Using Distributed Ledger Technologies to Support Complex Supply Chains

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Completed Research

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Abstract

The concept of blockchain, as part of distributed ledger technologies, has gained a lot of interest recently, especially in cryptocurrencies. With the addition of other technical capabilities, e.g., smart contracts and oracles, this interest has spread to other areas as well and affects a wide variety of business processes such as supply chain processes. However, in research, the wide variety of processes finds inadequate consideration to date. In this research paper, we provide an overview of the state of the art of distributed ledger technologies in supply chains and point out future research topics. Therefore, we conducted a structured literature review, systematized potential application areas in supply chain processes, and showed that research gaps exist. To address the research gaps, we derived open research questions, whereby conducting design studies to deal with the practical problems in the application areas plays a central role.

Keywords

Distributed Ledger Technology, Supply Chain, Adoption, Literature Review, Research Agenda.

Introduction

Due to the preceding changes within economic processes through the influence of globalization and digitalization, there is also pressure to modernize the logistical activities of companies. As simple supply chains (SC) have grown into complex and interconnected value-creating ecosystems, the need for supporting technologies increased (Gaur and Gaiha 2020). A current, challenging example is the worldwide distribution of vaccines against COVID-19, which poses difficulties for global supply chains. This is therefore a remarkable example of complex supply chains, as there are only a small number of manufacturers in the world who need to ensure safe, traceable, and verifiable manufacturing, distribution, and delivery of vaccines worldwide. In addition, there are often still paper-based information flows in logistical processes which, for example, lead to time delays in processing when documents are missing within customs clearance (Jensen et al. 2019). Furthermore, Electronic data interchange formats, e.g., XML, may support communications between companies, but this is not sufficient given the availability of smart Internet of Things (IoT) devices such as sensors and radio frequency identification tags as active parts of SCs. Therefore, that is a problem because there is no trustworthy way to control the identity of IoT data, such as the treatment of the vaccine during transport and its cold delivery (Alahmadi and Lin 2019; Kshetri 2018). Consumers are also demanding more information about the products they buy, such as where they are produced, as environmental and ethical considerations become more important (Agrawal et al. 2021). This is involving the concerns of proper handling of vaccines and their origin. There exist trust issues between different stakeholders in commonly deployed SC in practice. These trust issues can currently not be fully solved using existing centralized information systems (Loebbecke et al. 2018). Among other things, this is reinforced by different levels of information among the participating actors (Du et al. 2020).

A potential way for the technical support of SC processes is the use of distributed ledger technologies (DLT). Due to its decentralized data storage, this technology can create a uniform database for all actors involved

(Li and Zhou 2020). DLT provides solutions for transaction-based, trust-requiring processes in which multiple parties access shared data while ensuring security standards (Stahlbock et al. 2018). Furthermore, smart contracts or oracles can complement DLT, because oracles offer the possibility to extract data from the real world by acting as a middleware, whereas smart contracts realize digital contracts and automation potentials (Koirala et al. 2019).

Due to the technical possibilities offered by DLT, this research area has also gained relevance for SC research. However, this is a young field of research, as DLTs emerged with the appearance of the Bitcoin blockchain by Satoshi Nakamoto in 2008 (Nakamoto 2008). Caused by the constant development over the last decade, the potential benefits of DLT in SC processes are now realizable. Nevertheless, research must answer questions raised by the potential use of DLT. It is therefore important to identify and analyze SC processes that use DLT and offer value. Furthermore, it is important to find out how DLT can provide added value in suitable processes and how potential applications are designed (Jakob et al. 2018; Kummer et al. 2019). Therefore, this paper provides an in-depth analysis of the current state of the art as a starting point for further research. With the help of a structured literature review, the scientific and practical approaches of DLT deployment in supply chains are analyzed. Due to the high diversity and the scope of complex supply chains, a structured systematization of existing results is necessary. Based on the conducted structured literature review, we analyze the current literature, describe the outcomes, and postulate open research questions. Thus, we address the following research questions:

RQ1: How can research towards distributed ledger technology within supply chains be systematized?

RQ2: What are research gaps for the use of distributed ledger technology in supply chains?

