	No	No
47	aPriori	No	Yes	No	No	Yes	No	No	Yes
48	Backbone	No	Yes	Yes	No	Yes	Yes	No	Yes
49	Style Arcade	No	Yes	Yes	Yes	Yes	No	No	Yes
50	Craft.io	No	Yes	No	Yes	Yes	Yes	No	No
51	Anvyl	Yes	No	Yes	Yes	Yes	No	Yes	Yes
52	ACE PLM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
53	One Click LCA	No	Yes	No	Yes	Yes	No	Yes	No
54	ApparelMagic	No	Yes	No	Yes	Yes	Yes	No	Yes
55	Dot Compliance	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
56	SAP PLM	No	No	Yes	Yes	Yes	Yes	Yes	Yes
57	Planview Enterprise	No	No	Yes	No	No	No	Yes	No
58	Chronos	No	No	Yes	Yes	Yes	Yes	Yes	Yes
59	BQUADRO	No	No	Yes	Yes	Yes	No	Yes	Yes
60	Primary	No	Yes	No	No	Yes	Yes	No	No
61	Indigo8	No	Yes	Yes	No	Yes	Yes	No	Yes
62	Surefront	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
63	Autodesk Fusion Lifecycle	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
64	Aras	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
65	Aligni	Yes	Yes	Yes	No	Yes	No	No	Yes
66	Ciiva	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
67	3 Clicks Cloud	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
68	DevSuite	Yes	Yes	Yes	Yes	No	Yes	No	No
69	CMPRO	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
70	SyncForce	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
71	Zdesign	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
72	WFX PLM	No	Yes	Yes	No	Yes	Yes	No	Yes
73	EasyKost	No	Yes	No	Yes	Yes	No	No	Yes
74	PDM Dashboard for JIRA	Yes	No	Yes	Yes	Yes	Yes	No	No
75	STEP	No	No	Yes	No	No	No	No	No
76	ProductCenter	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
77	Centric PLM	Yes	Yes	No	No	Yes	No	Yes	Yes
78	Gatherspace.com	Yes	No	Yes	No	Yes	No	No	No
79	TD/OMS	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
80	Windchill	No	Yes	No	Yes	Yes	No	No	No
81	DevEX	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
82	Optiva	No	No	No	Yes	Yes	No	Yes	No
83	4G: PLM	Yes	Yes	Yes	No	Yes	No	No	Yes
84	Collaborate Cloud	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
85	DesignWin	Yes	No	Yes	Yes	Yes	No	Yes	Yes
86	PowerSteering	Yes	No	Yes	Yes	No	Yes	No	No
87	Prodigy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
88	Propel PLM	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
89	QuadRite	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
90	SourceHUB	Yes	No	Yes	Yes	Yes	Yes	No	Yes

S. No	PLM Software	Change Mgmt	Design Mgmt	Document Mgmt	Project Mgmt	Product Data Mgmt	Requireme-nts Mgmt	Q and C Mgmt	Supplier Mgmt
91	Woises	No	Yes	Yes	Yes	Yes	Yes	No	No
92	ChainReaction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
93	Lectra Fashion PLM	No	Yes	Yes	No	Yes	Yes	No	Yes
94	Upchain PLM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
95	YuniquePLM	No	Yes	No	Yes	Yes	No	Yes	Yes
96	DeSL	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
97	VisualNext	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
98	4PACK	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
99	Sopheon Accolade	No	Yes	No	Yes	Yes	No	No	No
100	Actify Centro	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
101	ARG Sourcing	No	Yes	Yes	No	Yes	No	Yes	Yes
102	Aptean PLM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
103	ARC Facilities	Yes	No	Yes	Yes	Yes	Yes	Yes	No
104	Bamboo Rose	No	No	No	No	Yes	Yes	No	Yes
105	Channel Plus	No	No	Yes	Yes	Yes	Yes	Yes	Yes
106	CIM Database PLM	No	Yes	Yes	Yes	Yes	Yes	Yes	No
107	Collaboration Desktop	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
108	Copy5	No	No	Yes	Yes	Yes	Yes	No	No
109	Duro	Yes	Yes	Yes	No	Yes	No	No	Yes
110	EdgeAX	Yes	Yes	No	No	No	No	No	Yes
111	Emissions Calculator	No	No	Yes	No	No	No	Yes	Yes
112	Factor	No	Yes	Yes	Yes	No	Yes	Yes	Yes
113	iasset.com	No	No	Yes	No	No	No	No	No
114	IFS EAM	No	No	Yes	Yes	Yes	No	Yes	Yes
115	Ignimission Platform	No	No	Yes	No	No	No	Yes	No
116	OpenPDM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
117	Pattern Design	Yes	Yes	No	Yes	Yes	Yes	No	No
118	PDMPlus	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
119	PLATO SCIO FMEA	Yes	No	Yes	Yes	No	Yes	Yes	No
120	PDM Dashboard	No	No	Yes	Yes	No	Yes	No	No
121	ProEvolve	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
122	ProjectOne	No	No	No	Yes	Yes	Yes	No	No
123	QADEX Vision	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
124	QATrax	Yes	No	Yes	Yes	Yes	No	Yes	No
125	RegulatoryOne	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
126	reINVENT	No	Yes	Yes	Yes	Yes	No	No	Yes
127	Seerene	Yes	No	No	Yes	No	Yes	Yes	Yes
128	SG Benchmarker	Yes	Yes	No	No	Yes	No	No	No
129	Sharp PLM	Yes	No	Yes	Yes	Yes	No	No	No
130	Skyjed	No	No	Yes	No	Yes	No	Yes	Yes
131	SoftExpert PLM Suite	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
132	Specright	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
133	Wave PLM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
134	Jile	No	No	Yes	Yes	Yes	Yes	Yes	No
135	keytech PLM	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes

* These PLMs provide both on-cloud and on-premises services.

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logistics

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Review

Blockchain Technology in the Food Industry: A Review of Potentials, Challenges and Future Research Directions

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Abstract: Blockchain technology has emerged as a promising technology with far-reaching implications for the food industry. The combination of immutability, enhanced visibility, transparency and data integrity provides numerous benefits that improve trust in extended food supply chains (FSCs). Blockchain can enhance traceability, enable more efficient recall and aids in risk reduction of counterfeits and other forms of illicit trade. Moreover, blockchain can enhance the integrity of credence claims such as sustainably sourced, organic or faith-based claims such as kosher or halal by integrating the authoritative source of the claim (e.g., the certification body or certification owner) into the blockchain to verify the claim integrity and reassure business customers and end consumers. Despite the promises and market hype, a comprehensive overview of the potential benefits and challenges of blockchain in FSCs is still missing. To bridge this knowledge gap, we present the findings from a systematic review and bibliometric analysis of sixty-one (61) journal articles and synthesize existing research. The main benefits of blockchain technology in FCSs are improved food traceability, enhanced collaboration, operational efficiencies and streamlined food trading processes. Potential challenges include technical, organizational and regulatory issues. We discuss the theoretical and practical implications of our research and present several ideas for future research.

Keywords: blockchain technology; food supply chain; potentials; challenges; systematic literature review; bibliometric analysis

1. Introduction

The globalization of food supply chains (FSCs) and markets has led to a significant increase in products and information movements between countries [1]. Traditional FSCs are characterized by strong vertical integration and coordination among supply chain partners to promote efficiency, for example, by lowering transaction, operating and marketing costs and fulfilling consumer needs for food quality and safety [2]. Therefore, FSC exchange partners have found themselves under increasing pressure to improve the transparency of their supply chains, enhance the exchange of trusted information, and improve the tracking and tracing capability (henceforth traceability) of agricultural products from farms through to retailers [3–5].

Additionally, the traceability of food products and overall supply chain transparency has become critical due to multiple scandals occurring in global FSCs (e.g., the horsemeat scandal in Europe, the melamine scandal in China). The need for effective traceability has intensified as regulations require that every ingredient of a food product is traceable to its source [6]. Consumer demand has led to the year-round availability of many agricultural products and intensified the pressure on businesses to provide details on product-specific attributes such as quality, safety, authenticity, traceability, provenance (food provenance is the geographic source or origin as determined by analytical science, and differs from data provenance) and conditions of production and supply [7,8]. The heightened demand for information is a driving factor for the introduction of new technologies. For example, radio-frequency identification (RFID) technology has been deployed in FSCs to aid visibility and traceability [9], reduce food waste [10], facilitate forward tracking [11–13], increase operational efficiencies [14–16], automate data collection, prevent errors in order picking and shipping [17] and intelligently control conditions (e.g., temperature, humidity) and supply chain processes [18–20]. Cloud computing platforms are used for storing information related to food products, and this information is made accessible to retailers and consumers through websites or barcode scans using a mobile device [21]. Srivastava and Wood [22] note that cloud computing enables short messaging services in agricultural supply chains, providing information about weather conditions, proper use of pesticides, alerts of disease outbreaks and government subsidies. While these platforms drive FSCs toward a digital and data-driven food ecosystem, several fundamental problems remain unaddressed. For instance, there is a lack of continuous monitoring of the FSC and an inability to predict the remaining shelf life of fresh produce [23]. Similarly, the conventional food supervision system suffers from data fragmentation, a lack of transparency caused by data discrepancies and inconsistencies, insufficient interoperability and lack of information traceability [24]. To address these problems, FSC scholars and practitioners envision the application of blockchain technology in the food industry to revolutionize the way FSCs are designed, developed, organized, and managed. According to Wang et al. [25], blockchain can potentially impact future supply chain practices and policies by providing extended visibility and traceability. Likewise, it has the potential to improve traditional supply chain processes that are characterized by a dominating actor serving as a central third-party provider imposing their own rules, governance mechanism and centralized architectures [26].

Blockchain is defined as "a digital, decentralized and distributed ledger in which transactions are logged and added in chronological order with the goal of creating permanent and tamperproof records" [27] (p. 574). Rejeb et al. [28] argue that blockchain is a combination of multiple technologies, tools, and methods to address a particular problem or business case. Aside from being a driving force behind cryptocurrencies, blockchain has gained widespread popularity in the supply chain and logistics community because of its ability to increase transparency, ensure the immutability of transactions and enhance trust among participating food stakeholders [29,30]. Since research on the integration of blockchain technology into the FSC has only recently started to emerge, there is a considerable demand for investigating its potentials for FSCs. The intricate complexity of FSCs brings about new health and safety challenges to which food stakeholders need to react by ensuring sustainable food ecosystems. For example, Dubai uses blockchain and other Internet-based technology to enhance food safety and provide consumers' with nutritional information through its "Food Watch" initiative—a technology platform that digitizes information and digitalizes food safety processes and roles as well as providing nutritional information of all edible items served through the 20,000 or more food establishments [31].

Additionally, Walmart, IBM, and Tsinghua University explored the use of blockchain to improve food safety across China and enhance the traceability of food items along the supply chain [32]. Similarly, Chinese retailer Jindong has partnered with Kerchin, an Inner Mongolia-based beef producer, to apply blockchain technology in compiling digital product information such as farm details, batch numbers, factory and processing data, expiration dates, storage temperatures and shipping details that are digitally connected to trace every step of in the processing of the food items. Their system enables customers to trace information about frozen meat, such as a cow's breed, weight and diet, and the location of farms by scanning the QR code available on the packaging [33]. On a larger scale, according to Edwards [34], Alibaba has launched an initiative to collaborate with Blackmores and several other Australian and New Zealand-based food producers and suppliers to prevent the rise of counterfeit food items sold across China through the application of blockchain. Slovenia-based Origin Trail, a not-for-profit technology developer, created an open-source data protocol (or middleware) based on the GS1 supply chain standards that act as a standards-based interoperability platform between blockchains and legacy systems [35]. Origin Trail has partnered with the British Standards Institute (BSI) to advance blockchain use cases, especially in the food industry [36]. On a global scale, and due primarily to the multitude of use cases, no comprehensive roadmap exists to streamline blockchain implementations and adoption of blockchain-based platforms across FSCs is lagging expectations [37].

To shed light on the potentials and challenges of blockchain in the FSC, in this study, we review the state-of-the-art of the technology, its recent developments, and the applications in the food industry. Moving beyond the discussion of whether FSC stakeholders should adopt blockchain technology, we investigate the opportunities resulting from blockchain technology applications already adopted in FSCs. More specifically, we seek answers to the following research question: *What are the potentials and challenges of blockchain adoption in the FSC?*

More specifically, the literature review presented in this paper

(1) provides a background of blockchain technology to allow researchers from different fields to position their research activities appropriately,
(2) summarizes existing research and developments concerning the implementation of blockchain technology toward sustainable FSCs by outlining the potentials and challenges and
(3) identifies gaps in current research that highlights areas for further investigation.

The remainder of this paper is structured as follows. Section 2 presents the methods applied in this research for literature collection and selection in Section 3. Section 4 provides a detailed discussion of the findings of this review, and in Section 5, we answer the research questions of this study. Finally, we conclude the paper, highlight the theoretical and managerial contributions and outline the study limitations and future research directions.

2. Research Methodology

We conducted a systematic literature review (SLR) to identify, evaluate and interpret research and developments relevant to the application of blockchain technology in the FSC. An SLR is a rigorous and replicable method [38] to assess and analyze previously published work relevant to a particular research question, research topic or other matter of interest [39]. The systematic process of literature collection and analysis is useful for extracting pertinent insights based on the findings of previous research and identifying possible knowledge gaps [40]. We precisely followed the guidelines of Tranfied et al. [40] and Aguinis et al. [41] for traditional qualitative reviews and supplemented our review with a co-citation network analysis. This method has three stages, namely (1) planning the review, (2) conducting the review and (3) reporting the review. The following subsections elaborate on each of these stages.

2.1. Planning the Review

Two methodical approaches were employed to answer our research question. At the initial stage, and in line with the goals of this project, we decided to employ a qualitative method to obtain a deeper understanding of the core issues regarding blockchain technology and FSC research. Then, we decided to carefully examine several knowledge domains of blockchain and FSC research by conducting a co-citation network analysis to reveal different domains, pending issues and future research directions.

