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A Systematic Literature Review Of Blockchain-Based Traceability Solutions

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Abstract

Blockchain technology shows great potential in providing object-related end-to-end traceability in complex multitiered supply networks. However, the first systematic literature reviews indicate the immaturity of current blockchain-based solutions and highlight difficulties in assessing their object traceability capabilities. Therefore, this paper provides a systematic literature review of blockchain-based traceability solutions and analyses their object-related mapping capabilities. As the systematic literature reveals, the vast majority of the identified traceability solutions deal with low-complexity architectures without the ability to map objects' compositional changes. Here, food and medical supply chains represent the most dominant domains. Supply chains in the automotive and manufacturing domain place the highest requirements for mapping object-related supply chain events. In this context, solutions incorporating the tokenisation of objects show the most advanced object-related mapping capabilities. However, the identified advanced solutions show limitations regarding their ability to map object deletions, aggregations, and disaggregations. Furthermore, current blockchain-based traceability solutions provide only limited validations based on industrial case studies.

Keywords

Blockchain; Traceability; Supply Chain; Object Mapping; Supply Chain Event Mapping

1. Introduction

In 2016, Abeyratne and Monfared published the first concept adopting an emerging technology – the blockchain technology – in manufacturing supply chains as a potential solution for solving their end-to-end traceability problems [1]. Blockchain technology, which Satoshi Nakamoto first introduced in 2008 [2], "is a multi-party system in which all participants or an agreed fraction of participants reach a consensus over shared transaction data summarised in linked data blocks and their validity, resulting in a linear and immutable chain of data blocks without requiring a central coordinator" [3]. In particular, blockchain technology's capabilities of providing a superordinate system without requiring a trusted third party, while still ensuring a secure, transparent, and immutable environment with globally unique 'digital profiles', brought it onto the map as a potential solution to the problem of achieving end-to-end traceability in complex multitiered supply networks [1,4,5]. Nowadays, such 'digital profiles' are referred to as blockchain tokens, which, generally, are "blockchain-based abstractions that can be owned and that represent assets, currency, or access rights" [6].

As a review and bibliometric analysis conducted by Fang, Fang, Hu, and Wan [7] reveals, over the years, technology-wise, the term 'blockchain' has become the most frequently used keyword related to supply

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chain management in recent publications. Accordingly, various blockchain-based traceability solutions have arisen, making blockchain technology arguably the "most promising technology for providing traceability-related services in supply chain [abbreviation deleted] networks" [8]. Olsen and Borit define traceability "as the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications" [9]. Interconnected traceability systems map objects through their object-related supply chain events [10] – also referred to as object-related 'visibility events' [11]. The international standard IEC 62507 distinguishes between physical and abstract objects in a traceability context. In contrast, an object-related supply chain event "is the record of the completion of a specific business process step acting upon one or more objects" [11]. Here, the Electronic Product Code Information Services (EPCIS) standard – which represents the most frequently applied standard in industrial traceability systems [12] – defines the following core supply chain events: Object creation and deletion, object aggregation and disaggregation, object transformation, and object transaction [11].

2. Rational and methodology of the paper

A systematic literature review by Chang and Chen [13] reviewed potential blockchain applications and their development status in the supply chain management domain to identify future trends. As a result, the authors identify that the vast majority of blockchain-based publications address traceability and transparency issues in supply chains. A further literature review conducted by Dasaklis et al. [8] specifically focuses on the implementation state of blockchain-enabled traceability solutions. As a result, the authors point out that even though blockchain-enabled traceability implementations encompass various supply chain domains, they currently lack advanced and functional interfaces and validations in industrial settings, making it difficult to assess the quality of the proposed solutions. Dasaklis et al. [8] state the hypothesis that each traceability problem may require a different blockchain platform since the design of most architectures aims to solve a specific problem in a particular supply chain domain without showing general-purpose capabilities.

