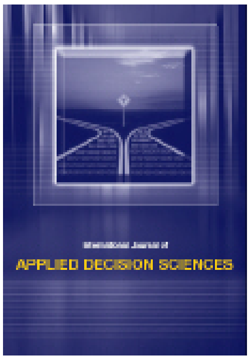

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Blockchain applications and challenges for supply chain and Industry 4.0: a literature review

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Blockchain applications and challenges for supply chain and Industry 4.0: a literature review

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Abstract: Application of blockchain technology to facilitate a flexible, reliable, and efficient supply chain is an emerging phenomenon. Motivated by its potential use, researchers have started investigating blockchain's use for managing complex global supply chains. In addition to established supply chain performance criteria, Industry 4.0 requires a more data driven supply chain (SC), where data collection, transmission and processing capabilities are embedded in smart products. However, review articles of blockchain in SC primarily report descriptive statistics, but do not provide sufficient evidence on how topics are studied together. This article discusses the role of blockchain in SC and presents a methodology to study co-occurrence of blockchain topics in SC. Three most often researched topics identified are transparency/traceability, transaction related issues and tracking. Using a machine learning algorithm, we further examine trends of co-occurrence among various topics of interest and identify 'gaps' in existing literature and point to future research directions.

Keywords: blockchain; Industry 4.0; Supply chain 4.0; supply chain management.

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1 Introduction

Blockchain and Industry 4.0 evolved separately in the last decades, but they both made their presence in today's supply chain (SC). Blockchain (BC), a technological innovation for a secured distributed transaction ledger, was introduced in 2008 (Nakamoto, 2008). It provides an immutable record of transactions and facilitates smart contract, supply chain visibility and non-repudiation of transactions. It also provides other business benefits including transparent transactions, tracking of product origin and engendering of trust among supply chain partners. Despite the increasing popularity of blockchain, not all companies have the technical expertise to build their own blockchain systems. As a result, multiple blockchain platforms begin to proliferate. Example platforms are Ethereum, Ripple, Hyperledger Fabric, IBM Open Blockchain, Intel Sawtooth Lake, etc.

[see Mattila et al. (2016) and the references listed therein]. Each platform provides its own blockchain capabilities, some include a wide range of software services (application programming interface or API, standardised toolkits, and protocols), but others (such as Intel Sawtooth) implement a hardware-based solution. Although platforms may differ on criteria such as scalability, usability, consensus mechanism, security etc. (Macdonald et al., 2017), it is clear that adoption of blockchain usually comes with benefits that frequently inter-correlate with each other. For example, cryptography, digital digests and other in-built security capabilities in blockchain makes it easier for tracking, monitoring, trust among partners and trustworthy distributed ledges.

For mass customisation of products while minimising waste and supply chain disruptions, Industry 4.0 initiative was introduced by German manufacturing industry in 2011 that creates data driven adaptive manufacturing processes. The requirements of Industry 4.0 impacts its supply chain by requiring interactive and close collaboration with stakeholders including automated generation, transmission, storage and use of data (some of which could be embedded in smart products). This revised expectation from supply chain was termed as Supply chain 4.0 (SC 4.0) (PWC, 2016; Ferrantino and Koten, 2019). Early research explored how the capabilities of blockchain could be harnessed to meet the need of Industry 4.0 and, consequently, SC 4.0.

As Industry 4.0, SC 4.0 and blockchain cut across multiple technology requirements, research that ties these three cover a wide spectrum of topics. For example, Kshetri (2018) expressed concerns about the performance criteria for BC and its associated mechanisms to support SC 4.0. Using a case study approach, Sundarakani et al. (2021) examined the use of blockchain in Industry 4.0 environment in managing big data and proposed guidelines for blockchain implementation. Wang et al. (2021) presented some important recommendation on 'how should a blockchain enabled supply chain be designed?' based on two-year study of smart contract initiative in UK's construction sector. Niu et al. (2021) discussed the use of blockchain in quality verification by global retailers. They found that, by using blockchain, multinational retailers increased profit from wholesale operations, while its usage reduced retail profits.