2.2. Conducting the Review

Scopus was used to obtain all pertinent articles from various disciplines or fields studying blockchain technology in the context of the FSC. Scopus is more comprehensive than the Web of Science (WoS), containing 84% of the WoS titles [42] and offering greater coverage of open access journals [43] including those indexed in DOAJ and other leading databases, such as IEEE Explorer, Springer, ScienceDirect and Taylor and Francis. According to Tober [44], Scopus is considered the most powerful search engine to get an overview of a particular topic. In terms of volume, Scopus contains more than 20,000 peer-reviewed journals from 5000 publishers and 1200 open access journals [45]. To collect and extract relevant articles, we initially created a pool of keywords and agreed-upon search criteria. First, the term "blockchain" was used in combination with terms that represent the FSC, including; *"food" OR "agriculture" OR "agri-food" OR "agro-food" OR "farming" OR "cold chain*" OR "fresh product*" OR "agri-fresh" OR "vegetables" OR "fruit*" OR "perishable."* The keywords were searched for in "article title, abstract and keywords." For transparency and clarity, the advanced search function used in Scopus is shown in Appendix A.

The scope of data collection was identified using several attributes, such as discipline, language, the period of publication, and document type [41]. In terms of disciplines, we restricted our search to business, computer science, engineering, decision sciences, social sciences, agriculture, environment, and economics. We only selected articles written in English and published in peer-reviewed journals. In doing so, we ensured that the reviewed literature originated from rigorous academic sources [46] and maintained a high quality of the retrieved publications. The publications were then scrutinized and treated independently and coded as (1) relevant, (2) irrelevant or (3) doubtful. After further screening, sixty-one (61) full-length articles were confirmed as the final dataset in the research.

3. Descriptive Results and Knowledge Domains

3.1. Publications by Year

The publication dates of the sixty-one (61) articles confirm the growing interest in this research area. Although blockchain technology emerged in 2008 as the underlying operating platform for Bitcoin [47], academic literature related to non-financial applications of blockchain has appeared only in more recent years. Recently, blockchain technology has been widely applied in fields such as healthcare [48–53], supply chain management [25,27,35,54–56], tourism [57–62], identity management [63–65], computer science [66], marketing [67,68] and smart cities [69]. The first publications in the food industry emerged from 2017 onwards, with most articles published in 2019. There is a sharp increase in the number of articles published between 2017 and 2019, as shown in Figure 1. The data indicate that this evolution will continue in the next few years as the technology matures and awareness of its potentials is heightened.

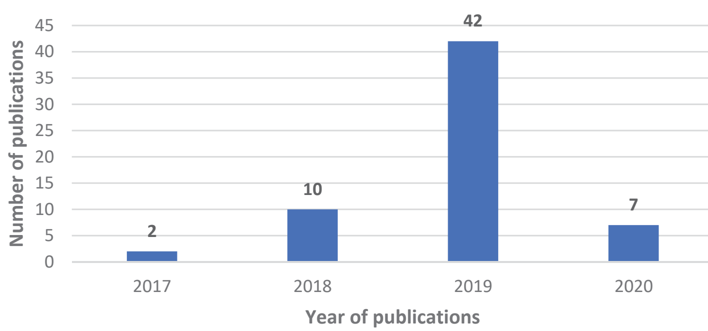

Figure 1. Year-wise publications.

3.2. Publications by Country

A significant number of the selected publications come from the USA and India, with 20 and 10 articles, respectively (see Figure 2). This is not surprising as several early blockchain adopters originate from the US, such as Walmart, who conducted trials to track pork in China and mangoes in Mexico [70]. Moreover, the USA is emerging as a leader in connecting blockchain technology with the food industry, thanks to the efforts of several companies applying blockchain to improve supply chain traceability systems. The proliferation of research and development activities can be explained by increasing food safety concerns and expectations that blockchain will promote transparency and facilitate more effective recall, resulting in greater trust in FSCs. Similarly, in India, the priority is on the agricultural sector, which accounts for nearly 18% of GDP, making the country the second-largest producer of agricultural products in the world [71]. Not surprisingly, Chinese and Italian scholars contributed substantially to the blockchain and FSC literature. In the case of China, improved food traceability is needed to enhance trust after a decade-long series of food fraud and food safety scandals. In Italy, pending problems in the agricultural FSCs such as fragmentation, lack of transparency and traceability, economic and financial waste, food fraud and food safety threats have contributed to the serious consideration of blockchain technology [72,73].

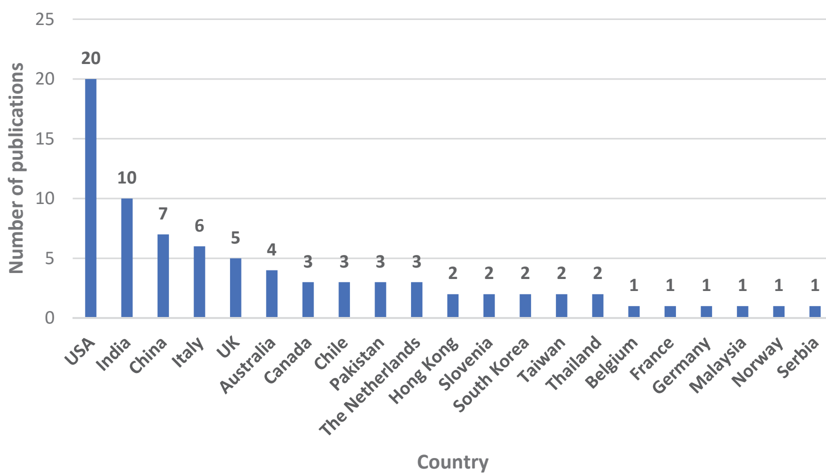

Figure 2. Country-wise publications.

3.3. Publications by Journal

Research on blockchain applications in the FSC is published in high-quality peer-reviewed journals such as IEEE Access, The International Journal of Information Management, Computers and Electrical Engineering and IEEE Internet of Things (see Figure 3). Overall, the reviewed articles were published in 48 different journals with the IEEE Access journal leading and followed by the International Journal of Advanced Computer Science and Applications and the International Journal of Information Management. Interestingly, the content of the 48 publication outlets spans across a wide variety of disciplines, including business, computer sciences, management, supply chain management, and information technology.

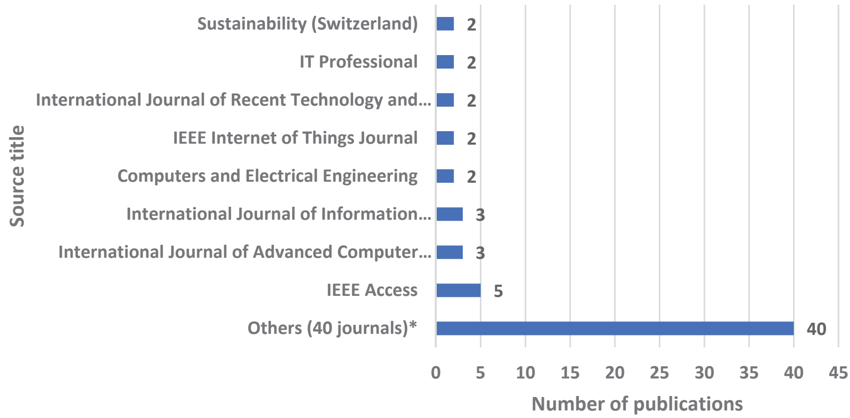

Figure 3. Journal-wise publications.

3.4. Bibliometric Analysis

The selected publications can be analyzed using several bibliometric methods and techniques such as citation analysis, co-citation analysis and co-authorship [74,75]. In this study, we review blockchain technology applications in the FSC and provide readers with an overview of current blockchain and FSC research. Using a scientometric analysis allows us to visualize knowledge in a way that is easy to interpret, highlight scholarly communities, discover knowledge domains, identify trends in different research areas and reveal relationships among scholars and institutions [76]. Several software packages are available to conduct bibliometric analyses, including BibExcel, VOSviewer, UCINET, CiteSpace and Gephi. In this study, we used VOSviewer to generate the keyword co-occurrence and bibliographic coupling networks. VOSviewer specializes in network visualization. It is a powerful tool to analyze many types of bibliometric networks, ranging from citation networks between documents and co-authorship networks between scholars to keyword co-occurrences [77]. In our study, network nodes represent either a keyword or an article. The color of the node reflects a particular property, and its radius indicates the frequency of a keyword or how often a document is cited.

3.4.1. Keyword Co-Occurrence

The analysis of keyword co-occurrence helps to identify the primary topics discussed in a particular research area by visualizing similarities among frequently co-occurring keywords or topics in the literature ([78]. The co-occurrence describes the number of times two words appear together in the title, abstract or list of keywords [79]. Applying this bibliometric technique, researchers can get a broad picture regarding the content of a paper, including its methods, objectives, and viewpoints. Thus, the analysis of keyword co-occurrence is critical to examine current topics and developments associated with blockchain technology applications in the FSC. The original data were prepared, and similar keywords, such as "*blockchain*" and "*blockchain technology*," were merged to generate the keyword co-occurrence network. After fixing the threshold of keyword co-occurrence at a minimum of two, the visualization of content results in 35 nodes with different colors, as shown in Figure 4. Each node in the figure represents a keyword, and the radius of the node corresponds to its frequency in the literature. Keywords that co-occur frequently tend to be located next to each other in the network. As shown in Figure 4, the keywords were grouped into four main clusters with a different level of significance.

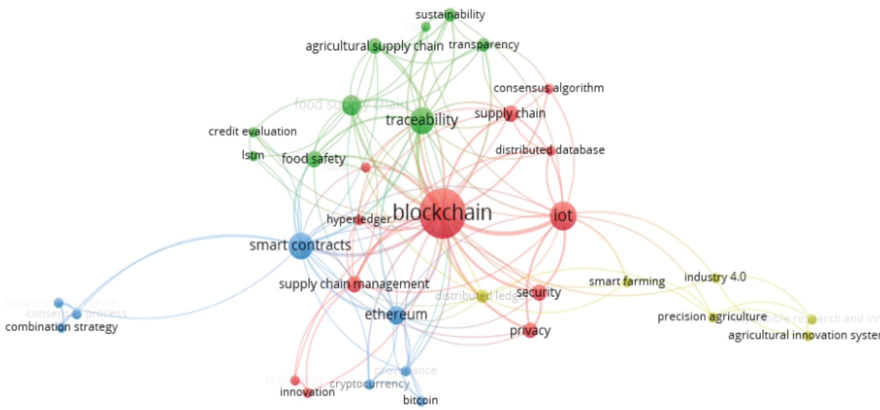

Figure 4. Keyword co-occurrence network.

In terms of size, the central red cluster is the most significant one, and it contains several terms strongly associated with the underlying technology blockchain. These include "*blockchain*", "*IoT*", "*supply chain*", "*consensus algorithm*", "*security*", "*privacy*", "*distributed database*" and "*hyperledger*". Most of these terms denote the technical characteristics and features of blockchain. As an example, the Internet of Things ("*IoT*") co-occurred frequently with "*blockchain*", indicating that this technology will increase the accuracy and speed of capturing information, help to manage data communication effectively and substantiate the value of blockchain technology for FSCs. The second cluster is the green one, and it consists of terms such as "*traceability*", "*food safety*", "*agricultural supply chain*", "*transparency*," and "*sustainability*". Combining these keywords reveals several critical use cases of blockchain technology in the FSC, such as traceability, which is identified as the primary driver for blockchain adoption in agricultural supply chains [80]. The blue cluster is related to applications of blockchain technology in cryptocurrencies and smart contracts. This cluster represents the first and second generations of blockchain applications for providing a ledger that records cryptographically signed transactions and offers a general-purpose programmable infrastructure using smart contracts [81]. The use of cryptocurrencies and smart contracts unlocks several potentials in the FSC because they help automate business processes and initiate transactions among FSC entities, resulting in better coordination and optimization of the entire FSC [30,82,83]. Finally, the yellow cluster includes keywords such as "*smart farming*", "*precision agriculture*", "*agricultural innovation system*," and "*industry 4.0*". Terms that appear in this cluster point toward blockchain technology to advance the digitization (i.e., from analog to digital) and business process modernization (i.e., digitalization) of the agricultural sector.

3.4.2. Knowledge Domains through Bibliographic Coupling

In this section, we elucidate several knowledge domains related to blockchain literature in the context of FSCs. Bibliographic coupling is conducted for all reviewed articles that cite the same literature. This implies that the higher the similarity of the referenced literature, the more similar the research content of the two articles is [84]. Knowledge mapping using bibliographic coupling analysis is an approach to study the intellectual structure of blockchain-enabled FSCs. Figure 5 presents the bibliographic coupling network of all reviewed articles, with each node representing an article. To enhance the visualization of the chart, the article titles were coded from A1 to A60. Table 1 lists the authors of the respective articles. The upper part of Figure 5 shows the co-citation clusters. In setting the threshold of bibliographic coupling to a minimum of two, four clusters were generated. The color and size of a node reflect the cluster it belongs to and its degree of centrality, representing the number of links connecting an article with related ones.