Building on the results of previously conducted systematic literature reviews, the systematic literature review provided in this publication intends to identify existing blockchain-based traceability solutions to evaluate their state regarding their mapping capabilities and to identify future trends. In addition, this review intends to point out the development of solutions in comparison to an past review and analysis from 2020 [14]. For the systematic literature review, this publication follows the guideline by Xiao and Watson [15], which consists of three different phases. **Figure 1** shows the process flow of the systematic literature review.

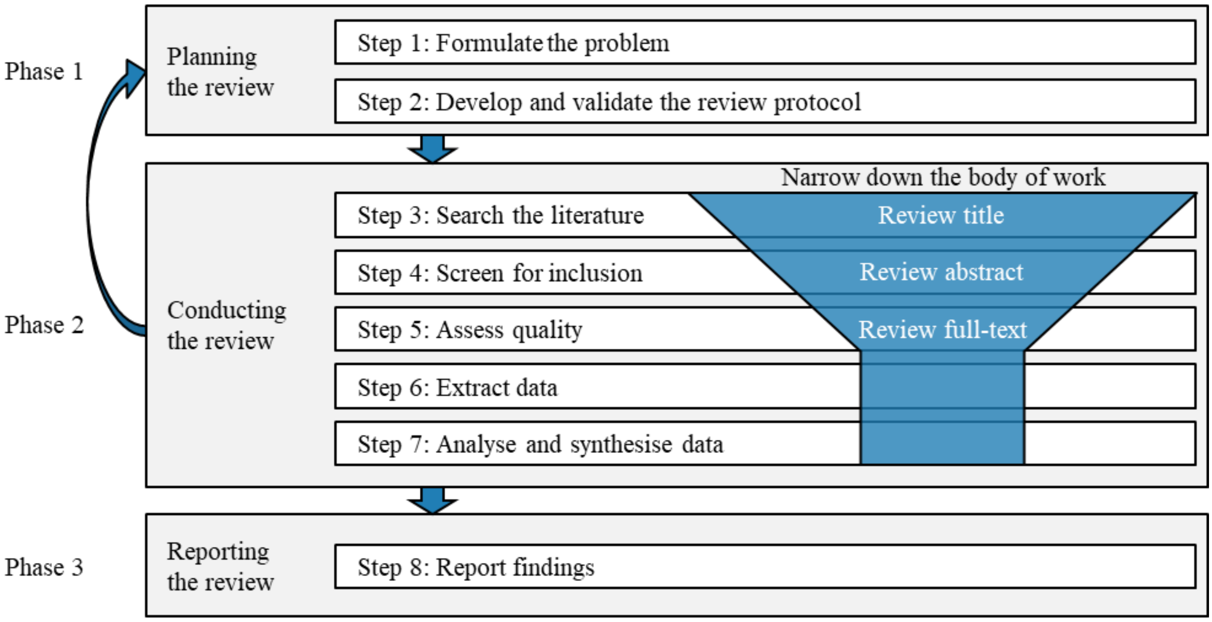

Figure 1: Process flow of the systematic literature review (based on [15])

Phase 1 guides the systematic literature review by defining a research question. The research question aims to investigate the mapping capabilities of blockchain-based traceability solutions described in the literature.

> *Research question: What are the object-related mapping capabilities of blockchain-based traceability solutions described in the literature?*

In addition to the research question, a purposive review protocol defines the literature selection process. It represents the research design for the systematic literature review specifying methods, boundary conditions, and quality measures [16]. This also involves an explicit description of the inclusion and exclusion criteria to limit selection bias on the reviewer's part [17]. For the selection of literature databases, the review of this publication takes into account the results of previously conducted systematic literature reviews in the blockchain and supply chain management domain by Chang and Chen [13] and Dasaklis et al. [8]. These reviews show that, in particular, the literature databases IEEE Xplore and MDPI contain a significant part of blockchain publications in supply chain management. In addition to these literature databases, this publication's systematic literature review supplements these two databases with Scopus and the Google Scholar search engine for the initial search. Furthermore, this publication extends the systematic literature review methodology of Xiao and Watson [15] with the 'snowballing' procedure proposed by Wohlin [18] to ensure a complete overview of all relevant publications – also beyond the initially listed literature databases. This procedure iterates until it no longer leads to additional publications.