As discussed earlier, blockchain and its associated technology have the capability to support some of the changing needs of SC 4.0. Examples include facilitation of automated collection and transmission of data, and assurance of data integrity and authenticity. Additionally, blockchain facilitates data integrity in an environment where authorisation for data update/manipulation is distributed to multiple partners (trusted or not), is a must. So, matching the supply chain performance requirements with appropriate BC platform is critical for successful adoption of BC in SC 4.0. As it stands now, both supply chain requirements and blockchain technology are evolving. Further, limited knowledge of the blockchain technology among supply chain partners adds to the complexity. Also, an adoption of a disruptive technology like blockchain tends to be slow, even though researchers and industry leaders believe in its potential. Hence, to understand the scope, opportunities and challenges of BC adoption in SC, and specifically in SC 4.0, it is critical to review, recently published, topic-related articles.

Blockchain at best is a technology solution to ensure authenticity of products. Adoption of blockchain does not always entail customer buy-in because technology solutions must work in tandem with human factors to reach the intended effect. For example, blockchain can be utilised to identify counterfeit products. However, blockchain adoption, even with government subsidy, may not always be beneficial to manufacturers for identifying counterfeit products, especially when customers have only marginal trust in the authenticity of the product, its quality or the manufacturer. This is human factors (e.g., consumer trust) intervening the benefits intended when adopting technology solutions. When customers have serious distrust about products, differential pricing strategy was found to be more effective than only the blockchain solution. The same requirement of human factors and technology is also observed in the business world. For example, Ghode et al. (2020) showed that adoption of blockchain in SCM requires success factors such as inter-organisational trust, relational governance, data transparency etc. Therefore, IT implementation in businesses often fails not only because of technical caveats, but also because of issues on the human-side (e.g., inability to meet business needs, resistance to technology adoption, habitual tendency and poor management of implementation). Implementation of blockchain technologies across a network of supply chain partners is more complex as it requires partner firms to implement, contribute, and share information. A study by Falcone et al. (2021) concluded that manager's perceptions of and willingness to use blockchain technologies in the SC network was crucial for successful implementation. Mathivathanan et al. (2021) noted that lack of understanding of the blockchain potential and business needs are the main barriers in adopting blockchain technology. Liu et al. (2021) investigated the use of blockchain in maritime industry and proposed an integrated system to mitigate the challenges faced by the industry. Another study surveyed 151 German machinery and equipment sector business managers and used Delphi study to identify new blockchain area of application in SC and provided structure to help managers understand where blockchain opportunities among the customer touchpoints may arise (Durach et al., 2021). It should be noted that most of the literature discusses either motivation, opportunities and challenges of using BC in SC or present post implementation analysis of BC in SC. As the above studies show, a more comprehensive view of the impact from blockchain is to uncover the interwoven relationships among technology, humans and data to produce a desired outcome. This is the backdrop of key principals defined by Industry 4.0. Such a wider view on reviewing BC literature is scarce.

Queiroz and Wamba (2019) reviewed 27 published papers to raise broad questions about:

a the main blockchain applications in SCM

b the disruptions and challenges in SCM because of blockchain

c the future of blockchain in SCM.

However, there is a paucity of published literature that addresses these questions. Reddy et al. (2021) provided a literature review of seventy blockchain related articles and proposed the implementation framework for blockchain in the automotive industry. Casino et al. (2019) reviewed literature to point out potential disruptive innovations of blockchain technology in SCM, such as proving provenance manufacturing without any third-party authentication and further streamlining and automating intra-organisational process for increased efficiency and cost savings. Hijazi et al. (2019) restricted their study to use blockchain in the supply chain of construction industry and concluded that most literature in the area are theoretical and there is a gap to address the usability of and limitations of adopting BC in construction supply chain and its integration with building information modelling (BIM). Another survey paper reviewed 106 articles and provided descriptive statistics and comparison of topics discussed based on industry, methodology used, country of the researchers, etc. (Lim et al., 2021). In a review of 46 articles, Kummer et al. (2020) aimed to identify specific organisational theories such as agency theory, information theory, institutional theory etc., to analyse blockchain application in SCM. Using co-citation analysis of 42 research papers, Pourander et al. (2020) explored potential key questions for each of the knowledge areas impacted by block chain in supply chain. They identified four main clusters, namely technology, trust, trade, and traceability/transparency, and used an inductive method of reasoning for each cluster to explore emerging themes for future research. Wang et al. (2019) reviewed extant literature to study blockchain diffusion in SCM. They analysed 29 articles and identified the four areas where blockchain may impact SCM: extended visibility and traceability, supply chain digitalisation and disintermediation, improved data security and smart contracts. They also suggested future research to explore these areas.