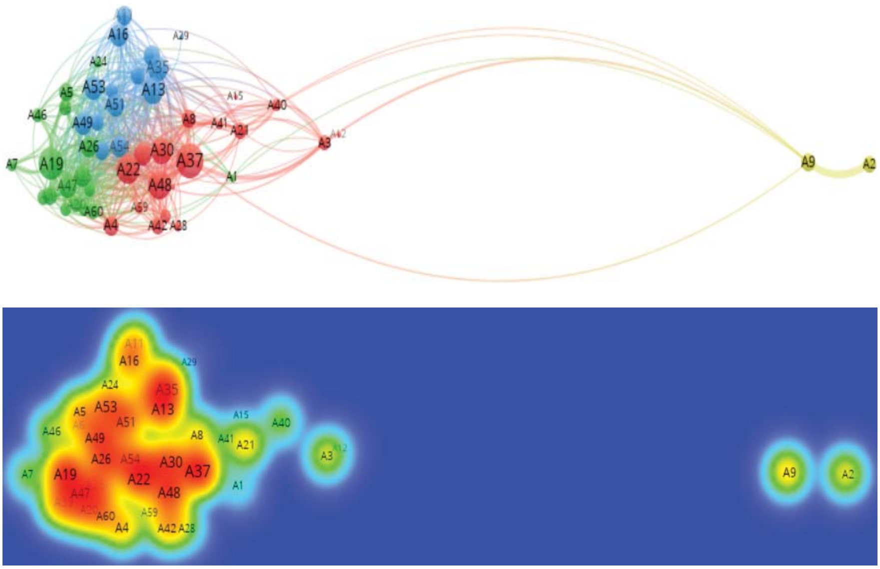

Figure 5. Knowledge domains in blockchain-enabled food supply chains (FSCs).

Table 1. Bibliographic coupling of the reviewed articles and their respective clusters.

Cluster	References
Red	[1,80,84–100]
Green	[3,30,101–115]
Blue	[47,73,82,83,116–125]
Yellow	[126,127]

The node size is proportional to the number of references a citing paper shares with other papers, thus indicating knowledge domains. A small distance between the two nodes shows that the papers are highly connected. The lower part of Figure 5 illustrates the generated clusters through a so-called "heat map." In this respect, bold fonts and warm colors (i.e., red, yellow) indicate that nodes located in the respective areas are valuable and influential. Table 1 lists the respective articles according to their cluster classification.

Based on the findings of the bibliographic coupling of the articles, four clusters emerged that were identified after reviewing the titles, abstracts, and keywords of articles in each cluster. To attribute a theme to each cluster, two authors independently reviewed the articles of each cluster and proposed an overarching topic. Typically, one cluster contains several themes, but one dominant theme often prevails and determines its overall structure. Therefore, after several rounds of discussions, the authors identified the dominant themes.

Starting at the bottom left corner of the network in Figure 5, a major part of nodes forming the knowledge domain in green represent articles related to blockchain, IoT, smart contracts and other technical characteristics. The heat map reveals that the concentration of research occurs around the nodes A19 [114], A26 [110] and A47 [3]. These articles establish the conceptual foundation to understand blockchain technology, its working mechanism and its combination with IoT. The second concentration appears around the nodes A22 [100], A30 [89], A37 [80] and A48 [1]. As indicated by the blue nodes, the third knowledge domain includes academic literature dealing with blockchain applications in the food trade, agriculture, and the sustainable operations of FSC processes. Taking into consideration the radius of nodes and their position on the heat map, nodes such as A13 [116], A16 [83], A35 [122], A51 [82], A53 [125] are the most popular works in this knowledge domain. The central themes in this cluster are the role of blockchain in improving food trade, supporting the transition toward agriculture 4.0, and enabling the development of sustainable FSCs. Other nodes in this cluster emphasize efficiencies [117], automation [115] and food safety [123] brought by blockchain into the FSC.

The nodes scattered at the right corner of Figure 5 show the last knowledge domain, which has the least number of nodes with a low degree of centrality. Research in this cluster studies the impact of blockchain adoption on financial transactions, agricultural activities and FSC operations. However, this cluster's overall influence is considerable compared to those of the other knowledge domains, as is illustrated by the small size of the nodes. In the next section, we go into further detail and provide an in-depth discussion of the possibilities and challenges of blockchain adoption in the FSC.

4. Discussion

Figure 6 presents a conceptual framework that highlights the potentials and challenges of blockchain in the FSC. As for the potentials, food traceability represents the foundation of increasingly sophisticated, industrialized and globalized food value chains [128] because it helps to ensure food safety and quality, thereby fulfilling consumer expectations and demands [129]. Moreover, blockchain supports FSC collaboration and resource sharing, strengthening relationships and trust between FSC partners and may lead to quality improvements and innovation. Supply chain efficiencies are at the core of sustainable food security, and blockchain technology holds the potential to reduce transaction costs and increase overall efficiency and supply chain resilience in the food industry. Food trade is an essential economic activity that can be facilitated by the implementation of blockchain. As such, the globalization of FSCs has posed additional challenges for businesses due to the need to ensure trust, transparency and security in food trade processes. Despite several benefits of blockchain, the implementation of the technology in FSCs does not come without its drawbacks. Technical, organizational, and regulatory challenges constitute significant barriers that impede blockchain adoption and diminish its potentials for FSCs. In the next subsections, we provide a more detailed discussion of the core elements of our framework (see Figure 6).

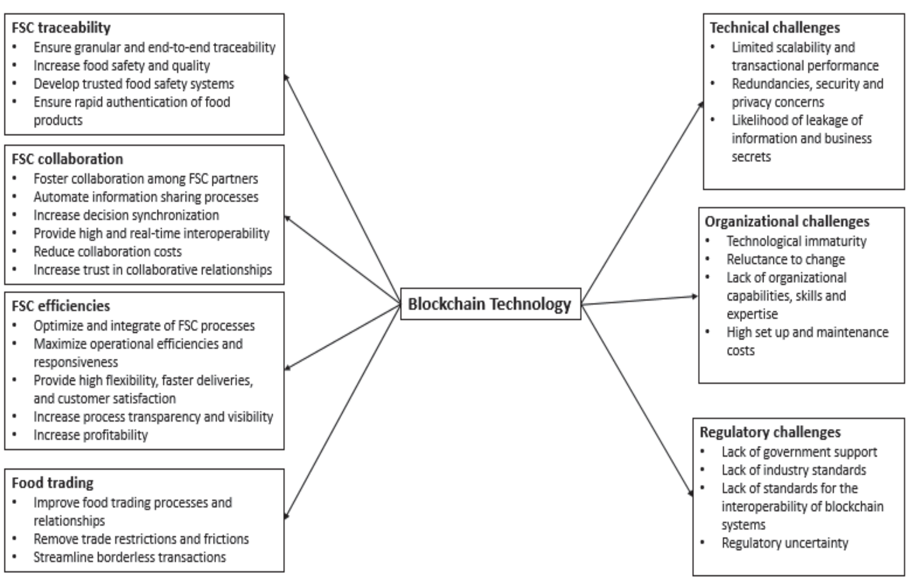

Figure 6. A conceptual framework for the literature analysis.

4.1. Potentials of Blockchain Technology in the FSC

4.1.1. Food Traceability

According to Bosona and Gebresenbet [130], food traceability is part of logistics management. It deals with the capture, storage, and transmission of information about food products throughout the stages of the FSC in order to facilitate the control of food quality and safety and ensure the backward tracing and forward tracking of the food. Traceability is increasingly regarded as a vital aspect of providing safe and wholesome food [131–133] and the assurance of consumer satisfaction and trust. The need for food traceability is clearly emphasized among consumers, particularly after consecutive scandals around the world [134,135], such as the melamine crisis in China, the European horsemeat scandal [136], and the Bovine Spongiform Encephalopathy (BSC) crisis [137]. As a result, stronger regulations demand the introduction of food traceability systems and represents an opportunity for FSC exchange partners to share essential data and information about food products [130,138–144]. Food traceability benefits consumers, the food industry, retailers and regulators alike [145]. Moreover, blockchain technology can provide supply chain traceability and information transparency and enable the rapid identification of the history, movement, and current location of consumer products (or a lot or batch) with food safety issues [3]. FSC trading partners will be able to maintain a transaction recording system that can be used to aid the integrity of food products as they move along the supply chain, helping to increase control over all transactions and interactions between food suppliers, producers, logistics providers and customers [112].

Blockchain technology can add substantial value to food businesses as traceability of end products is feasible at every point in the FSC, with the ability to rapidly retrieve all data related to food in a matter of seconds [97]. For example, Lin et al. [82] propose a food safety traceability system that is based on blockchain technology and EPCIS (i.e., a GS1 global standard enabling interoperability, which is also the accepted ISO standard) to simplify the process of acquisition, management and exchange of product information. In this system, consumers can trace information about the food they purchase through the consumer traceability client application. Similarly, Hao et al. [117] propose another blockchain system for the traceability of agricultural products. Combined with IoT sensors, blockchain technology allows stakeholders to provide retrievable data storage records of agricultural products. Salah et al. [122] suggest an approach that leverages the Ethereum blockchain and smart contracts to optimize the food traceability processes of soybean across the agricultural supply chain. All events and transactions are recorded and stored in the blockchain system, providing a high level of data and information transparency and product traceability. Likewise, He et al. [118] develop a decentralized and non-reversible traceability system for optimizing commodity data storage. Alonso et al. [101] present a platform that combines IoT, edge computing, artificial intelligence and blockchain technology to manage farming environments. When using blockchain technology, all data generated by IoT sensors are securely recorded for traceability purposes. The goal of maintaining end-to-end food traceability within a very complex and fragmented FSC is no longer a challenging task using blockchain because it creates a common platform for data collection all along the FSC. Blockchain makes it possible to rapidly track (forward) and trace (backward) all batches of products and to safely withdraw from the market if unsafe or non-compliant with regulations [120]. The application of blockchain improves FSC management processes and helps food operators to differentiate products based on their quality attributes. Unlike traditional food traceability systems, blockchain technology can ensure the capture of all traceability records covering all critical information exchange points between stakeholders in the FSC [89]. Therefore, blockchain technology can increase consumer confidence in the quality, safety, authenticity, and provenance of food products and related data and information integrity.

It should be noted explicitly that food quality, safety, authenticity, and provenance must be validated through analytical science methods. For example, data provenance is often confused in blockchain marketing with the scientific provenance of food products. Scientific provenance (geographic source or origin) can only be guaranteed through analytical science methods, such as the Carbon-13 (^{13}C) analysis of the food or through other scientific techniques [146]. Furthermore, documents (e.g., certificates, credence claims verification such as organic, halal, kosher) from analytical science testing can be added to a blockchain to enhance the data records' overall integrity. This is especially true if the authoritative source (e.g., a laboratory or certification body) directly adds the documents to the blockchain as they cannot be altered [147]. For FSC trading partners, access to a blockchain-enabled traceability system with enhanced data integrity for food safety, product authenticity and provenance might be highly valued and used as a driving force to boost competitiveness and increase consumer purchases [47].

4.1.2. FSC Collaboration

Increased supply chain collaboration and integration have led to more flexible information sharing [148], a more cohesive market focus, better coordination of sales and demand fulfilment and fewer risks related to demand uncertainty [149]. Um and Kim [150] conclude that supply chain collaboration improves firm performance and leads to transaction cost advantages. In an FSC context, supply chain collaboration is crucial because the agri-food industry structure is inherently complex. For example, multi-ingredient food products usually comprise an intricate supply chain with several business entities and multiple information exchanges. Accordingly, when multiple exchange partners form a specific FSC, interoperability issues arise due to non-compatible systems required for information sharing. To address this issue, blockchain technology platforms can utilize GS1 standards to facilitate interoperability among the different parties of the FSC. On 10 June 2020, the GS1 USA organization announced a successful proof of concept for data sharing was completed between four competing platforms and solution providers (IBM Food Trust, SAP, RIPE.IO and FoodLogiQ) [151]. According to Bumblauskas et al. [86], blockchain is a suitable solution for FSCs and agriculture because of its ability to share immutable data between exchange partners and automate information sharing processes.

The generation of rich data in the FSC is well suited for blockchain to support the collection, storage and visualization of information. Moreover, blockchain technology is expected to be a basic data-driven collaboration framework which shortens the FSC and offers new opportunities for information sharing and efficient decision-making [91]. To streamline the beef FSC processes, Surasak et al. [152] develop a system that uses blockchain to share information related to location tracking, temperature, humidity and ownership transfers. Companies advocating greater FSC transparency also envision blockchain as a potential solution for accelerating across a vast network of trusted exchange partners. For example, IBM launched its IBM Food Trust platform, which represents a cloud-based, permissioned blockchain solution for ensuring a trusted method for participants to share food-related data, extract value from others' contributions, and develop a safer, smarter, more efficient and sustainable food ecosystem [153]. Blockchain technology is a crucial enabler in the FSC, acting as the facilitator of business process and role automation (e.g., digitalization), information sharing and enhanced decision-making. The reviewed literature illustrates the virtues of blockchain technology by increasing supply chain visibility and optimizing information flows. For instance, Perboli et al. [120] argue that blockchain can guarantee end-to-end integration and transfer of information flows associated with items and batches by driving high and real-time interoperability within existing Enterprise Resource Planning (ERP) software. Similarly, Kamble et al. [91] note that blockchain can overcome several efficiency and transparency issues in the agricultural supply chain as the technology can consolidate links between producers, farmers and markets. Furthermore, FSC stakeholders can optimize several functions such as the movement of highly perishable food products through the supply chain network and the fast and targeted removal of foods unfit for consumption. More specifically, blockchain aids in establishing cooperative FSCs by lowering collaboration and administrative costs, such as costs for the design of collaborative agricultural activities, the sharing of equipment, tools and transportation [107]. The focus on developing more synchronized and collaborative relationships between FSC partners is fostered by blockchain because of its ability to secure resource exchanges and increase trust [1].

4.1.3. FSC Efficiencies

As competition has intensified within and between FSCs, food organizations must maintain higher levels of efficiencies and deliver added value to consumers [90]. Companies that can create more efficient FSCs will be able to achieve a significant competitive advantage. The digitization (and digitalization) of supply chains has brought tremendous opportunities for companies and created new opportunities and business models [154]. Accordingly, the evolution of FSCs has necessitated the deployment of modern technologies to enable process and role automation between information exchange partners. The adoption of blockchain technology can improve inbound efficiency and optimize planning decisions by providing reliable data and information and increasing the visibility of supply chain inventory and processes [120]. The critical assumption here is that the exchange parties do not collude to enter false data into the blockchain, which is a potential threat to the integrity of the FSC. Technology is particularly crucial for integrating FSC processes, accelerating the flow of information (i.e., transparency relates to visibility and flow of information) among FSC partners, and maximizing the efficiency, responsiveness and resilience of the food chain to account for changing market conditions and potential system shocks (e.g., COVID-19 pandemic). Food enterprises and logistics service providers can significantly reduce the inefficiencies resulting from paperwork and other fragmented and bureaucratic procedures in the supply chain.