The publication by Abeyratne and Monfared [1] represents one of the first rough concepts described in literature connecting blockchain technology and supply chain management. Based on this scientific starting point, the systematic literature review considers publications published in the time span from January 2016 to March 2022. This review includes only peer-reviewed publications describing advanced architectures, concepts, and frameworks written in English. Here, the term 'advanced' refers to publications that provide at least a proof of concept, such as initial experiments, which explicitly excludes rough concepts without any hints of theoretical or practical feasibility. For the initial search, the systematic literature review searches for the following predefined set of terms within publication titles, abstracts, and keywords: 'Supply Chain' OR 'Supply Chain Management' AND 'Blockchain' OR 'Blockchain Technology' AND 'Traceability'.

3. Data extraction

The data extraction consists of two iterations. The first iteration extracts methodology, industry/domain, project objective, and object complexity from all included studies. Here, object complexity refers to the ability of the proposed solution to map objects' changes in terms of their modular composition. While 'single' indicates that the architecture only maps single objects, complex refers to the ability to map objects' compositional changes. Subsequently, the second iteration further classifies all publications dealing with complex objects regarding their general completeness in terms of mapping the object-related core supply chain events defined by the EPCIS standard [11].

When applying the research protocol, the search results in 57 publications included for data extraction. **Table 1** lists the identified literature, sorted by year of publication and alphabetically within the same publication year and extracts the research methodology, industry/domain, project objective, and the object complexity.