These literature review articles lay the foundation for future research by reporting topic count, descriptive statistics and clustering to answer the 'what happened' question, but such methodology may be limited in uncovering how topics are studied together and the level of interest in topic combinations. Answering these latter questions will build on these existing studies to provide further practical, methodological and theoretical advancements in the following ways:

First, blockchain touches on several technologies (e.g., cryptography, one-way hash, distributed computing, immutable ledgers) and offers multiple benefits when implemented. Many of these benefits are inter-related to each other. Hence, it is rare that a blockchain article in SCM will cover only one topic area. Multiple topic areas being discussed in the same article is a norm. Therefore, a simple topic count is not sufficient to offer insights on how topics are studied together. Second, certain topic areas (such as security) may be represented in a large number of articles due to the underlying requirement of cryptographic capabilities in blockchain. Staying at a simple topic count or descriptive statistics may show a skewed distribution that certain topics are favoured. Not all articles concerning a topic area only research in that topic area. For example, a search of scholarly articles using 'blockchain' and 'security' as keywords shows that blockchain security is studied with IoT, privacy, cryptocurrency, decentralised framework, system performance, cloud computing, healthcare, smart city, etc. Therefore, staying only with traditional literature survey methodologies of article count will miss out the opportunities connecting a blockchain topic to the others.

Third, adoption of blockchain comes with multiple inter-correlated benefits, but insights regarding existing research for the link among these benefits or topics are rarely analysed. For example, Kumar et al.'s (2020) work provides illustrative use cases where trust, traceability, visibility and privacy are recommended to be relevant for each use case. This offers conceptual relevance among these blockchain benefits, but it does not answer whether these benefits are actually studied together in the existing literature. Nor does it intend to report the level of attention from researchers on the relevance of multiple benefits together. Similarly, Pourander et al.'s (2020) work moves beyond the simple topic count into the identification of topic clusters through a co-citation analysis. Four topic clusters are identified, including technology, trust, trade and traceability/transparency. This co-citation approach answers the question of the current topic interest in the published works, but it does not offer insights as to how topics are studied together and the strengths of links between topics. Similarly, Bodkhe et al.'s (2020) work also employs the topic count approach to survey the technical underpinnings (e.g., technology used, recommended software tools, design and implementation, and possibilities for smart applications) across articles.

Without knowing the strengths and links of topics, it will be difficult to see what is lacking and where the filed research is going, and how one should position their research in the relevant literature. On these counts, current literature review studies on blockchain that employ descriptive statistics and simple topic counts may not be as useful in reporting topic relationships in blockchain articles. Hence, a sound methodology is needed that goes beyond treating each topic independently and examining the relationships among different attributes of blockchain in relation to the SCM. In this study, we propose a co-occurrence analysis to fill the void of topic relationships. More specifically, this paper:

a synthesises a comprehensive list of published research papers on blockchain in supply chain area

b examines current research trends in the various topics

c uses machine learning technique to explore the relationships between the various topics of blockchain as they pertain to supply chain management

d based on co-occurrence analysis, identifies opportunities for future research.

The manuscript is laid out as follows: in section 1 we provide a detailed background information on Industry 4.0, Supply chain 4.0, and blockchain. Next, the methodology and a detailed analysis of the published articles are presented in Sections 2 and 3, respectively. This is followed by discussion and conclusion in Section 4. Finally, future research directions are presented in Section 5.