Blockchain contributes to the automation of organizational processes and encourages firms to engage in more efficient FSC collaboration. As a result of these benefits, lower costs can be achieved through greater efficiency and better access to reliable information. Blockchain can reinforce multi-party trust and be combined with other established B2B technologies such as EDI, XML and API-based B2B [47]. The use of blockchain within these systems helps to enhance big data integration and automate certain activities within food safety management governance systems. It plays a more significant role in increasing the flexibility of the FSC, the efficient flow of information and materials through the chain [120], ensuring fresher products and faster deliveries, reduced stock levels and quick response to consumer demands and concerns. In the case of issues related to food safety, retailers can quickly and efficiently trace back along the products' supply chain to remove a specific batch of contaminated food instead of recalling the entire inventory [89]. The speed of locating food products can be done within seconds on blockchain compared to the same activity in a non-integrated system [90]. This capability is beneficial in food poisoning and food fraud, as a recall action of a suspicious item is mandatory by law and necessary to increase confidence in the brand [89]. Implementing blockchain in food recall processes in multi-party supply chains can further help save costs due to the specificity or granularity of the recorded transactions. Consequently, food companies can prevent defective or unsafe food distribution and mitigate potential economic losses and reputational damage [110]. Therefore, the integration of blockchain into the food industry gives way to a new information architecture for FSCs that will replace existing siloed databases and fosters sharing all events carried out across the supply chain, resulting in streamlined FSC processes.

4.1.4. Food Trading

Food is a unique commodity, and its trade has significant economic importance for both developed and developing countries [155]. For example, China's food trade significantly contributes to its national economy, the progress of agricultural innovation activities, and the population's nutritional health status [156]. Although the rapid growth of international food trade drastically changed the global food system over the past decades [157] and still exerts a considerable impact on sustainable economic development, there are multiple technological problems in today's FSCs, according to Mao et al. [83]. To address these issues and promote food trade practices among the many FSC stakeholders, blockchain technology can be used to enforce automated trading mechanisms [83].

The application of blockchain brings enhanced optimization and automation to business processes and roles between trading relationships and increases trust in exchange transactions. The auditability of blockchain technology is a crucial feature by which FSCs can establish an authoritative record for trade data and information, perform real-time order checking and achieve visibility regarding inventory levels and automatic reconciliation of invoices [91]. Moreover, blockchain can expand food trade through the removal of certain trade restrictions. It can accelerate commercialization processes—blockchain guarantees all FSC exchange partners can attain information symmetry, credibility and trust [125]. Similarly, several companies consider blockchain a workable solution for managing trade-related documentation and streamlining borderless transactions [3]. Global FSC trading partners can benefit from blockchain's ability to reduce logistics costs, streamline transportation processes and formalize trade relationships. Also, blockchain has the potential to dismantle specific trade barriers and create new market opportunities for firms to grow, thrive and become more competitive. Mao et al. [125] note that blockchain can open up new avenues for trade that extend beyond national boundaries by enhancing traceability and efficiency in trade and addressing food safety issues. Blockchain technology represents a significant paradigm shift in terms of how transactions are conducted [3]. Therefore, the implementation of blockchain in the FSC can enable organizations to perform business beyond existing corporate boundaries almost as effectively and efficiently as they operate within the firm.

4.2. Challenges of Blockchain Technology in FSCs

4.2.1. Technical Challenges

According to Behnke and Janssen [1], several technical issues of blockchain remain unresolved, despite the advantages it offers in FSCs. For example, scalability needs to be addressed because the technology might become inefficient if the number of FSC transactions is increasing exponentially [114]. The validation process of transactions might limit the applicability of blockchain and reduce transaction efficiency in situations of high transaction throughput [125]. Wu et al. [114] argue that blockchains are not suitable for FSCs in general because the technology has a limited capacity to handle and store massive amounts of data. The authors further note that a multi-tier supply chain network necessitates the processing of many transactions in a short period, and blockchain technology can lead to transaction inefficiencies as well as redundancies. Perboli et al. [120] stress that the performance of blockchain still lags when compared with transaction-based technologies such as Visa, which is capable of handling thousands of transactions per second on average. In contrast, a Bitcoin blockchain, is tremendously lower in both transaction speed and volume. Although several solutions are currently underway to address the limited scalability of blockchain, they are still in a nascent development stage. As an illustration, the use of off-chain data storage can improve the efficiency of blockchain; however, this solution may surface new issues related to data integrity and privacy [114]. Therefore, the application of blockchain in the FSC depends on high scalability and decentralization [103] so that FSC operations become smoother and more flexible.

Blockchain-based FSCs require more intelligence and automation to increase the resiliency of the food supply network by lessening the restrictions for users to join, execute transactions, and access smart contracts' source codes [115]. Code errors and security vulnerabilities might result in significant financial losses for FSC actors. Wu et al. [114] claim that blockchain might be subject to several security threats such as a mining attack, which can put food companies at risk of data and revenue loss, whereas Zhao et al. [100] highlight that the decentralized architecture of blockchain and its integration with an extensive peer-to-peer wireless sensor network might give rise to several privacy and security issues in the agri-food value chain. Zhao et al. [100] claim that operating a blockchain may entail an unprecedented level of transparency and visibility of FSC processes leading to a potential risk in confidentiality. Blockchains may not guarantee privacy for FSC actors as information will be available and accessible to all members belonging to a network. If information is deemed strategic, confidential or secret, food firms might be hesitant to engage in blockchain-based FSCs until the risk can be mitigated [114].

4.2.2. Organizational Challenges

The technological immaturity of blockchains is a significant barrier to its adoption in the FSC alongside the nascent nature of research and development [121]. The immaturity level of the technology exacerbates the uncertainties concerning its usefulness for FSC activities [127]. Many blockchain projects in the food industry are in a proof-of-concept stage of development. As such, many blockchain start-ups and established technology firms have introduced solutions based on blockchain technology, but not many applications have gone beyond a pilot stage [1]. Moreover, food organizations interested in adopting blockchain might be hesitant to place the technology at the core of their organizational processes due to the lack of previous experiences. Longo et al. [47] state that FSC players, such as food manufacturers, logistics operators and especially small- and medium-sized food enterprises, must invest more resources and money in harnessing and operating a blockchain-enabled supply chain. The initial set up and maintenance costs might outweigh the benefits of such FSCs. Firms with limited financial resources might be unable to increase their adaptation capabilities, thereby being at a competitive disadvantage compared to their competitors. Failure to understand that the adoption of blockchain needs enhanced organizational capabilities can result in severe operational problems.

In terms of implementation costs, the use of blockchain might require significant capital investments [158]. Klerkx et al. [127] argue that the digitalization of supply chain processes requires the mobilization of diverse skills, knowledge, and materials to translate digital data and capabilities into better decisions for FSC management. The novelty of blockchain technology presents additional challenges for FSC operators because they may be unfamiliar with the principles (e.g., immutability), functioning, and maintenance of the technology [100]. Therefore, the need arises to develop workers' skills and technical understanding and capabilities to ensure effective implementation. Moreover, in the digitalization of FSC processes and the automation of manual roles, blockchain technology may force worker layoffs and poses a threat to the digitally illiterate [127].

4.2.3. Regulatory Challenges

To ensure the sustainable functioning of blockchain-enabled FSCs, food industry stakeholders have to follow regional, national and international policies and regulations [85]. Government support and regulations can be a driving force for the greater diffusion of the technology. Furthermore, blockchain technology implementation should be seen as a facilitator for regulatory and certification norms, especially those requiring the traceability of food products [80]. The lack of industry standards related to blockchain technology makes it hard to integrate all FSC exchange partners into a single regulatory framework. However, the GS1 EPCIS-enabled protocol from Origin Trail offers an open-source solution to address the problem of blockchain to blockchain and blockchain to legacy interoperability (other solutions may also exist). Cooperation among different industry players needs to be fostered to ensure greater regulatory harmonization. GS1 standards are also intended to aid FSCs to collaborate on specific aspects of regulatory compliance (e.g., traceability, recall, product and trading party identity, farm or factory identity and location, labelling). Misconceptions regarding blockchain technology need to be addressed as they may result in regulatory and legal restrictions and limit the value obtained from adopting the technology [80]. In this respect, Behnke and Janssen [1] maintain that standardization of food traceability processes and the development of a unified framework is a crucial boundary requirement before blockchain can be applied to the FSC. As a result, blockchain promoters in governmental roles need to involve technical experts to establish the regulation upon which blockchain technology can be developed.

5. Discussion, Implications and Conclusions

5.1. General Discussion

In this paper, we synthesize the current knowledge base concerning the potentials and challenges of blockchain in the FSC. We report findings from an SLR and bibliometric analysis showcasing the role of blockchain in the food industry. The network and content analysis results show that blockchain is a promising technology and an effective solution for modernizing FSCs [159]. The intrinsic characteristics of blockchain have the potential to solve several problems inherent to FSCs. For example, food companies using blockchain technology can enhance product traceability and quickly identify the location and source of products implicated in a food safety recall, adulteration, or counterfeit. Numerous studies advocate using blockchain as a means for achieving end-to-end product traceability, making the tracking and tracing of food products feasible at every point in the supply chain [160]. It can be noted that traceability of food products can be done without blockchain. However, it is often cumbersome and inefficient when multiple stakeholders are involved due to a frequent lack of interoperability and the limitations of a one-up/one-down regulatory requirement for traceability. Blockchain-based traceability can help determine the different actors' identity, food product identity, origins, and all related information [161]. From a supply chain perspective, blockchain will help to ensure efficient and trusted transactions while simultaneously enhancing traceability and recall capability, aiding food safety and the rapid identification of potential food fraud, counterfeits and other forms of illicit trade [162]. Blockchain can reduce information asymmetry and provide more accurate, timely and trusted information to the public while minimizes damage to a company's brand image and reputation.

Our findings also highlight the value of blockchain for FSC collaboration. More specifically, blockchain provides opportunities for FSC stakeholders to collaborate more efficiently and effectively, increasing trust in business interactions. In FSCs, trust is a precursor or antecedent for successful collaborative arrangements and vital for information sharing and transparency [163]. As a result, food companies can rely on blockchain to forge closer partner collaboration, sustain FSC activities, and mitigate the adverse effects of process failures. Similarly, blockchain deployment for FSC collaboration can be an impetus for higher supply chain responsiveness and organizational performance. Our findings suggest that blockchain may lead to better performance in process automation, information sharing and decision synchronization. FSC stakeholders can benefit from using blockchain to foster collaboration among the different tiers of the food chain since the exchange of information and resources is independently verified by blockchain participants and can be inspected by food suppliers, distributors and customers. It is also conceivable that the technology can be a means by which all FSC stakeholders can be involved in a collaborative environment that promotes shared responsibility, fairness and transparency [163].

Blockchain is anticipated to synchronize information sharing among FSC stakeholders to significantly reduce excess inventory and protect against the harmful bullwhip effect. Thanks to the increased visibility of FSC processes, blockchain helps the food industry stakeholders overcome the common problems of conventional collaborative systems by enhancing response time, increasing cost-effectiveness, reducing potential errors, and assuring instant availability of accurate and reliable FSC information [164]. Therefore, it is essential to integrate blockchain in FSC collaboration to establish trust in the relationships among FSC partners, which is a critical element for achieving successful collaborative practices. Successful collaborative practices also open opportunities for social sustainability. When it comes to human rights and fair work, a complete record of a product's history helps product buyers be confident that their purchase originates from ethically sound sources.

Several studies stress blockchain's ability to improve the operational efficiencies of FSCs. In this regard, the most apparent feature of blockchain to increase efficiency is disintermediation by helping FSC partners automate business transactions, reduce lead times, and reduce costs. Blockchain can create an ecosystem wherein frictionless value transfers can be performed efficiently. The automation of FSC transactions paves the way to optimizing FSC processes such as food sourcing, ordering and distribution, thereby helping businesses identify potential sources of process inefficiencies, redundant tasks and fraud. The virtues of getting an improved view of the flow of food products can aid FSC partners in managing their production, inventory, and food safety mechanisms, thereby reducing food waste and spoilage. Blockchain coordinates FSC operations to enable faster customer responsiveness and maximize customer service levels. It may help reduce the size and scope of rework and recalls by delivering these services, thus providing considerable greenhouse gas reductions and other resource savings. Access to more complete longitudinal supply chain datasets will lead to improved practices, including eliminating redundancies and bottlenecks, and ultimately, decreases in resource consumption, all of which are positive outcomes of blockchain technology from a sustainability perspective [165].

Additionally, FSC stakeholders must consider the integration of blockchain in their trading processes. The opportunity to develop a fair-trade environment is frequently highlighted in the reviewed literature. The persistent inefficiencies associated with the movement of food products from one country to another can be partially resolved with blockchain. In this sense, blockchain can simplify food trade logistics and distribution, eliminating information asymmetry and establishing a more credible and sustainable food trading environment.

Our review of the literature also scrutinizes the challenges encountered when deploying technology in the food industry. For example, the technical limitations of blockchain, including scalability, security, and privacy issues [166], represent a significant hindrance to its application in FSCs. In practice, scalability is crucial when deciding to deploy blockchain because the technology might not be suitable for managing FSC data, especially when substantial, high-velocity information needs to be processed. The storage capacity and performance of blockchain might not work for data-intensive FSCs since all blocks must store a copy of all transaction data fed into the network, resulting in data redundancy. Although several solutions have been introduced to improve scalability, further efforts are needed to develop highly scalable blockchains that respond to the needs of all FSC stakeholders. Furthermore, using blockchain in a multi-tier FSC network poses additional risks for security attacks and privacy intrusions [167,168] due to the technology's decentralized architecture.

