

Article

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.

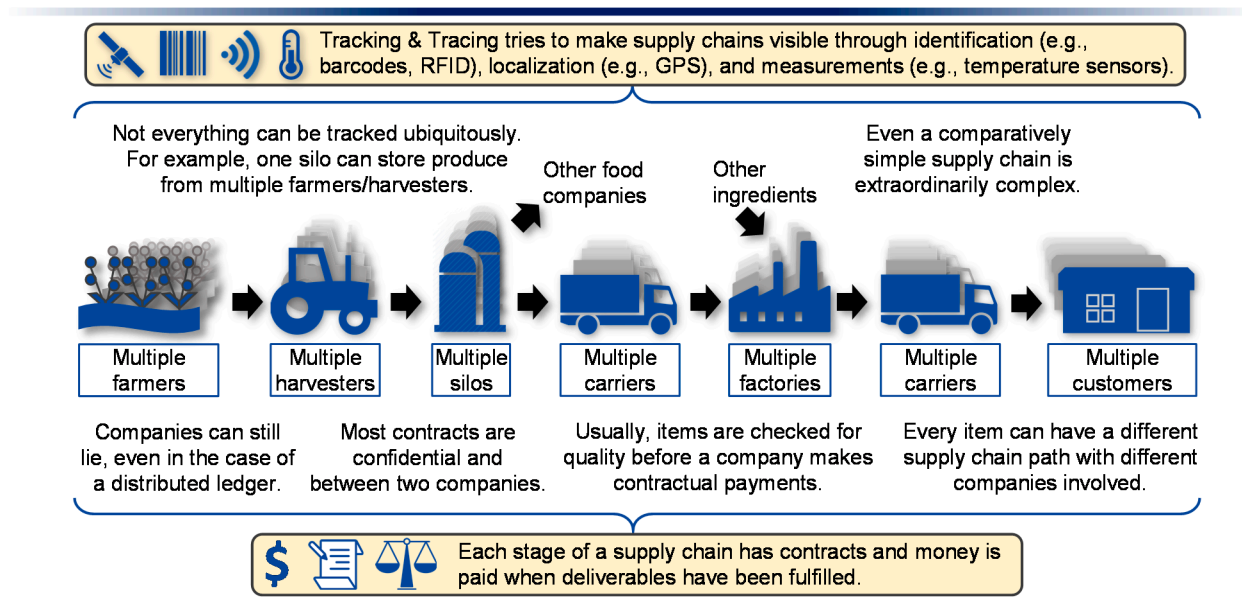


Figure 1. The structure of a supply chain system; illustrated by a simple food SC example.

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 $TI = (* blockchain * AND (* track * OR * trace * OR * provenance * OR * visible * OR * authen *))$ 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 Immutability	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 \approx 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.

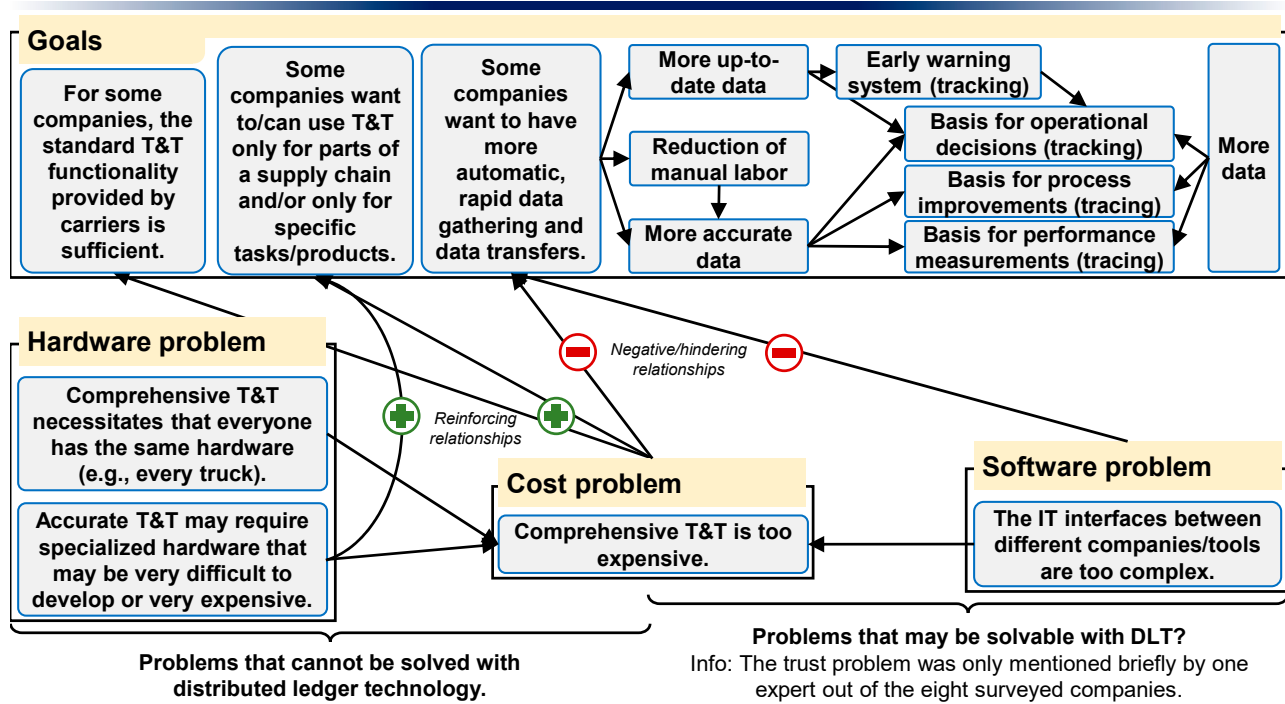


Figure 2. Cognitive map of the survey results and partial answer to RQ0.

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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