First, we present the theoretical foundations and related research in section 2. Subsequently, section 3 explains the underlying methodology to present the results in section 4. For these, a discussion follows in section 5 and shows the need for further research in section 6. Finally, we conclude within section 7.

Theoretical Background and Related Research

Supply Chains are generally understood as systems that serve to carry out logistical tasks and processes (Werner 2020). A complex SC consists of further, smaller subsystems that also realize logistical subtasks and sub-processes. For example, procurement, production, and distribution services as subsystems of the overall network (Schuh 2012; Werner 2020). From the raw material supplier to the end consumer, the logistical tasks and the flow of service objects relate to each other through the overall network of value creation partners. The manufacture of products thus requires many processes that go beyond simple production and confront companies with logistical challenges, such as transport across national borders.

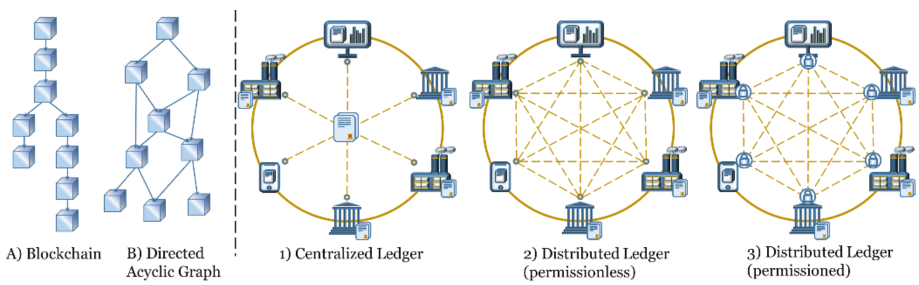

Figure 1. Comparison of DLT-Options and Data-Ledgers (Ballandies et al. 2021; El Ioini and Pahl 2018)

A promising technology to address the outlined challenges of complex SC is **Distributed Ledger Technology**. It has become an emerging topic of research in the past ten years. DLT serves as an umbrella term for blockchain technology (Figure 1, see A) and is often used synonymously. In addition, however, DLT also includes technologies such as the directed acyclic graph and hybrid variants in which an arrangement of blocks does not take place along a chain, after which the blockchain is named (Figure 1, see B). For a general understanding of the technology, the paper is based on existing definitions by Ballandies et al. (2021), and El Ioini and Pahl (2018), in which DLT serves as the implementing technology for operating a decentralized database. Consequently, a decentralized database exists that allows participating nodes of the peer-to-peer network to agree on an (almost) immutable record of transactions using a consensus mechanism (Figure 1, see 2 and 3). In contrast to a central database (Figure 1, see 1), in a distributed ledger

(DL) each authorized participant owns a local copy of the database. To ensure the functionality of the DL, some participants perform the validation of transactions. Participants can access the network either permissionless (Figure 1, see 2) or with permission (Figure 1, see 3). Within a DLT the consensus mechanism, which may differ in its operation depending on the DLT type, performs the validation of transactions. However, the goal of ensuring a consistent state of the database at all participating nodes via consensus is identical. For this, proof must be provided, e.g., by solving a mathematical problem (proof of work), although share- or vote-based mechanisms also provide such proof (Nakamoto 2008). Moreover, in recent years, DLTs have been augmented with technologies such as **Smart Contracts** and oracles to enhance their utility. Smart contracts are intelligent contracts that follow a simple if-then logic, whereby the underlying data of the DLT can be accessed. To provide information outside of the DLT, so-called **Oracles** can be used as an interface which, for example, provides data for smart contracts via RFID tags (Albizri and Appelbaum 2021).

The research area of DLT usage within SC has not been addressed widely yet, but due to the growing technical maturity of available DLTs, it became of greater interest in the last years. For example, the Bitcoin blockchain lacked scalability or smart contract support. This explains the lack of adaptability for SC processes in the past. Addressing the challenges through recent DLT developments justifies the emergence of the research area. In most cases, existing contributions focus on the positive characteristics of decentralization, trust, anonymity, transparency, and tamper-resistance inherent to DLTs. Here, research mainly focuses on specific industries or use cases such as tracking of products or financing matters (Antal et al. 2021; Du et al. 2020; Eggers et al. 2021; Ferdousi et al. 2020). Thus, there are considerations of individual logistics use cases for the application of DLT, but a structured overview and systematization of the current state of the art is missing. Furthermore, science does not give a comprehensive presentation of application areas of DLT in SC. In addition, existing research focuses on the theoretical analysis of specific cases but mostly neglects empirical research, building prototypes, evaluating them, or generating generalizable knowledge. Hence, there is a need to address and answer our research questions.