Consequently, if FSC partners feel that their business information is not secure, they will be discouraged from using blockchain. Previous research also shows that the adoption of blockchain in the FSC may be slowed down by many organizational factors such as technology immaturity, resistance to change and the lack of necessary resources and operational capabilities [169]. Applying blockchain for FSCs is still a challenging endeavor as the technology and its design are still unable to cope with highly globalized FSCs. The uncertainties surrounding the technology and the fear of losing control may explain many managers' reluctance to support blockchain-enabled business models. FSC actors might be unwilling to operate in a blockchain environment [170] if their competitors develop a competitive edge by concealing a particular product or processing information. Moreover, the commitment of significant resources for the engagement in a blockchain operational model is highlighted in the literature as a pressing challenge for small and budget-constrained FSC partners because they are required to incur additional costs for organizational development capabilities and system maintenance. Lastly, the literature also discusses regulatory issues facing blockchain adoption in FSCs [55]. The legal environment of blockchain is still full of uncertainties [171]. For example, there is a need for regulations and industry standards that FSC stakeholders can refer to when encountering potential incidents while operating in a blockchain setting. Therefore, industry standards and regulatory initiatives are necessary to accelerate blockchain adoption in FSCs and develop best practices and protocols for FSC interoperability.

5.2. Implications for Researchers and Practitioners

The pressing need for maintaining highly efficient, integrated and responsive FSCs is driving researchers and organizations to rethink the supply chain design. Substantial efforts are devoted to studying promising opportunities for this technology in the food industry. The findings of this study are useful for researchers to capture the dynamics surrounding blockchain technology. More specifically, we unfold the potential areas where food organizations can use blockchain to add substantial business value and achieve sustainable performance. Reviewing the potentials and challenges of blockchain is crucial for leading FSC stakeholders, who need to scrutinize the technology enablers to create strategies and policies, incentivizing the transition from conventional FSC systems to blockchain.

Innovation in blockchain through improved scalability, performance and security, can contribute to the wide-scale implementation of the technology in FSCs. Regulatory bodies and key FSC stakeholders that exert pressure on transitioning toward blockchain-driven FSCs need to develop policies and standards that facilitate regulatory document expedition and streamline business processes, such as the checking, control, control, monitoring and certification of food products. The shift toward a blockchain ecosystem may necessitate a different modus operandi regarding the orchestration of FSCs. Therefore, we recommend that food organizations and stakeholders diminish the main barriers to blockchain adoption at the organizational level (i.e., resistance to change) and develop the organization's needed operational capabilities by providing specialized corporate training programs and developing systems to enhance coordination and information sharing between FSC partners. Blockchain has the potential to empower the technological advancement of FSCs as it can augment the capabilities of other Industry 4.0 technologies, such as IoT, Big Data, Artificial Intelligence, Augmented Reality and Cyber-Physical Systems to generate new efficiencies. Thus, managers and practitioners need to be cognizant of the transition toward blockchain-enabled FSCs to deliver high quality, safe and authentic food to consumers.

Managers should also be aware of the additional challenges and tensions that can emerge from blockchain adoption, and they should work to overcome issues threatening the sustainable functioning of FSCs. This study reveals that blockchain adoption in FSCs is worthwhile in terms of food traceability, collaborative relationships, operational efficiencies, and food trade activities. Thus, managers need to ensure their digital transformation plans consider the potential transformative power of blockchain-based business models. Investments in blockchain promise improved food traceability, trust, transparency and efficient use of resources, and strong relationships with customers and supply chain partners, which can help food firms sustain their competitive advantage.

Our literature review framework provides a comprehensive analysis of opportunities and constraints of blockchain in the FSC that drives or impedes sustainable management to inspire further research. We propose the following research gaps that need further attention and investigation:

- This review highlights the potentials of blockchain for FSCs. However, insufficient attention has been paid to the role of blockchain in supporting internal activities within food organizations, namely, raw materials procurement, inventory management, document and credentials management, specification and recipe management, product life cycle management, quality management and the role of smart contracts.
- Additional studies on the role of blockchain in FSC collaboration are required to understand better the tensions and paradoxes that can arise from the technology's integration and interoperability in complex and multi-tier FSCs.
- Empirical studies are required to test whether the technological capabilities of blockchain can enable and constrain FSC performance.
- Our findings illustrate that blockchain helps to improve FSC processes. However, exactly how blockchain can help to overcome problems and bottlenecks of organizational performance remains unknown. Another important research topic is examining the impact of blockchain on FSC resource sharing, decision synchronization and joint knowledge creation.
- Future research needs to provide a quantitative assessment of the impact of blockchain on FSC performance and provide clear guidelines on how to tailor blockchain characteristics to increase the efficiency of FSCs and respond to the needs of all stakeholders involved in the food industry. The framework that emerged from the literature analysis can be a starting tool to map the different needs of FSC partners and introduce appropriate blockchain solutions to respond to concerns in terms of food security, safety and convenience using technology.
- Future research needs to discern workable solutions to overcome the technical, organizational, and regulatory challenges facing blockchain implementation in FSCs.

- Future studies need to investigate the impact of blockchain on consumer purchasing habits and consumption of food products. Additionally, researchers should focus on the use of blockchain to design mechanisms for more sustainable and ethical food production, thereby improving consumer satisfaction and trust in food products.
- Future studies need to examine blockchain's added value when used together with forensic testing methods to ensure food authenticity, provenance, and safety.
- Additional case studies need to be conducted to validate the diverse themes of our framework and highlight the applicability and suitability of blockchain to diverse areas in the FSC.
- Researchers are required to elaborate on blockchain's role to foster FSC sustainability, detailing the impact of the technology on economic, social and environmental dimensions of FSC sustainability. Addressing this knowledge gap is necessary to grasp the transformational impact of technology on the economy and society.

5.3. Conclusions

An essential task of a literature review is to provide a timely synthesis and analysis of published literature. Even though previous studies have explored the numerous possibilities of blockchain technology in supply chain management, they have not captured the latest technology developments from the FSC perspective. Therefore, our review study aims to enhance scholars' understanding regarding the potentials and challenges of leveraging blockchain in the food industry.

In this study, we employ an SLR and investigate the current state of knowledge on blockchain applications in the FSC. The review was conducted with sixty-one (61) relevant journal articles, which were thoroughly examined and analyzed using bibliometric tools and techniques. This study reveals that blockchain technology is still in a nascent stage and has a potentially transformational and foundational (rather than disruptive) impact on the FSC. As for the benefits of the technology, we found that blockchain adoption can improve food traceability, enhance FSC collaborative relationships, maximize operational efficiencies, and sustain food trading activities. The downsides of blockchain mainly fall under three categories, namely, technical, organizational and regulatory barriers. Issues, including blockchain scalability, security and privacy, are the key factors inhibiting the widespread implementation of the technology. The lack of standards and regulatory support is also expected to restrain blockchain's value in the food industry.

Through conducting this review, our primary goal is to inform scholars and practitioners on the importance of blockchain technology in sustaining FSCs. Moreover, we seek to summarize the current research state and provide several implications for researchers and practitioners. Furthermore, the compilation of our review and its findings should encourage further research in the field. Aside from offering valuable contributions to the blockchain literature and deepening the extant literature's overall understanding, we highlighted the main knowledge domains.

From a theoretical perspective, we provide three contributions. First, this paper adds to the few studies that have previously explored blockchain technology in the FSC. Second, we synthesize related literature using keyword co-occurrence and bibliographic coupling techniques. So far, bibliometric methods have not fully exploited the review of blockchain research in the food area. Hence, this study offers a detailed analysis and timely synthesis of the literature. Third, our findings identify several areas that are not sufficiently dealt with, such as blockchain technology's role in enhancing FSC sustainability through better collaborations with partners in multi-tier global food supply networks.

This review has several practical implications. For instance, blockchain technology benefits may provide a reference for practitioners interested in understanding the expected outcomes from the deployment of the technology in the FSC. The welfare of various FSC stakeholders such as food suppliers, producers, retailers and final consumers may be substantially improved with blockchain technology. In this regard, this review can help practitioners to understand these far-reaching implications better. In contrast, blockchain challenges may guide FSC managers to identify the pain points encountered by organizations during the shift toward blockchain-enabled FSCs.

As with any research, this study has some limitations. The selection of Scopus for the collection of the literature does not guarantee the full coverage of research works published on blockchain technology from the FSC context. The final list of retrieved articles was generated based on the set of search keywords used. Although keyword entries provide a comprehensive list of research articles, the remaining keywords may not be exhaustive. Future studies may want to consider using other databases such as ISI Web of Science. We also recommend that researchers empirically validate the research questions raised in this review using surveys and case studies.

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Appendix A

TITLE-ABS-KEY (blockchain* AND (food* OR agriculture OR agri-food OR farming OR "cold chain*" OR "fresh product*" OR "agri-fresh" OR vegetable* OR fruit* OR perishable)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "DECI") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ECON") OR LIMIT-TO (SUBJAREA, "MULT"))

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Article

Applying Distributed Ledger Concepts to a Swiss Regional Label Ecosystem

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Abstract: Improving current supply chains by using distributed ledger technology (DLT) has been a highly researched topic during the last years. Currently, there are numerous articles elaborating on how such technologies can theoretically improve supply chains. However, case studies of such concepts and their economic value are scarce. In order to bridge this gap, we collaborated with a regional label company to clarify how a distributed ledger technology would benefit their ecosystem. This work answers the question of how such a prototype would look and whether it adds value. By following design science research practices, we design two artifacts based on requirements gathered in 14 interviews and discuss the artifacts' elements within an evaluation panel. Our findings show that a distributed ledger application for the regional label ecosystem should have an open and decentralized architecture giving all participants full access to the shared data while still providing security and privacy for sensitive data. Additionally, data capturing should be simple. However, such an application does not add sufficient economic value and is currently of no practical interest in the regional label ecosystem as the expenditure likely exceeds the benefit.

Keywords: supply chain; blockchain; distributed ledger; regional label ecosystem; traceability

1. Introduction

Knowing how food is produced and knowing the involved parties is gaining more importance for consumers. A recent report, which surveyed US-consumers, points out that they are requesting a high degree of transparency regarding the origin and production process of their food. The report states that more than 90 per cent say that it is important for "manufacturers to provide detailed information about what is in food and how it's made" [1] (p. 2). Moreover, around two-thirds of the surveyed consumers reveal that they would switch from the brand they usually buy to another one, if it provided more information on the product.

To satisfy the consumers' request, many producers inform consumers that their products are produced according to certain standards, by using a certified third-party quality label. Commonly known examples of such quality labels are vegetarian, meaning the products do not consist of animals or any animal parts [2] and fair trade, meaning the production of the product improves the livelihood of producers while respecting the human rights [3]. Generally spoken, such labels are thereby not providing more transparency to consumers but rather more 'trust' by creditably certifying a certain quality trait of a product. Nevertheless, scandals have occasionally occurred, since the quality label's certification process is not always transparent and sometimes vulnerable to fraud. Prominent examples of such events are label scandals in Italy [4], in the US [5] and in Germany [6], where regular food was sold as organic. Other examples are the recall of falsely labelled vegan food in Great Britain [7] and more recently the fraud allegations against products labelled with the Aquaculture Stewardship Council (ASC) label [8].

Meanwhile, distributed ledger technology (DLT) has become well known to provide more supply chain visibility and transparency as shown by Wang et al. [9] and Saberi et al. [10]. This technology was originally developed for the transfer of cryptographic coins, while keeping the degree of security and transparency within the system high [11]. According to Rauchs et al. [12] (p. 12) a distributed ledger can be defined as a *multi-party consensus system* that allows multiple distrusting parties to reach and maintain agreement on replicated, shared and synchronized data in an adversarial environment without having to rely on a central trusted party. Probably the best-known kind of a distributed ledger is the blockchain, which is why the term 'blockchain' is often used as a synonym. However, as blockchains are only one possible form of distributed ledger designs, we will use in this article the more generic term 'distributed ledger' to describe the above defined multi-party consensus system. Since its invention in the context of cryptocurrencies, the conceptual idea of distributed ledgers has been further developed and applied to many other use cases ranging from the energy sector to the pharma industry to public administration [13]. Although these use cases focus on different economic sectors, they often involve the company's supply chain as the primary subject of interest [14–16].

Wang et al. [17] present an overview of recent studies about using DLT for supply chains. Amongst other findings, they state that such applications are expected to add the most value by increasing product visibility and traceability along the supply chain. Nevertheless, to the best of our knowledge, there is only one study exploring the application of DLT for regional label supply chains and its potential benefits within this context [18]. The authors emphasize the potential to improve the efficiency and transparency of regional label ecosystems. However, the question of whether these theoretically stated benefits of a distributed ledger technology can be achieved in practice remains open. Therefore, based on those findings and by using a design science approach, this paper aims to further clarify whether such a value can be realized in practice, and to provide new insights and knowledge about the application of DLT in a business environment. By cooperating with different quality labels certifying regional products in Switzerland, we aim to answer the following research questions (RQ):

RQ1: What would a distributed ledger application look like to provide higher efficiency and/or transparency for a Swiss regional label ecosystem?

RQ2: Can such a distributed ledger application add value to a Swiss regional label ecosystem in practice by providing higher efficiency and/or transparency?

By answering these research questions, this work contributes in three ways. First, the certification process of regional labels is mapped, and current challenges are identified. Second, we present two different distributed ledger prototypes for facilitating the certification process of regional labels. Third, we elaborate on the necessary conditions for benefiting from such a distributed ledger application, which ultimately leads to new knowledge that can be used to design distributed ledger applications for solving challenges in practice.