2 Background

2.1 Industry 4.0

Industry 4.0 aims at manufacturing customised goods and delivering them to consumers with minimal human interaction, thus, increasing customer satisfaction and efficiency (Hofmann et al., 2019). Enhanced data collection, transmission, and analytic techniques are used to establish responsive and nimble manufacturing processes. Using data analysis, such an adaptive process anticipates a change in demand or environment and makes necessary adjustments to manufacture customised smart products. This initiative was introduced by German industry around 2011, and labelled as Industry 4.0. According to Kagermann et al. (2013), "in Industry 4.0 manufacturing systems are vertically networked with business processes within factories and enterprises, and horizontally connected to dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics". More recently, Industry 4.0 was defined as "… The sum of all disruptive innovations derived and implemented in a value chain to address the trends of digitalization, autonomization, transparency, mobility, modularization, network-collaboration, and socializing of products and processes" (Pfohl et al., 2015). Thus, Industry 4.0 allows for an integration of manufacturing processes, with enhanced supply chain functionalities using smart products, that are capable of collecting, storing and transmitting data.

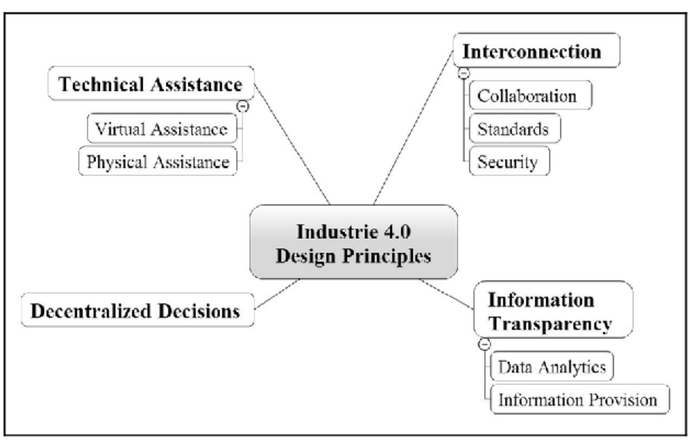
Like any evolving initiative, there is no generally accepted clear definition of Industry 4.0. However, according to Hermann et al. (2015), four key components of Industry 4.0 are:

- Cyber-physical systems (CPS): is a fusion or integration of virtual and physical processes. For example, automated data collection by RFID or infrared cameras triggering a physical process such as, starting or switching a production process or ordering replenishment. It is important to recognise that smart products are sub-components of these systems.
- Internet of things (IoT): where products are automatically identifiable, locatable and allow to collect data with sensing devices. These smart products transmit stored data using internet for further processing and action. Note that machine-to-machine communication is an enabler of IoT.
- Internet of services (big data and cloud computing are data services) – where vendors offer their services via Internet.
- Smart factory – based on the definitions given for CPS and the IoT, the smart factory can be defined as a facility where CPS communicates with the IoT devices and assists people and machines in the execution of the tasks.

Hermann et al. (2016) present Industry 4.0 design principles as shown in Figure 1.

As Ardito et al. (2019) put it, "summing up, the goal of the Industry 4.0 is to boost the digitisation and, thus, the integration of firm processes both horizontally (i.e., across functional areas) and vertically (i.e., across the entire value chain), from product development and purchasing through manufacturing, distribution and customer service". Therefore, it is expected that manufacturing processes, products, and transport facilities, all with embedded internet of things (IoT) that are capable of capturing and transmitting data, will redefine the role of the supply chain. Such a supply chain is referred to as Supply chain 4.0 (SC 4.0).

Figure 1 Industry 4.0 design principles



2.2 Supply chain 4.0

Supply chain issues were investigated by researchers and practitioners since mid-1980s [see Cooper et al. (1997) and the references listed therein]. However, there was little consensus among them about the definition of supply chain management (SCM). For example, some considered SCM as a flow of products and materials, while others viewed it as a management philosophy (Tyndall et al., 1998). Stock and Boyer (2009) presented the all-encompassing definition of SCM as "the management of a network of relationships within a firm and between interdependent organizations and business units consisting of material suppliers, purchasing, production facilities, logistics, marketing, and related systems that facilitate the forward and reverse flow of materials, services, finances and information from the original producer to final customer with the benefits of adding value, maximizing profitability through efficiencies, and achieving customer satisfaction". Thus, with the objective of achieving customer satisfaction, SCM focuses on creating efficiencies and values throughout the supply chain, including materials and information flow.