Research Design

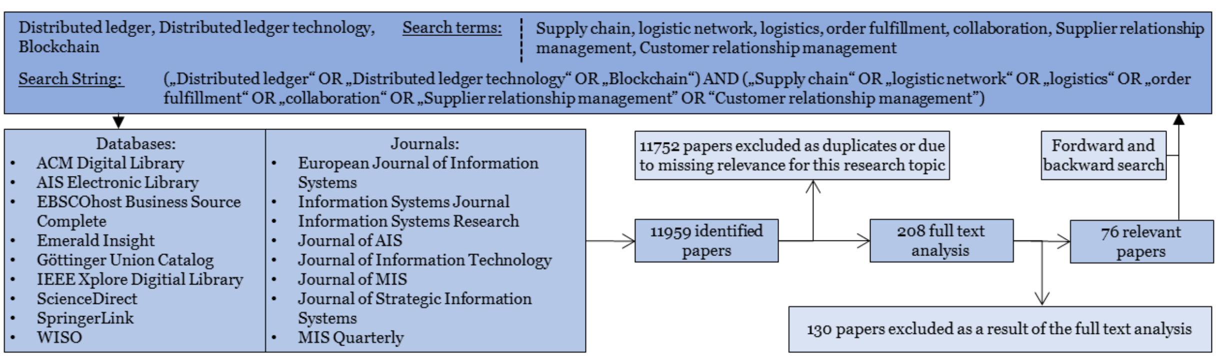

Figure 2. Research Framework

To answer the proposed research questions, we conducted a structured literature review to systemize the existing research and identify research gaps for the usage of DLT within SC processes (Fettke 2006; vom Brocke et al. 2015; Webster and Watson 2002). The aim was to provide a complete overview of the relevant literature as a solid foundation for further research (e.g., exploratory studies). We searched several scientific (e.g., IEEE) as well as practice-oriented (e.g., WISO) databases and journals for available literature using the presented search term in a full text search and considering the German equivalent. This corresponds to the languages the authors are proficient in. Also, we did not narrow down the search period, due to the young research field of DLT. We initially identified 11959 papers and checked them for duplicates and relevance to the research topic, e.g., by checking the titles and abstracts. Here, many articles have already been marked as irrelevant, as well as articles in which DLT is only mentioned as a brief outlook for future developments in supply chains but is not in focus of the study. Before a paper was included in the in-depth analysis, we further used inclusion and exclusion criteria to check whether it is relevant for answering the research questions (see online Appendix: https://tinyurl.com/2p8w8u9f). The full-text analysis of the remaining 208 papers resulted in 73 papers. Finally, we performed a forward and backward search to obtain a result set of 76 papers (Figure 2).

Descriptive Results and identified Application Domains

The distribution of relevant contributions in terms of publication type and the course of the considered contributions over time is shown in the online appendix (https://tinyurl.com/2p8w8u9f). We identified the first relevant papers in 2017. This goes along with the continuous development of the technical possibilities of DLT, which justify the relevance for SC processes. Since 2017, the number of papers increased steadily.

Our first research objective was to identify and categorize the existing research into a variety of supply chain processes. The online appendix shows the application domains that emerge from the literature and a complete listing of the assigned sources: https://tinyurl.com/2p8w8u9f. The application domains are, (1) tracking products and processes within the supply network, (2) supporting document-based information processes, (3) supporting customs processes, (4) implementing and automating financial flows, and (5) observing rules and laws and checking them for compliance. Within these domains, we surveyed the current state of research and identified potential research gaps.