The remainder of this paper is structured as follows: First, we conduct a literature review and give an overview of related articles. Second, we explain the design science methodology and how it applies to the research conducted in this paper. Third, we perform an environment analysis of regional labels in Switzerland and present the current process problems. Fourth, we define requirements for an artifact. In a fifth step, we develop two artifacts and apply them to our use case. Afterwards, the evaluation and discussion follow. Lastly, we state the conclusion of our work.

2. Literature Review

2.1. Challenges in Quality Label Supply Chains

Nowadays, supply chains are confronted with multiple challenges, which impede their efficiency. A thorough investigation of such challenges was conducted by Taylor [19]. The analysis concludes that there are three main challenges: First, there are issues related to the physical product flow if the links between the actors are weak. This can lead to over/undersupply, to non-value adding steps or to product waste, due to non-standardization along the chain. Secondly, the information flow is obstructed by the complexity of the supply chain, because of a multiplicity of forecasts, a lack of synchronization, and bad formats for transferring information between adjacent actors. Moreover, Özer and Zheng [20] add that companies do not want to exchange sensitive information since they fear it could be used to their disadvantage. Third, the management and control of the supply chain are difficult as there is no single entity in charge of the whole supply chain and independent decision making can prevent improvement of the supply chain. Furthermore, without a central control it is difficult to create key performance indicators, which would drive improvements [19].

An overview of the specific challenges for the supply chain of an organic label company is given by Keller and Kessler [21]. They state that the physical goods are difficult to trace, since only the financial flow is monitored. Especially during the first mile fraud can happen and non-organic food could be wrongfully labelled as organic. On top of that, there is a lack of international transparency.

Specific challenges for regional label supply chains have only been identified in a paper by Lustenberger et al. [18]. A major challenge is tracing a finished product back to its sources. This lack of transparency on a product level means that only the actors themselves are certified and not the products themselves. Moreover, the information is scattered amongst many heterogeneous actors in regional label supply chains, which makes it difficult to oversee the whole process. This also leads to a lack of coordination, which is further amplified by the fact that the actors often use separate information systems.

2.2. Distributed Ledger Applications for Supply Chain Traceability

A systematic literature review on understanding distributed ledger technology (DLT) in supply chains is given in the article [17]. They state that distributed ledgers are expected to add the most value by increasing product visibility and traceability. Another review is presented by Kamilaris et al. [22]. They offer theoretical insights into the impact of DLT on agriculture supply chains, analyze ongoing projects, and conclude that DLT has the potential to make agriculture supply chains more transparent and traceable.

This potential in the agricultural sector has led to the development of a multitude of DLT applications for food supply chains. A rather specific approach on how to improve efficiency and transparency in food supply chains is presented by [23]. The paper proposes a traceability system built on RFID and DLT for an agri-food supply chain. Through the combination of these two technologies it is possible to collect data while producing, processing, warehousing, distributing, and selling a product. At the same time, the data can be shared and validated. This has the benefit that external organizations, such as governments or quality assessors can also check the data. A concrete example is the possibility of monitoring the temperature during transportation. As soon as the temperature is out of the predefined range, a report is created and made visible on the distributed ledger for all participants.

A concrete project of using DLT for labels is called OpenSC, which is a supply chain transparency and traceability platform [24]. The technology stack can be used to certify that a product was produced according to environmental, social, safety, or other quality standards. In an example they demonstrate how in combination with Internet of Things (IoT) a distributed ledger is able to track wood and record its location, temperature, and exposure to light. During the whole process, the data is securely and tamper-proof stored on the distributed ledger.

A further example of using DLT for organic food companies is presented in the paper by Keller and Kessler [21]. They approach the identified challenges with a distributed ledger platform guaranteeing the traceability of certified products. The platform also serves as a trading platform. However, the authors conclude that such an approach makes little sense for a single label company, since the identified problems could theoretically be solved by a traditional centralized approach with the label itself as the central trusted third party.

A recently published study by Stiller et al. [25] examines the tracking of dairy products in Switzerland. They argue that if a company wants to add value to its products by using a DLT to label milk as 'Swiss made', the standards of the Swiss milk must be different from those in other countries. Such an additional standard could be represented by 'sustainability'. If such a differentiation is given, then distributed technologies such as DLT could improve and create transparency between the actors.

3. Methodology

3.1. Design Science

Our paper follows the general design science research (DSR) approach to build and apply designed artifacts in practice with the aim to produce knowledge that can be used for solving specific practical challenges [26,27]. According to Hevner et al. [27] the DSR framework consists of three different pillars. The first pillar represents the Information System (IS) research, which is performed by conducting behavioral science and design science research. Behavioral science develops theories and justifies them, whereas design science builds an artifact and evaluates it. Such an artifact can be classified into the four broad categories of construct, model, method or instantiation. Their assessment offers better insights and leads to a new refinement, which is often shown as a future research possibility. The final goal of IS research is the application of the results in the appropriate environment and to contribute to the knowledge base.

However, IS research can only be performed if a business need is given by the environment [28]. Therefore, the second pillar of DSR is the business environment. The environment consists of the people within the organization, the organization itself, and the technology. The people need to be identified and their roles and capabilities must be stated. They affect the environment by perceiving opportunities and challenges and acting according to them. The organization itself delivers the needed context and defines the scope of the environment. The technology plays a major role, because the two previous subcategories are positioned according to current technology, infrastructure, and communication architecture.

The last pillar of DSR is the knowledge base. It is used to demonstrate the rigor of the research. It offers the researcher an artifact type to conduct IS research. Furthermore, a research methodology is drawn from the knowledge base. It defines critical points such as the data analysis technique and the data measurement.

3.2. Application of Design Science Research

Our research approach can be divided into five steps as shown in Figure 1. First, we conducted an initial literature review following the principle of Okoli and Schabram [29], while keeping in mind the recommendations by vom Brocke et al. [30]. We used a keyword search on EBSCO, ScienceDirect, and Google Scholar. Moreover, we applied forward and backward search to expand the number of articles. Through a synthesis of the literature it was then possible to capture a snapshot of the current state of research. The literature review was followed by the organization's environment analysis. In order to understand the environment, we conducted 14 semi-structured interviews [31] with different stakeholders of the regional label ecosystem in Switzerland (5 producers, 3 regional labels, 3 umbrella organizations, 2 certifiers and 1 retailer) and defined the actors and their roles. To conduct the interviews, we developed an interview guideline as shown in Appendix A. The analysis of the semi-structured interviews followed the guidelines set by Mayring [32]. In a first step we summarized the most important statements from the recorded interviews, which afterwards were categorized in a second step into process descriptions, problem-statements, and requirements for a potential application. In a third step, based on the process descriptions, we could then model the different processes by using the BPMN 2.0 standard [33]. The resulting ecosystem and process maps were reviewed by the interview partners and their suggestions for improvement were adopted. In a fourth step, we derived from the problem-statements the specific problems of the current certification process. In a fifth step, we used some of the interviews (with three producers, three regional labels, the umbrella organization, and the certifier) to derive requirements for an information system. The elicitation of requirements was conducted in accordance with the article published by Nuseibeh and Easterbrook [34].

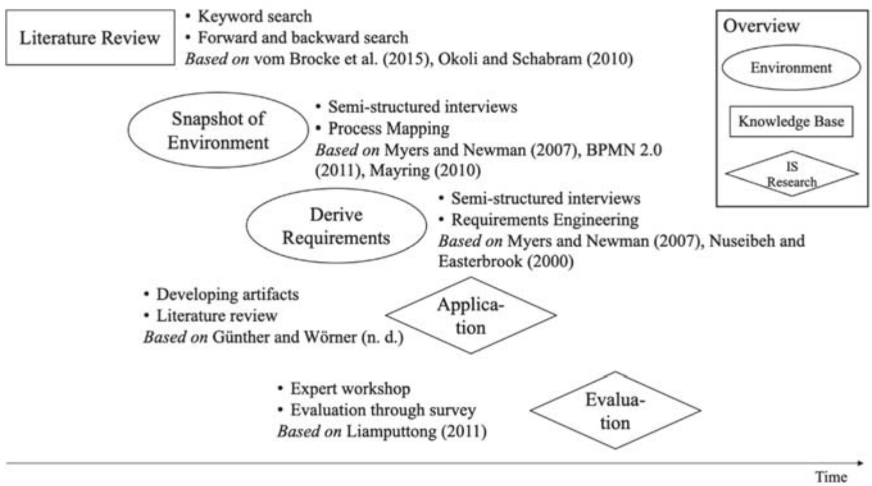

Figure 1. The DSR approach applies a five-step procedure.

After having defined the requirements, we searched for Swiss distributed ledger concepts for traceability in general supply chains, since no specific regional label solution existed. We found four suitable distributed ledger concepts within Switzerland and after a first short evaluation we selected two of them for further evaluation. We contacted the developers and asked them if they can adapt their concepts to our specific case. The outcome of the adaptations represents the IT artifacts for our research in the form of models according to Hevner et al. [27]. Asking the creators to build the artifacts is beneficial since it offers a high accuracy while avoiding misunderstandings. Next, each IT artifact was presented at a workshop held on 28 January 2020. An evaluation panel consisting of the two concept creators, six DLT experts, and three regional label ecosystem stakeholders as application users evaluated each artifact through a questionnaire. After analyzing the questionnaires, we assessed–based on the approach proposed by Liamputtong [35]–together with the involved stakeholders, whether the proposed IT artifacts can solve the current challenges in the certification process and add value in practice. Based on the evaluation and discussion of the two artifacts, we could then derive further insights and knowledge about the design and the application of DLT solutions within a specific environmental context.

4. Swiss Regional Label Ecosystem Analysis

4.1. Stakeholders

The primary subject of interest for this study is the regional label ecosystem. Its structure is depicted in Figure 2. The umbrella organization is at the highest level of the hierarchy. It has fifteen regional labels as its members. Each member operates within a different geographic part of Switzerland. Their main business process consists of certifying products of producers (e.g., farmers) as regional, which is defined as at least 80% of the ingredients and at least two-thirds of the generated value of any certified product coming from the declared geographic region. Any certification will be assessed and regularly reassessed by an independent certification body. The certification is used to increase the value of the product by communicating to the consumer that it is produced regionally and complies with certain additional predefined rules and standards (e.g., higher animal breeding standards). The umbrella organization's as well as the regional labels' source of income is the producers, who pay a certain amount to be certified. Additionally, they also receive governmental funds for regional development.

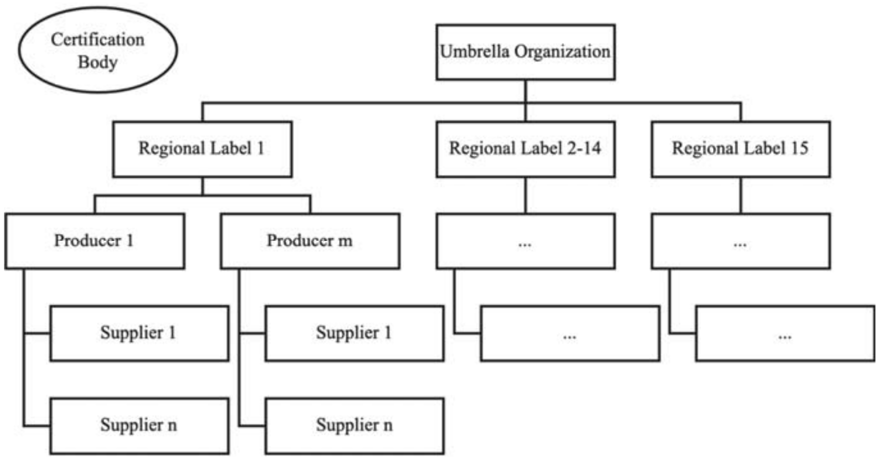

Figure 2. The regional label ecosystem consists of an umbrella organization, regional labels, producers, and a certification body.

4.2. Certification Process

A simplified certification process is shown in Figure 3. The process starts with the regional labels acquiring a producer as a new customer. Then the producer has to fill out up to eight registration documents and save them in his database. Since a signature and additional information of the producer's suppliers are needed, the producer has to transmit the documents (often via e-mail) to them. Transferring and signing documents are normally done physically; therefore, documents are often saved physically, then signed, and scanned again.

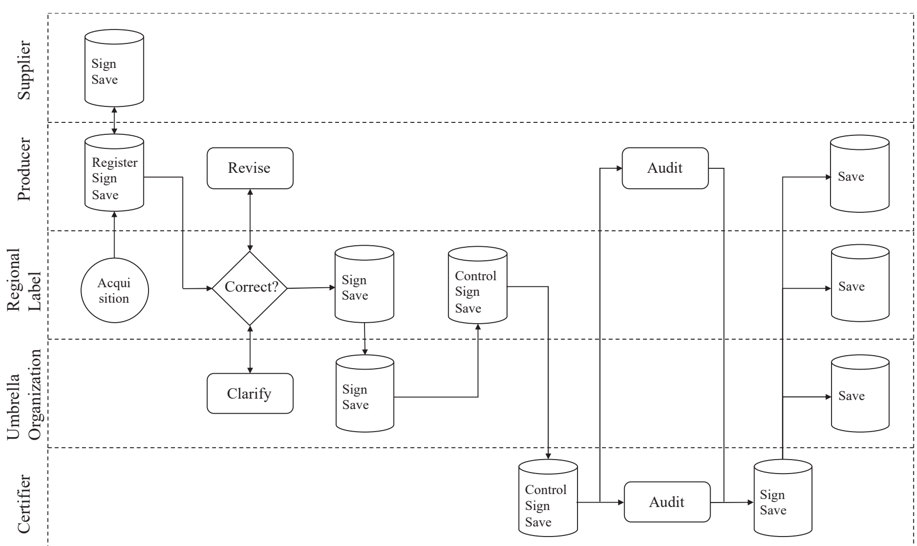

Figure 3. The certification process requires signing and storing documents by all participants.