Table 1: Publications included for data extraction

No.	Source	Year	Methodology	Industry/domain	Project objective	Object complexity
1	[19]	2017	Architecture, pilot project	Medical supplies	Traceability, automation	Single
2	[20]	2017	Architecture, prototype	Retail	Traceability	Single
3	[21]	2018	Architecture, experiment	Food	Traceability, automation	Single
4	[22]	2018	Architecture, prototype	Wood	Traceability	Single
5	[23]	2018	Architecture, Prototype	E-commerce	Traceability, automation, payments	Single
6	[24]	2018	Architecture, prototype	Transport	Automation, payments	Single
7	[25]	2018	Concept, experiment	Food	Traceability	Single
8	[26]	2018	Architecture, pilot project	Food	Traceability	Single
9	[27]	2018	Architecture, experiment	Food	Quality assurance, disintermediation	Single
10	[28]	2018	Architecture, prototype	Food	Traceability	Complex
11	[29]	2018	Architecture, experiment	Transport	Traceability	Single
13	[30]	2018	Architecture, experiment	Food	Traceability	Single
12	[31]	2019	Framework, prototype	Food	Traceability	Single
14	[32]	2019	Architecture, experiment	Food	Traceability, disintermediation	Single
15	[33]	2019	Concept, experiment	Food	Traceability	Single
16	[34]	2019	Architecture, industrialisation	Transport	Traceability, automation, disintermediation	Single
17	[35]	2019	Architecture, experiment	Transport	Automation, payments, disintermediation	Single
18	[36]	2019	Architecture, experiment	Food	Traceability	Complex
19	[37]	2019	Architecture, prototype	Automotive	Traceability	Complex
20	[38]	2019	Architecture, prototype	Food	Automation, payments	Single
21	[39]	2019	Architecture, prototype	Automotive	Traceability	Complex
22	[40]	2019	Architecture, experiment	Food	Traceability, quality assurance	Single
23	[41]	2019	Architecture, experiment	Medical supplies	Traceability	Single
24	[42]	2019	Architecture, prototype	Automotive	Traceability	Complex
25	[43]	2019	Architecture, prototype	Food	Traceability, disintermediation	Single
26	[44]	2019	Architecture, prototype	Medical supplies	Traceability	Single
27	[45]	2019	Architecture, experiment	Food	Traceability	Single
28	[46]	2019	Architecture, experiment	Transport	Traceability, payments	Single
29	[47]	2019	Architecture, prototype, case study	Food	Traceability	Single
30	[48]	2019	Architecture, prototype	Food	Traceability	Complex
31	[49]	2019	Architecture, prototype	Manufacturing	Traceability	Complex
32	[50]	2020	Architecture, prototype	Manufacturing	Traceability, disintermediation	Single
33	[51]	2020	Architecture, prototype,	Food	Traceability, payments	Single
34	[52]	2020	Architecture, experiment	Medical supplies	Automation, payments, disintermediation	Single
35	[53]	2020	Architecture, case study	Retail	Automation, payments, disintermediation	Single
36	[54]	2020	Architecture, prototype	Manufacturing	Traceability	Single
37	[55]	2020	Architecture, prototype	Medical supplies	Traceability	Single
38	[56]	2020	Architecture, prototype	Food	Traceability	Single
39	[57]	2020	Architecture, prototype	Medical supplies	Traceability	Single
40	[58]	2020	Architecture, prototype	Food	Traceability	Single
41	[59]	2020	Architecture, prototype	Food	Traceability	Single
42	[60]	2020	Architecture, prototype, case study	Medical supplies	Traceability	Single
43	[61]	2020	Architecture, prototype	Food	Traceability, automation, payments	Single
44	[62]	2020	Architecture, experiment	Transport	Traceability	Single
45	[63]	2020	Architecture, prototype	Manufacturing	Traceability	Complex
46	[64]	2020	Architecture, prototype	Food	Traceability	Single
47	[65]	2020	Architecture, prototype	Medical supplies	Traceability, disintermediation	Single
48	[66]	2021	Architecture, prototype	E-commerce	Traceability, disintermediation	Single
49	[67]	2021	Architecture, prototype, case study	Manufacturing	Traceability	Complex
50	[68]	2021	Architecture, prototype	Medical supplies	Traceability, disintermediation	Single
51	[69]	2021	Architecture, prototype	Medical supplies	Traceability	Single
52	[70]	2021	Framework, prototype	Food	Traceability, disintermediation	Single
53	[71]	2021	Architecture, prototype	Food	Traceability	Single
54	[72]	2021	Architecture, prototype	Food	Traceability	Single
55	[73]	2022	Architecture, prototype	Food	Traceability	Single
56	[74]	2022	Architecture, prototype	Medical supplies	Traceability	Single
57	[75]	2022	Architecture, prototype	Food	Traceability	Single

The second iteration aims at further classifying all solutions dealing with complex objects. Accordingly, **Table 2** lists all publications with the ability to map complex objects and classifies them regarding their object-related mapping capabilities according to the supply chain events defined by EPCIS [11].

Table 2: Data extraction of publications dealing with the mapping of complex objects

No.	Source	Object event		Aggregation event		Transformation	Transaction
		Create	Delete	Aggregate	Disaggregate		
10	[28]	x		x			x
18	[36]	x				x	x
19	[37]	x				x	x
21	[39]	x				x	x
24	[42]	x				x	x
30	[48]	x		x			x
31	[49]	x		x		x	x
45	[63]	x		x		x	x
49	[67]	x		x		x	x