SC 4.0 is defined as "a supply chain which involves close collaboration of different stakeholders (e.g., suppliers and customers) and is built on digital technology, including but not limited to, web-enabled technology, cloud computing and internet of things" (Makris et al., 2019). Supply chain 4.0 can be viewed as an integrated ecosystem (PWC, 2016) where the information flows in all directions connecting all parties in the supply chain (Ferrantino and Koten, 2019). In SC 4.0 digitisation, improvement in transmission and processing of data, 3D printing, etc. transform production environment. Ferrantino and Koten (2019) present "an hypothetical example as follows: a consumer checking out of an AT&T store in California with a newly purchased Samsung smartphone may, by the single act of purchase, trigger a chain of information going all the way back to a company that supplies Samsung with touch screens relatively quickly, with tight linkages between the 'supply chain control towers' of Samsung and AT&T".

Industry 4.0 impacts SC 4.0. But, the nature and severity of the impact depends on factors like industry type, size of the organisations, etc. Technologies like IoT make it easier to capture and transmit large volume of data. Increased digitisation is expected to increase transparency leading to better decision making and increased supply chain flexibility (Makris et al., 2019). Despite these advantages, a survey by McKinsey Consulting Group concludes that "less than 30% of companies have an overall Industry 4.0 strategy in place and even fewer have a clear road map" (McKinsey, 2016). The survey identifies major implementation barriers for Industry 4.0 that manufacturers need to overcome. They include:

- difficulty in coordinating actions across different organisational units
- concerns about data ownership when working with third-party providers
- lack of a clear business case that justifies investments in the underlying IT architecture
- lack of necessary talent, e.g., data scientists
- concerns about cybersecurity when working with third-party providers
- challenges with integrating data from diverse sources in order to enable Industry 4.0 applications.

Thus, the implementation of Industry 4.0 (and SC 4.0) has business and managerial challenges that may slow-down its implementation. However, it is expected that the challenges such as concerns about cyber security, integrating data from varied sources, and data integrity will be mitigated by blockchain technology.

2.3 The blockchain technology

Blockchain was first introduced by Nakamoto (2008) as distributed transaction ledger in a peer-to-peer network. Each block is immutable, contains transaction information and is replicated at multiple nodes of the network. Any member (i.e., node) can introduce a transaction, i.e., a block. Special nodes are designated the role of 'miners'. They have the capacity to process data, create BC blocks, and validate the BC chain. BC is a distributed system that does not have a central authority to govern block creation and management. This responsibility lies within a group of miners. Since there are multiple miners who can generate blocks, a consensus model has to be implemented to ensure authenticity and trust. A consensus model called proof of work (PoW) requires all miners to compete with each other to generate the next block for a chain. The first miner who generates the next block receives awards (e.g., fees and other incentives). The new block is later validated by the rest of the miners before being added to the chain.

Although the consensus model deters denial of service (DoS) (the kind of attacks often seen in centralised systems) it taxes the energy required to generate a block. Additionally, PoW may not scale well. The difficulty level of the mathematical challenge needed to generate a block is usually very high, and it cannot be solved in a short amount of time. As a result, some latency may be experienced before a block is added and propagated to the entire community. Proof of stake (PoS) is another consensus model that aims to accomplish the same goal. Similar to PoW, it deters DoS because of difficulties for anyone to predict who will solve the mathematical challenge. PoS uses a pseudo-randomisation approach to pick a node based on factors, such as staking age, the stake owned by a node, other randomisation algorithms, etc. As a result, the next node that will be added to a blockchain is difficult to predict.

Although PoW and PoS are the two well-known consensus models. There are other models and variations for node selection and block verification. This diversity leads to different operational characteristics of a blockchain such a security, latency, scalability, etc. Therefore, selection of appropriate blockchain algorithm, for meeting the Supply chain 4.0 challenges for a specific industry/environment, is extremely important.

Blockchain could be private (closed) or public (open). In the private BC, members in the network are pre-approved. Hence, their identities are known to all participants. Transactions in such networks are secure. Since validation of transactions (i.e., adding blocks) often does need proof or consensus from other members, they are faster and more scalable. While, in the public networks identities of members may remain anonymous, and the authenticity of a transaction is provided by a consensus algorithm. This makes addition of a block to the chain slower and less scalable. Recognising the potential of blockchain, researchers started examining its usefulness in mitigating the challenges of supply chain management. Several articles have appeared in the public domain since 2008; including many literature review papers.