After signing the documents, the suppliers save a copy and send the original document back to the producer. The producer saves the new documents. Later, the documents are sent to the corresponding regional label for checking. If something is faulty, the documents are either sent back to the producer, and amendments are demanded, or they try to clarify the issues with the umbrella organization. If the documents are valid, the regional label signs them and scans the documents to store them in its database. The documents are delivered by mail or e-mail to the umbrella organization. There, the documents are signed and saved to the respective database. After completion, they are sent back to the corresponding regional label so it can be controlled for completeness. Afterwards they include an updated version of the documents in their own database. Then they transmit the latest version to the external certifier responsible for the audit to check whether the requirements are met by the producer. However, before the certifier can initiate the audit process, he checks all documents and saves them in his local database. Only then, if all these steps are performed correctly, does the certifier undertake the audit on the producer site and sends the final audit report together with the signed documents to all the other participants. Consequently, everybody updates their local database one more time.

For the on-site audit, the certifier arranges an appointment with the producer. The certifier checks the invoices and delivery notes of the producer's suppliers in order to assure that all ingredients are regional. Besides that, the production processes are checked to verify that a mix-up with non-compliant raw materials can be excluded.

In the whole process, standard Microsoft Office tools are used by all parties. The umbrella organization emphasized that they rely on Excel for calculations, as well as for defining recipes for complex goods. For data sharing, Dropbox and WeTransfer are often being mentioned. However, these tools are normally used for intra-company communication. Additionally, the umbrella organization stated that they use AdobePro to edit documents.

4.3. Current Problems

The certification and audit process offer insight into various challenges. The certification involves cumbersome multi-step communication. The communication paths lead from point to point through the entire process chain. This renders high throughput times of the entire process and producers need to wait for a long time until being awarded the label. Moreover, this communication process is quite static and does not quickly adapt to changes. If the state of a document changes, it has to be communicated to all participants.

Furthermore, the lack of transparency and traceability of the products and the certification process influence the consumers as well as the participants in the supply chain. On one hand, the consumers are not able to understand easily how the label on a product translates to quality standards. They would first have to read all the guidelines on the internet to understand the process. On the other hand, they are not able to trace the product on their own and have to rely on the promise of the regional label and the diligence of the involved actors. The producers are affected by the lack of transparency as well. It has become apparent that the effort for a small business to check the origin of the raw materials is high. The producers do not influence the suppliers' suppliers and need therefore to trust in the declaration of their direct suppliers.

In addition, however, the data and information saving practices by the actors are challenging. The process model explicitly shows that the certifier, the umbrella organization, the regional labels, the producers and all the suppliers maintain their separate databases and save the documents differently (e.g., digitally or physically). With these practices it takes more time to find documents than usual. The on-site audit process becomes especially inefficient, because the producers gather all the documents, print them, put them into a folder and the certifier goes then through each document. The transparency and traceability suffer from these information silos since no overarching framework is available. What is more, these redundant storages pose a high threat of creating inconsistencies within the ecosystem.

Lastly, there are no standards for the files. This aspect is two-fold. On one hand, there is no standard on how to store the files. Currently, they are either being printed out or saved electronically (or a combination of both). On the other hand, the standard on how to structure the documents can be improved as well. Although there is a form for the certification and the audit process, there is still a lack of standardization for documents. These variations can lead to confusion and increase the process complexity.

5. Requirements Engineering

Based on the work by Myers [31] and Nuseibeh [34] we extract requirements from the conducted interviews with the producers, regional labels, the umbrella organization, and the certifier. In the interviews, we asked the stakeholder the following question: "What must a digital certification application be able to do?". For the umbrella organization it is important that the introduction of the new application is accompanied by the application providers since new IT-systems can be overwhelming for the producers. Moreover, it became clear that the application should be simple and unify all the processes.

The regional labels desire an application that can reduce redundancies. Currently, many steps such as signing and sending papers during the certification process are done multiple times. Furthermore, it was mentioned that it is difficult to trace the product along the supply chain. While offering traceability, the application should also integrate all the involved actors. The regional labels emphasized the need for a simple application, meaning that the user interface (UI) should be customer-friendly, and it should provide an efficient method of data input. Additionally, one regional label mentioned that there should be a certain degree of privacy since they do not want to offer insights on critical business processes. Security is also one of the regional labels' demands since they do not want any sensitive data to be leaked.

The producers pointed out that a new application must make the current audit process more economical. They think that it is sufficient that only one certifier does the audit (instead of two) and that the recertification process could happen fewer times. They also indicated that the application should offer the ability to trace the products since this would reduce their workload during the certification process. Moreover, they raised concerns about a too complicated application and therefore simplicity was yet again named. Lastly, the producers stated that they want a high degree of privacy and security as well. The certifier stated that they require a guaranteed and credible traceability.

In conclusion, as shown in Figure 4, we could derive eight requirements from the evaluation of the interviews. The four requirements 'redundancy reduction' (R1), 'traceability of products' (R2), 'unification of all parties' (R3) and 'reduction of costs' (R4) can be directly related to the identified problems within the certification process. Whereas the four requirements 'simplicity' (R5), 'easy data capturing' (R6), 'privacy' (R7) and 'security' (R8) are more general requirements for a new IT solution not directly related to the current issues, but still mentioned in the interviews. These requirements serve as a basis for evaluating the artifacts presented in the next section.

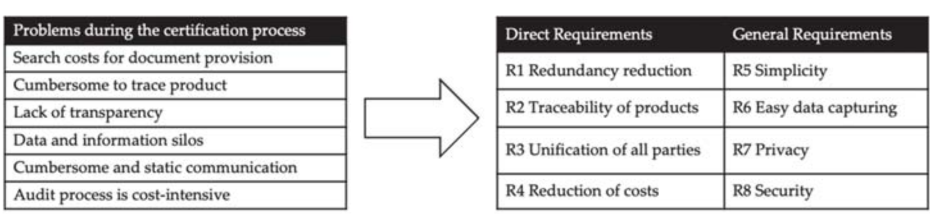

Figure 4. Overview of requirements.

6. Artifact Development

6.1. Ethereum-Based Artifact

The first artifact is based on a client-server architecture, as shown in Figure 5. A database (in this case NEO4J), a graph index manager, and the synchronization service together form a node. The nodes have direct access to the Ethereum distributed ledger [36] and the InterPlanetary File System (IPFS) [37]. A node is able to create acyclic graphs and to save them on the distributed ledger. Web clients can access the Ethereum distributed ledger by using the remote interface. Based on that basic architecture, a specific application for our use case would have the goal of offering a faster and traceable (R2) process. The focus would also be on redundancy reduction (R1) and the unification of all the stakeholders (R3). The realization of those goals happens by replacing the physical signatures currently used through digital ones and by exchanging documents over IPFS.

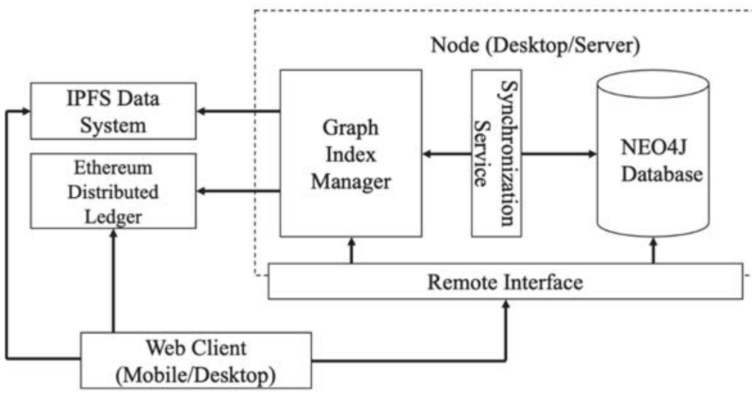

Figure 5. The Ethereum-based artifact has a classic client-server architecture with a distributed ledger backend.

The proposed architecture could be applied to our use case as follows: Full clients (e.g., some regional labels, certifier, umbrella organization) can be compared as full nodes in a distributed ledger network. They participate in the validation process, communicate to the peers and store all the validated transactions. On the other hand, simple clients (producers, consumers) access the network over full clients. Thereby, they do not have to have a lot of computational power, but still benefit from the DLT solution. On the network side we have two public networks. The Ethereum distributed ledger is used for verification purposes. The other network is a distributed database system (i.e., IPFS) in order to store the documents. Lastly, documents will be stored in the form of acyclic graphs on the distributed ledger and IPFS.

The workflow, depicted in Figure 6, begins with the producer registering for the labeling process (1). The registration form would be represented through a step by step guide. As soon as the producer uploads all the needed documents, a smart contract is created for the suppliers (2). Then, the suppliers have to upload their documents and sign everything (3). This then goes back to the registration form (4), which creates another smart contract for the agreement (5). The regional label and the umbrella organization check whether all the documents fulfill the requirements and if so, they sign the documents as well (6). By signing the documents, the producer has the proof of fulfilling the requirements and has the right to call the certifier for the audit.

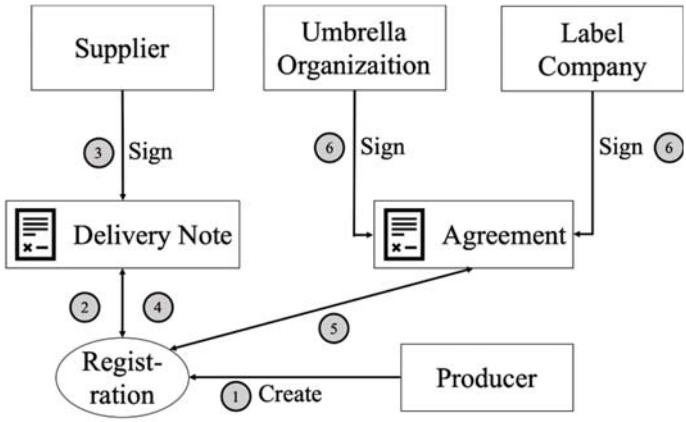

Figure 6. The workflow of the certification process in the Ethereum-based artifact.

6.2. *SupplyTree Artifact*

The work of Guenther and Woerner [38] introduces the concept of SupplyTrees. The authors propose to use a federated system, instead of using a fully distributed system to keep track of the data within a supply chain. They point out that the characteristics of a distributed ledger such as auditability and immutability can still be achieved, while providing a better scaling behavior. In Figure 7 we demonstrate how such SupplyTrees work. Companies are represented through node objects N on a certain tier X. The data objects D flow from tier to tier, until the finished product reaches the root node RN. To guarantee the confidentiality and integrity of data objects, they are being hashed h(D). Later, the hash h(D) is added to the node object N in the current tier. Then a hash of the node object h(N) is created and sent to the next tier. This process is done until the final hash reaches the root node.

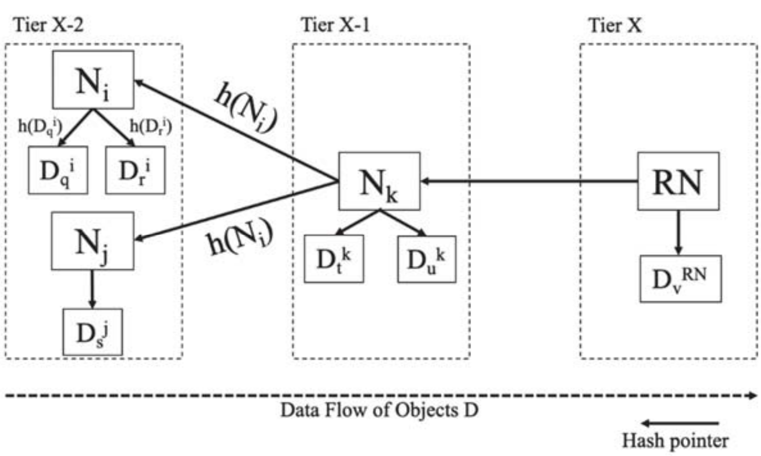

Figure 7. The SupplyTree concept uses hashed links to the previous supply chain tiers.

If the root node RN wants to trace a product's supply chain, it requests the node object content from the previous tier X-1. Afterwards, it hashes the content and compares the hashes. If there is a match, the node object content of the tier X-2 is requested and the process continues.

Based on that architecture, a specific adoption to our case would have the main goal of guarantying traceability (R2) within the certification process. This would additionally require that self-sovereign identities are established and that the nodes are capable of creating digital signatures. In contrary to the previous artifact, traceability would only be obtained if one entity requests it. Without a request of an entity and the permissions of the previous tier, traceability is not possible. Thereby, a high degree of privacy (R7) is achieved. Moreover, this artifact focuses on reducing process costs due to a lightweight implementation (R4). Figure 8 shows the adaption of SupplyTree to the regional label ecosystem.

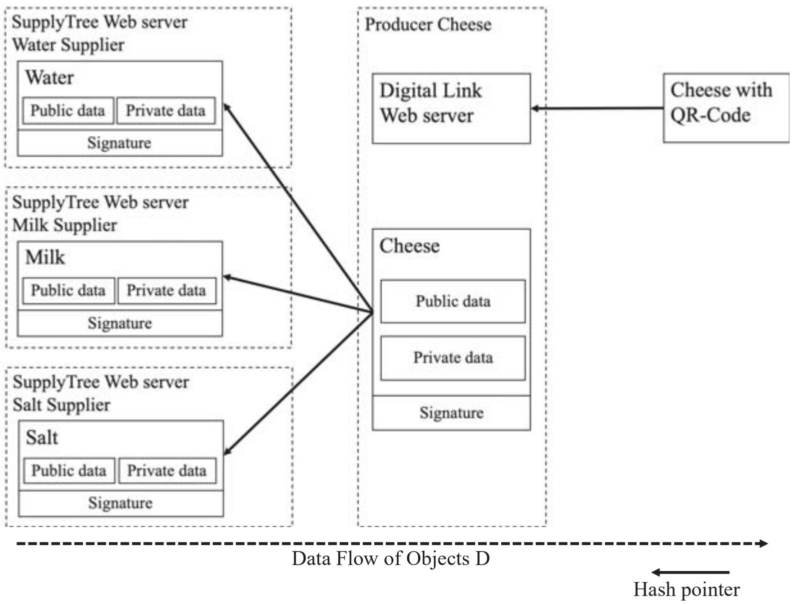

Figure 8. The SupplyTree artifact applied to the production of cheese, where each actor possesses its own web server and database.