4. Data analysis and synthesis

The extraction of the first iteration results in a total number of 57 publications describing architectures (53), concepts (2), and frameworks (2). Most publications validate the solution based on prototypes (38), followed by experiments (15), case studies (4), pilot projects (2), and industrialisation (1), whereas some publications combine a prototypical validation with case studies. Experiments differ from prototypes in terms of completeness. While prototypes implement all required components, experiments prove the feasibility based on implementing only certain key elements. Solutions for food supply chains (27) represent the most dominant industry/domain among the identified publications, followed by medical supplies (11), transport (6), manufacturing (5), automotive (3), e-commerce (2), retail (2), and wood (1). In total, 51 publications aim to improve the traceability of objects, representing the identified solutions' major objective. Since solutions can have several objectives, 12 publications mention disintermediation as an objective, 10 automation, 8 payments, and 2 ensuring quality. Furthermore, a vast majority of the publications only present solutions with the ability to map single objects (48), while only 9 publications include solutions with the ability to map complex objects. **Figure 2** illustrates these findings and their distribution among the identified publications.

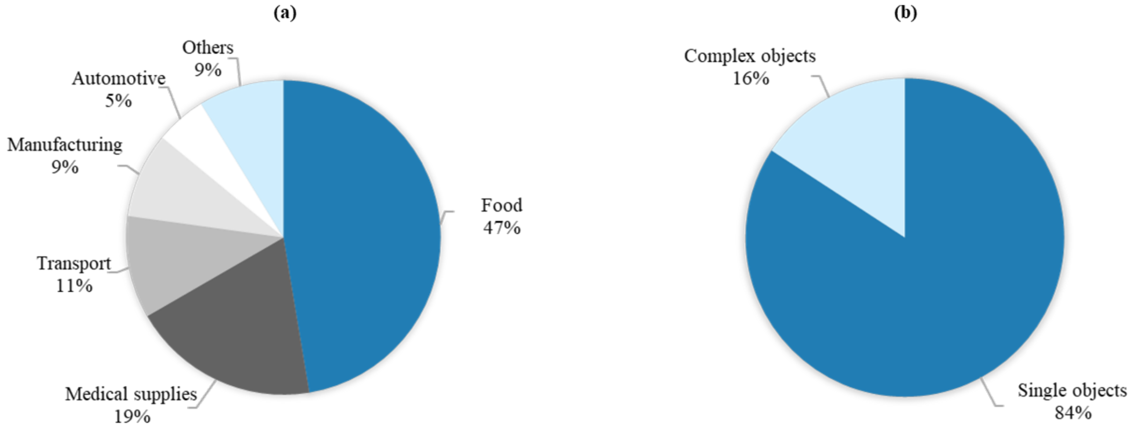

Figure 2: (a) Industry/domain distribution; (b) Mapping complexity distribution

All publications with the ability to map complex objects show incompleteness regarding the capabilities to map the supply chain events defined by EPCIS [11]. Nevertheless, the three solutions by Westerkamp et al. [63], Watanabe et al. [49], and Kuhn et al. [67] – all adopting the tokenisation of objects – represent the most advanced solutions in this comparison. However, the analysis of their object-related mapping capabilities reveals the following limitations:

Token deletion. The advanced solutions do not describe the possibility of an explicit token deletion. For example, the traceability architectures by Westerkamp et al. [63] and Watanabe et al. [49] provide logic for 'consuming' tokens. Here, consumed tokens receive a mark indicating their state to avoid the reusability of consumed tokens in further token recipes. Kuhn et al. [67] describe a similar logic, but referring to the consumption of tokens as the 'burning' of tokens. Even though the logic to consume or burn tokens intentionally serves as functionality to avoid the reusability of tokens, for example, after assembling processes, this logic also allows the creation of a token recipe to remove tokens from the supply chain. Although all three architectures do not further specify this procedure, a recipe that consumes or burns its input tokens supposedly results in a new, albeit useless, 'waste token'. Therefore, strictly speaking, this logic does not allow the deletion of tokens in the sense of EPCIS [11].