Within the literature, 59 publications consider the tracking of products and processes (1). Many of these publications highlight industries in which the use of DLT makes sense, by guaranteeing transparent tracking of products and processes for food, pharmaceuticals, or luxury goods (Ferdousi et al. 2020; Loebbecke et al. 2018; Musamih et al. 2021). Particularly in the case of products such as food and medicines, special quality criteria for product and transport processes must be assured, e.g., compliance with the cooling chain or the prevention of product counterfeiting (Antal et al. 2021; Musamih et al. 2021). Numerous concepts and a few requirement analyses are presented in this area, one of which was empirically collected through expert interviews (Beck et al. 2020). The derivation of many requirements is possible in publications without a design science research (DSR) focus. The existing literature defines the requirements in terms of industry specifics and in general. For example, Kshetri (2018), Li and Zhou (2020), and Martinez et al. (2019) consider various marketable applications and cases for the use of DLT in delivery networks to analyze them in terms of requirements. Martinez et al. (2019) go a step further and work out a prototype based on their analysis and test it in real-world processes. However, this contribution forms a rarity, as prototypes are created, but the evaluation is mostly done only via proof of concepts and technical evaluations based on industry-specific scenarios. The only empirical evaluation of the prototype via interviews can be found in Beck et al. (2020), where two experts were interviewed. Furthermore, the derivation of generally valid design principles is lacking.

The second area of application, the digitization of freight documents and their management, is less considered (2). Here, the DLT serves as a document management system. In 20 cases, the derivation of requirements is possible within the literature examined. In many cases, these requirements are mentioned in connection with the application area of tracking and tracing, as the presentation of accompanying documents is closely linked to this application domain (Asprion et al. 2019; Chang et al. 2020; Liotine and Ginocchio 2020). Tan and Sundarakani (2021), Jensen et al. (2019), and Sund et al. (2020) raise requirements in their papers, with Sund et al. (2020) doing so with the help of an interview study. Other papers and practice reports allow the derivation of further requirements. Jensen et al. (2019) and Sund et al. (2020) even go one step further and present a concept to manage freight documents. Here, Jensen et al. (2019) are looking at the marketable DLT application Tradelens with the help of a case study. The development of Tradelens was carried out through cooperation between IBM and Maersk on the technical basis of Hyperledger Fabric to ensure an exchange of information between all parties involved in the delivery network, including customs authorities. A case study was also conducted by Sund et al. (2020). This case study deals with the furniture manufacturer IKEA and covers event processing including the enclosed documents for goods within SC. Furthermore, Wang et al. (2018) present a third concept in which document and workflow management within logistics is optimized using smart contracts which send an automated notification when certain supply chain processes are completed. As part of the IKEA case study by Sund et al. (2020) and in the paper by Wang et al. (2019), the concept is implemented in a prototype. Only Sund et al. (2020) are evaluating the prototype in real-world conditions, but no design principles are derived from Sund et al. (2020) or other literature.

Especially logistical documents must be viewed, evaluated, and confirmed by many parties within the SCs. Customs are also part of this, and their processes could also be supported using DLT (3). A market-ready application that considers this area is the Tradelens application. TradeLens provides supply chain stakeholders with direct and transparent access to digitized, cross-company processes and documentation workflows for their maritime supply chains. Thus, Jensen et al. (2019) also set out requirements and a concept for supporting customs processes. This is the only concept identified for this application domain. The publications by Chang et al. (2020), Li et al. (2020), Liotine and Ginocchio (2020), and Tan and Sundarakani (2021) are the only ones that consider the cross-border movement of goods and thus enable the derivation of requirements. Further research on prototypes, their evaluation, and the derivation of design principles is missing.

Cryptocurrencies, as part of DLT, have been strongly discussed and tested for use cases in the financial industry through the introduction of Bitcoin (4) (Beck et al. 2020). Such adaptations for trade finance, i.e., for the processing of financial flows within a SC, find consideration within the considered literature. The use of smart contracts to manage financial flows within SCs is closely linked to the flow of goods and information and is often considered in this way in the literature (Beck et al. 2020). In this context, various SC activities use smart contracts to trigger a payment after their fulfillment. This can be the presentation of accompanying documents or the fulfillment of a delivery (Asprion et al. 2019; Du et al. 2020). Yet, there has rarely been a focus on trade finance in the literature. For example, the prototype of Beck (2020), which has already been mentioned for the tracking of products and processes, only marginally considers the area of supply chain finance (SCF). It is therefore only possible to derive requirements here in most cases. The exceptions, who only considered SCF, are Guerar et al. (2019) and Omar et al. (2021). Guerar et al. (2019) establish requirements and a concept for invoice financing. Omar et al. (2021) on the other hand propose a concept for the automation of procurement contracts with the help of smart contracts. Du et al. (2020) present another concept focusing on warehouse receipt financing and accounts receivable financing. An implementation of this concept shows the only comprehensive prototype with SCF focus and enables the corresponding trade financing within the two mentioned use cases. A comprehensive evaluation is not available, apart from Beck (2020), whose work does not have an SCF focus. There is no derivation of design principles from the literature assigned to this area.