Our exemplary use case focuses on the production of cheese, where multiple actors are involved. Prerequisites are that each of those actors in the supply chain must own a web server and a database. Moreover, each participant creates a self-sovereign identity and defines publicly and privately available data. Each participant hashes the data and the node object and sends it to the cheese producer. Additionally, the hash is saved on the web server. Digital signatures are used to establish authenticity.

Later, the producer includes each hash in his node, adds additional data, hashes everything and puts it on his web server. The activity of hosting the servers could be done by the regional label. The final product receives a QR-code, which creates a link to the corresponding web server. If customers want to trace the product, they can ask the producer to hand over the data in the node object. Next, they can hash and compare the hash output to the initial value.

7. Evaluation

During a workshop, the two concept creators, six DLT experts, and three regional label ecosystem stakeholders (two representatives from two different regional labels and one representative from the umbrella company) evaluated with a questionnaire if the two designed artifacts satisfy the requirements. Each artifact was presented by the respective creator and afterwards the participants directly wrote down whether the artifact fulfills the stated requirements. We asked specifically for each requirement, except for privacy (R7) and security (R8), since those are given by the nature of a distributed ledger. The results of the questionnaire are shown in the second and third column of Table 1. The evaluation showed that all participants agree that the Ethereum-based artifact would reduce redundancies (R1) and would integrate all involved actors (R3), whereas the SupplyTree artifact profited from the fact that a UI was already developed and presented. This allowed the less IT-affine participants to see what a prototype version would look like. Therefore, in comparison to the other results, the results regarding the perception of the simplicity of the application (R5) and data capturing (R6) were perceived better compared to the Ethereum-based artifact.

Table 1. Results of the discussion.

Requirements	Ethereum	SupplyTree	Artifact Elements Ethereum	Artifact Elements SupplyTree
R1 Redundancy reduction	11	8	Smart Contract & IPFS	Shared Infrastructure & Standardized Processes
R2 Traceability of products	5	5	Distributed Ledger	Linked List
R3 Unification of all parties	11	7	Full & Light Clients	Shared Infrastructure
R4 Reduction of costs	6	5	Automated Workflow	Automated Workflow
R5 Simplicity	3	7	Web Client	UI
R6 Easy data capturing	4	7	Web Client	UI
R7 Privacy			Encryption & NEO4J Database	No Shared Database
R8 Security			Distributed Ledger	Hash Pointers

Nevertheless, the questionnaire clearly demonstrated that most participants were not able to accurately evaluate whether the proposed artifacts fulfill the requirement of traceability (R2) and reduction in costs (R4) based upon the presentations. Therefore, the requirements were further assessed during a discussion within the evaluation panel following the presentations. The aim of the open discussion was to understand better how the designed and presented DLT solutions fulfill the specified requirements. To visualize the outcome of this discussion, we show the elements of each artifact corresponding to the respective requirement in the same Table 1.

In the discussion about the Ethereum-based artifact it became again visible that for most participants the advantage of this artifact is the elimination of redundancies (R1) since the Ethereum distributed ledger allows the implementation of smart contracts and the IPFS data system provides a single point of truth. Additionally, it allows the unification of all parties (R3) as all stakeholders are either full or simple clients in the distributed network. However, when it comes to traceability (R2), reduction of costs (R4), simplicity (R5) and easy data capturing (R6) many of the regional label ecosystem stakeholders could not provide a clear statement. Due to the high complexity of the distributed systems, it became obvious that for them it was difficult to understand how traceability (R2) is achieved, how costs are reduced (R4), how simplicity (R5) would be guaranteed and how data is captured (R6). That is why they abstained the vote on those four points. The concept creators and the DLT experts within the evaluation panel agreed that traceability (R2) was achieved because Ethereum offers a fully distributed ledger providing transparency and immutability. However, they were split over the simplicity (R5) of the application, since a UI for the web client could be developed later. Consequently, whether easy data capturing (R6) could be achieved depends strongly on the realization of the UI. The requirement regarding the reduction in costs (R4) received mixed feedback as well. Even though the majority of the entire evaluation panel agreed on the improved speed of the processes, many are concerned about the costs of developing and operating such an Ethereum-based application. The last two requirements of privacy (R7) and security (R8) were assessed only by the concept creators and the DLT experts. The regional label ecosystem stakeholders were purposefully excluded, since they already stated at the beginning of the workshop that they cannot make accurate estimations. The concept creators and DLT experts concluded that privacy (R7) can be achieved, since encryption algorithms are used and since there is an individual NEO4J database for each node. This would be sufficient to, e.g., guarantee the secrecy of critical business processes. Regarding the last requirement concerning the security (R8) the creators and the experts concluded that this is given as well, due to the nature of distributed ledgers.

The discussion regarding the designed SupplyTree artifact was mainly focused on the already existing UI and the inability of creating traceability (R2) within the ecosystem. The UI showed everybody how simple such an application could be (R5) and that the capturing of data happens easily

(R6). In contrast to the Ethereum-based artifact, the DLT experts and concept creators agreed that traceability (R2) cannot be achieved to the same extent due to the artifact's architecture. Since it is a linked list, the data is only visible to the consumers if it is explicitly demanded by them. Otherwise, the data remains with the nodes. Therefore, the proposed artifact is dependent on the cooperation of all nodes. If that is not the case, then tracing is not possible. The evaluation panel further stated that the SupplyTree reduces redundancies (R1) due to the shared infrastructure and the standardized processes. This shared infrastructure also unifies the involved parties (R3). However, in contrast to the Ethereum-based artifact the unification happens to a smaller degree, since the actors can by default not see the entire supply chain, but only adjacent actors. Furthermore, it was agreed that the SupplyTree artifact can reduce the costs (R4), because the process gets optimized and there are no transaction costs involved. Lastly, the DLT experts and concept creators agreed that privacy (R7) is achieved due to the fact that there are no shared databases and data are stored individually. Moreover, security (R8) is also given since the architecture relies on the utilization of hash pointers.

The participants concluded that if the evaluation is corrected for the UI-factor, the outcome is in favor of the designed Ethereum-based artifact. The main reason for correcting the evaluation is the fact that the UI can be developed at a later point in time. Additionally, the discussion brought to light the fact that the fully distributed and completely decentralized system of the Ethereum-based artifact fulfills the requirement traceability (R2) and unification (R3) better. The better results of the SupplyTree artifact regarding the requirements simplicity (R5) and easy data capturing (R6) were caused by the presented UI.

During the open discussion, the value of a distributed ledger application for the regional label ecosystem was generally questioned. The group discussion raised the following four concerns:

First, all parties involved in the certification process already have a high trust in each other, which implies that a much simpler file sharing application provided by any centralized third party could be a more efficient and effective solution. Second, a short benchmark with two other regional label ecosystems from other regions in Switzerland revealed that they only need two parties to check and sign all required documents for the same certification process, which makes their process by design much more efficient. Third, while conducting our interviews with the stakeholders as well as during the workshop discussion, we could not find any evidence that consumers would be willing to pay more or to buy more of a labeled product just because its origin and production steps are traceable. This consideration goes along with the findings of [25], where the authors conclude that the consumers do not see a benefit of using a QR code to receive more information about the Swiss milk supply chain. Fourth, in the current certification process neither the producers nor the regional labels are required to provide an extensive track and trace of all their raw materials and production steps. A short statement signed by all involved parties, covered by the correct delivery notes and invoices is currently enough to pass the audit process and to establish transparency into the supply chain.

8. Discussion

The development and evaluation of the two distributed ledger artifacts produced some insights, which we would like to discuss further. Based on our designed artifacts, it seems safe to say that a distributed ledger application can mainly generate practical value if it is truly distributed and decentralized, as otherwise the traditional governance and therefore trust problems of centralized applications will arise again. To create a transparent and unified regional label ecosystem, our designed artifacts have also shown how important it is that all parties involved have direct access to the data of the distributed ledger as full or light client. In order to simplify this access and to enable easy data entry, a corresponding user interface in the way of a well-designed web client is required. Once a shared infrastructure and automated workflows in the form of smart contracts are established, it is safe to assume that current process redundancies and therefore costs could be reduced. Security and data privacy concerns can thereby be ensured by appropriate encryption mechanisms and by storing sensitive data in an individual database.

However, even though a distributed ledger system can create a common platform for exchanging, signing and storing all needed documents in a secure and transparent manner and therefore reduce process redundancies and costs, such an application is currently not a good fit for the regional label ecosystem. This is mainly because we could see that the perceived high costs and complexity of DLT applications cause at least smaller organizations to be reluctant to invest in this new technology. In the light of the efficient processes of other regional labels, we would therefore suggest that the umbrella organization needs first to eliminate all unnecessary and inefficient steps in their certification process as identified in Section 4.3. Only in a later step, the digitalization of the process should be taken on to achieve further optimizations, and the implementation of a DLT application can be again considered.

Moreover, the often-stated request of consumers for more transparency and product traceability [1] does not necessarily hold true in every context and environment. At least for regional labels in Switzerland it seems implausible to assume that a distributed ledger system can add value by increasing the transparency for consumers in regional supply chains and thereby increasing the buying intentions for a specific certified product. Based on the evaluation panel's opinion, consumers in Switzerland already trust the statements of regional labels and do not explicitly demand more transparency. For short and regional supply chains, where the involved parties are well known (and to some degree trusted), it might be therefore questionable whether DLT can provide enough benefits in comparison to its–at least currently–high development and implementation costs.

Furthermore, the regional labels in Switzerland can create the required transparency with relatively simple documentation and audit processes. Currently, producers can prove their compliance with basic (physical) documents like delivery notes, invoices or signed statements as well as simple process adaption to avoid the mix-up in their supply chain. The current process satisfies the trust-demands of the consumers and the regional label regulations in Switzerland. Any comprehensive end-to-end track and trace application would inevitably create additional efforts and costs along the entire supply chain without creating (enough) value for the regional label ecosystem. It seems therefore, that for low regulated markets, distributed ledger applications are currently a too complicated and costly solution. To put it the other way: DLT applications seem to be particularly valuable in environments where a high level of transparency is mandatory (e.g., by regulations) but difficult to achieve due to the lack of a shared trusted solution.

9. Conclusions

In this study, we performed multiple steps for answering our research questions with the aim to produce new knowledge that can be used to design distributed ledger applications for solving current challenges in practice. Our findings offer insights into current challenges of the regional label ecosystem. Those challenges are embodied in a lack of traceability, inefficient and static communication paths, data and information silos, no standardization for files or file storage, a cumbersome audit process, and high search costs for document provision. As a consequence, an application should satisfy the elicited requirements. In particular it should make the certification and audit process simple, unify all parties, reduce redundancies, increase data security and privacy, improve the traceability of products, offer easy data capturing and lower certification costs. Intending to fulfil those requirements, we designed two distributed ledger artifacts, which should overcome the current challenges and add value to the regional label ecosystem.

To answer the first research question–what a distributed ledger application could look like to provide higher efficiency and transparency for a Swiss regional label ecosystem–we point to the designed and discussed artifact elements. To be a good match for the Swiss regional label ecosystem, such a distributed ledger application should have (a) an open and decentralized architecture, (b) give all participants full access to the shared data via full or light clients, (c) provide security and privacy by encryption and individual storage for sensitive data, and (d) offer simplicity and easy data capturing by a well-designed web client.

However, we answer our second research question–if the concept can add value–negatively. The challenges of the regional label can be better solved by conventional process optimization. A distributed ledger application seems in the current situation an over-engineered approach for a Swiss regional label ecosystem.

Lastly, we would also like to point out that our conducted research has certain limitations. On one hand, we would like to emphasize that our results may only apply to Switzerland. In other countries the initial situation could be different, and the consumers could have a different perception of labels. On the other hand, our evaluation was based on the opinion of experts and the artifacts were not implemented and tested. Therefore, we were not able to evaluate possible positive effects such as marketing opportunities, synergies, or first-mover advantage or possible negative effects such as transaction cost, implementation difficulties or governance issues. However, as the perceived value was low by all relevant Swiss regional label ecosystem stakeholders, it is also not surprising that they stopped further adoption and development efforts.

We therefore propose for future research to look deeper into conditions under which a DLT approach could add value for a regional label environment and to elaborate on possible designs for DLT application for small-scale label applications. The insights from our research regarding the spatial extension and complexity of a supply chain and the regulatory requirements of a specific market environment could thereby provide a good starting point.

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Appendix A

Interview Guideline (translated–Original is in German)

Topic 1: Getting an overview of the (re-)certification process–questions:

- Could you describe the (re-)certification process?
- Who is involved in the process? When? With which role? (e.g., what role does the certification body play? e.g., what role does the regional label play? The umbrella organization?)
- Which documents/data do you have to keep? Where are they stored? For how long?
- How do you create or where do you get these documents/data/information from?
- How do you check the authenticity/validity of the documents/data you receive?
- What does the certification company check? And how does it check data/documents/information?
- What effort is involved in creating, collecting and storing the documents?
- What effort do you have for certification? And re-certification?
- What happens if something is wrong? Get lost? Forgotten? Wrongly stated or entered?
- . . .

Final objective: We should be able to describe and map the current (re-)certification process in detail and understand the current issues/problems/barriers/challenges.

Topic 2: Understanding the requirements for a 'digital platform' ('App')—questions:

- Which IT tools to support the certification process do you know or currently use?
- Where do you see the biggest problems/difficulties in the certification process today?

- What should or can be improved in your opinion?
- What would a digital platform have to 'do' to help in the certification process? Or in your everyday business in general?
- Under what conditions would you use a digital platform ("app")? (e.g., only if on cell phone? or only if on computer? etc.)
- ...

Final objective: We should be able to record and describe the digital 'desired certification process' including the requirements for a 'digital platform (app)'.

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