Token aggregation. Kuhn et al. [67] point out the ill-suited capabilities of the applied token standard by Westerkamp et al. when mapping objects with great variety and assembly complexity. As a solution, Kuhn et al. [67] adopt a new token standard, which, however, only shows advantages when applying it to batches of fungible assemblies of various fungible components, such as incorporated by the electrical and electronic system case study of Kuhn et al. [67]. However, when mapping multiple non-fungible assemblies of the same type with non-fungible inputs of the same type, the solution by Kuhn et al. [67] reaches the same limitations as the solution by Westerkamp et al. [63].

Token disaggregation. Among the advanced solutions, only the architecture by Watanabe et al. [49] describes a mechanism for token 'forking'. The architecture of Westerkamp et al. [63] and Kuhn et al. [67] solely includes a logic for 'splitting' token batches, which describes distributing a share of a token batch to different owners. Westerkamp et al. [63] even state the missing ability for token disaggregations as a limitation of their architecture and refer to a possible example of packaging processes, which require the extraction of the original good when unpacking [63]. Even though the 'forking' described by Watanabe et al. [49] forks a token into two tokens, these forked tokens receive new identifiers and new smart contract addresses, which does not 'restore' the previously aggregated tokens and therefore does not solve the limitation mentioned by Westerkamp et al. [63] and represent a disaggregation according to EPCIS [11].

Case study validation. Among the advanced architectures, only the architecture of Kuhn et al. [67] provides – besides the prototyping-based validation – a validation with an industrial case study. Even though the authors claim general-purpose mapping capabilities transferable to a large number of manufacturing scenarios, the case study includes mapping several fungible assembly batches, which may not be common in other manufacturing supply chains. Particularly since Westerkamp et al. [63] state that mapping of delivery processes is a limitation of their token-based traceability solution, a general-purpose architecture requires further evaluation based on a case study from a logistics management perspective.

5. Key findings

This chapter summarises the key findings in accordance with the initially stated research question.

> *Research question: What are the object-related mapping capabilities of blockchain-based traceability solutions described in the literature?*

As the publication's systematic literature reveals, 84% of the identified traceability solutions deal with low-complexity solutions allowing the traceability of single objects without the ability to map objects' compositional changes. Domain-specific, this applies to 89% of the solutions in food and 100% in medical supply chains. This represents 27 (food supply chains) and 11 (medical supply chains) publications, the most dominant industries/domains among the 57 publications identified in this review. Besides the traceability's importance in these strongly represented domains, these results imply, on the one hand, the low complexity traceability requirements of food and medical supply chains. On the other hand, the strong propagation of these supply chains can result from the currently available low-complexity solutions that are sufficient for meeting their requirements.

This publication identifies three advanced blockchain-based traceability solutions – all of which apply the concept of object tokenisation – that show certain general-purpose capabilities among the nine identified architectures with the ability to map compositional changes. However, as the architecture analysis reveals, these architectures show limitations in their ability to map object-related supply chain events. This is necessary for ensuring end-to-end traceability in complex supply chains that involve dynamic sequences of object flows, such as in manufacturing or delivery supply chains. On a system level, this particularly applies to objects' deletion, aggregation, and disaggregation.

6. Conclusion

Blockchain technology shows great potential in providing object-related end-to-end traceability in contemporary supply chain networks. However, the majority of currently available blockchain-based traceability solutions incorporate low-complexity architectures without the ability to map objects' compositional changes – which is sufficient for some industries and domains such as food supply chains and medical supplies. Three advanced blockchain-based traceability solutions show certain general-purpose capabilities that can map compositional changes – all of which incorporate the concept of tokenisation of objects. However, the applied architectural means by the advanced solutions show limitations regarding their ability to map all object-related supply chain events and validations based on case studies from operations and logistics management perspectives. Therefore, in order to provide general-purpose blockchain-based traceability solutions for industries and domains with complex objects, such as the automotive industry and general manufacturing, further research is necessary to develop traceability architectures that show completeness regarding their ability to map object-related supply chain events as well as to validate their capabilities based on industrial case studies in various domains.

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