The last mentionable area of application is SC compliance (5). There is a close link with other processes, about checking the regulations for the inherent activities. Requirements can be derived from the literature, as in all the application domains considered above, whereby the monitoring of cooling chains, transport duration, or delivery quantity are monitored and associated with contractual consequences (Alahmadi and Lin 2019; Antal et al. 2021; Berneis 2021). Using DLT, Antal et al. (2021) and Musamih et al. (2021), for example, present a concept for using DLT in the COVID-19 vaccine distribution sector to check relevant regulations such as refrigeration and link them to consequences for breaches of contract. Automated rule checking offers, apart from product tracking, the possibility to support SCF. Beverungen et al. (2021) combine the use of equipment in SCs with a pay-per-use model controlled by smart contracts. Antal et al. (2021) and Musamih et al. (2021) also implemented corresponding prototypes for vaccine distribution, but they were not empirically evaluated. The literature shows no design principles either.

Discussion of the results

Previous literature reviews focussed on certain industries (like Kumar Reddy et al. (2021) for the automotive industry, or Tsiulin et al. (2020) for shipping and port management), consider the use of DLT and the design of the examined supply chains, and do not have a general valid scope. Furthermore, reviews often take a very technical view of DLT implementation in supply chains (Berneis 2021; Chang et al. 2020; Tsiulin et al. 2020). As mentioned in the Research Design, we performed a nearly complete literature review to conduct a generally applicable cross-sectional analysis for the use of DLT in supply chains that is not limited to individual industries or use cases. Due to the chosen focus, this study contributes an almost complete and comprehensive literature review on SC processes, by not limiting itself to individual industries, use cases, or the technical view on DLT, which leads to the main result of this literature review, where five application domains of DLT in SCs are identified as a systematization. The most frequently considered application domain is the tracking of products and processes in SCs. Concepts and prototypes can be found especially for the food and pharmaceutical industries (Antal et al. 2021; Musamih et al. 2021). Evaluations of the prototypes are rarely done and if at all rather in a technical way (Koirala et al. 2019; Sund et al. 2020). The application domains of document management, SCF, and compliance checking find less consideration. We found some concepts for these domains and the possibility to derive requirements. The scientific literature hardly considers the application domain of customs law support. We, therefore, conclude that generalized statements on the design of DLT applications for use in SCs are not derivable, as both empirically collected requirements and evaluations for the designed approaches are missing. To sharpen this research gap in more detail and to derive a research agenda in form of open research questions for design-oriented research on the DLT use in SCs, we further analyzed and categorized the contributions concerning the design knowledge base. A DSR examination of the literature was conducted because the literature review suggests that there are gaps in research within this area. For this purpose, we examined whether the contributions provide insights into (derivable) requirements, concepts, prototypes, evaluations, and generalized design principles. Our aggregation of the design contributions visualized in Table 1 proposes that there are no findings for general design recommendations and most of the requirements and concepts found have a strong focus on a specific economic sector. Even though numerous concepts and prototypes are available for tracking products and processes, there is no similarly strong foundation of research for other areas in SCs. Further, we could not identify generalized design knowledge, e.g., design principles, for any area. By applying DSR, it is possible to test DLT in the field of SCs, such as vaccine distribution. This helps to identify the expectations of DLT within SCs, e.g., providing trust or optimizing processes, because there is a need to test DLT applications in the field.

Table 1. Contributions to the design of DLT in Supply chain processes

Application context	Paper	RE	CO	PR	EV	DP	RE	CO	PR	EV	DP
Traceability of products and processes	59	58	30	16	9	0	●	●	◐	◐	○
Digital freight documents and document management	21	20	3	2	1	0	●	◐	○	○	○
Support for customs processes	5	5	1	0	0	0	○	○	○	○	○
Supply chain financing	19	17	6	2	1	0	◐	◐	○	○	○
Compliance in supply chains	19	19	9	3	1	0	●	◐	○	○	○
Requirements (RE) - Conception (CO) - Prototyping (PR) - Evaluation (EV) - Design Principles (DP) || Double assignment are possible											
● = Research results available (●); ◐ = Research results partially available (●); ○ = No sufficient research results available (●)											

However, to derive general results such as requirements or design principles, it is necessary to identify design patterns for different application areas. In this way, the creation of generally valid concepts and prototypes is possible by analyzing and systematizing the existing requirement analyses as well as the derivable requirements of further contributions for the different application areas. These requirements could be confirmed and supplemented e.g., through expert interviews, as there are no comprehensive empirical studies on the use of DLT in SCs. Therefore, an extensive analysis of application areas and their requirements as well as framework conditions, underpinned by practical insights, is required. Since the use of DLT only makes sense in certain scenarios due to its technological properties, it is necessary to examine these possible uses in detail and, if necessary, compare them with central as well as existing solutions. This comparison of existing process solutions in supply chains, such as EDI, against DLT solutions should be conducted in a structured way and the added value of DLT should be assessed. We provided the first approach for this through our structured literature research, but further, there is a need to collect practice-oriented findings to identify and validate areas of application and benefits in companies.

Open research questions

Based on the results of our literature review and the discussion on design-oriented research on DLT for complex SC, we derive the following open research questions (see Table 2):

Table 2. Open research questions

Topics to address
Q1: In which SC processes is the DLT superior compared to centralised data storage technologies?
Q2: Which factors influence the usage of DLT in supply chain processes positively or negatively?
Q3: What effects can be achieved using DLT in supply chain processes?
Q4: What framework conditions must be considered for the use of DLT in supply chain processes?
Q5: How must DLT be designed for supply chain processes?

Before addressing the use of DLT in the SC domain and deepening the knowledge, the use of this technology should be analyzed and compared with common solutions, e.g., centralized data storage, within SC processes (Q1). Based on this, inhibiting and supporting factors for the use of DLT in supply chain processes should be identified (Q2). The general use of DLT in supply chains requires research to this end. Although there may also be specifics in individual application domains. Furthermore, it is of interest for the five application domains to answer the research questions and derive theories based on practice-oriented studies. In addition, we demonstrated in the discussion that only a few contributions exist that deal with the design of DLT applications for SCs. Because only rare cases of a structured requirement analysis exist, most of the contributions only enable the derivation of requirements. Currently, academia and practitioners are considering the application domain for tracking products and processes as the only one in more detail. However, only concepts and prototypes, if at all, are available. We hardly identified any empirical research approaches, such as expert interviews. Questions arise as what effects can be achieved using DLT in SCs (Q3). Furthermore, there is a need to analyze and identify the required framework conditions (Q4). Finally, because no results are yet available in the research domain there is a need to derive design knowledge. Therefore, generally applicable design principles for the use of DLT in SCs should be collected (Q5).

Conclusion

In this paper, we systematized the current research for the use of DLT in SCs by mapping them to SC processes and identified research gaps. We found different application domains that find consideration for the use of DLT in SCs. Here, we found contributions especially for the application domain of the use of DLT for the tracking of products and processes, while other application domains, such as the support of customs processes are hardly considered. During the literature review, we showed that there is little design science research for the identified application domains of DLT in SCs. As with any research contribution, limitations apply. We reviewed the existing academic and practitioner literature through November 2021, so new articles could have appeared since that time. Furthermore, many articles were included that allow the derivation of requirements and concepts, as there are hardly any empirically collected requirements analyses that could have been included. Therefore, it is still necessary to gain practical insights into the topic to validate our findings to extend insights. To achieve this, we recommend answering our proposed open-ended questions. Thereby, we aim at building the fundamentals to reduce complexity and improve the comprehensibility of complex SCs by using DLT.

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