A key distinction of our work (as compared to the extant literature survey articles) is that they analyse each concept topic independently. However, the use of blockchain impacts multiple areas of interest concurrently. Therefore, it is hard to get a clear understanding of inter-dependence among the topics covered. For example, traceability and trust are the related concepts. Studying them separately would not easily uncover the association between the two. Hence, the construction of multiple concept categories being studied together is consistent with the nature characteristics of blockchain, and investigating relationships among them marks the central theme of our work.

3 Methodology

As stated earlier, blockchain technology was first introduced in 2008. Hence, a search for published articles on blockchain in supply chain was limited: from 2008 until March 2020. Also, respectable non-peer reviewed literature such as white papers from reputed sources (e.g., McKinsey Consulting Group and World Trade Organization) were considered as a part of our initial search process. We started the search with a combination of key words:

a ‘blockchain’ and its variations such as ‘block chain’, ‘distributed ledger’

b ‘supply chain’ and its variations such as ‘supply chain’.

The goal of this initial screening was to identify articles relevant to blockchain and supply chain. Two databases, Business Source Premier and Google Scholar, were used for searching the title and abstract of the published papers. After eliminating the duplicates, the search resulted in identifying 525 potential articles for further review. Full text of these articles was downloaded and shared among the authors.

Next, the content verification phase commenced. The goal of this phase was to further filter out articles that treated the key topics of the present research (i.e., blockchain and supply chain) only superficially. This was a much-needed step because keyword search could only identify whether an article contained the keywords or not, but the search could not identify articles with a sufficient coverage of the keywords. As a result, the 525 articles also included those that barely mentioned blockchain or supply chain, or only gave it a brief coverage.

The 525 articles were randomly and equally divided between the three authors for a review. Each article was reviewed to see if it covered the ‘blockchain in supply chain’ topic. An article that used any of the key words but did not discuss the topic or only cover the topic briefly was eliminated from detailed examination. This review process resulted in 173 articles and manuscripts (such as white papers and thesis) for further analysis. Of the 173 articles, 161 were from peer reviewed journals, nine were either conference papers or thesis, and the remaining three manuscripts were from consulting firms. To avoid double counting, any conference paper that was later published as a journal article was eliminated from further consideration. A bibliography of the 173 articles is provided herewith. Note that a bibliography of articles cited in the paper is presented separately.

Since journal articles go through a rigorous peer-review process, we chose to undertake the detailed analysis of the 161 articles. To ensure consistency in the review process, thirty articles were commonly reviewed by the three authors, and any discrepancy was resolved through a follow-up discussion. The reviewed research papers broadly focused on the use, benefits and challenges of using block chain in SCM. We also explored if an article discussed the impact of blockchain in meeting the demands of

SC 4.0. To organise the topics discussed in 161 articles, we used a concept matrix developed by Webster and Watson (2002). This resulted in identifying thirty topics. The excel spreadsheet was prepared to reflect the discussions in the 161 articles on 30 topics.

4 Analysis

For data analysis, the 30 topics covered in the 161 journal articles were grouped in six categories:

a benefits provided by blockchain (group 1)

b effects of blockchain on products (group 2)

c research methodology used (group 3)

d application of blockchain in supply chain (group 4)

e challenges and opportunities (group 5)

f other business processes (group 6).

See Table 1 for topics listed in each of these six groups. Overall, an article covers an average of 8.384 topics (median = 8, minimum = 1, maximum = 19). The following subsections report findings from descriptive statistics (Section 4.1), trend analysis by group (Section 4.2) and topic association (Section 4.3). The division of these sections follows the traditional literature review methodology of topic count, expands it to topic trend, and finally topic association. This approach allows one to compare our results with existing literature review studies using the findings from a similar methodology, and it goes beyond the traditional approach to uncover topic association, an area frequently lacking in block chain and supply chain literature papers.

4.1 Descriptive statistics and trends in topical coverage

Table 1 shows the categories of focus. As seen in the overall rank column, transparency/traceability received the most attention with 63.58% articles discussing the topic. This is followed by transaction (45.09%), and track/monitoring (44.51%). In group 1, transparency/traceability, transaction, and tracking/monitoring received the most attention. All concepts in group 2 are fairly similar in the number count with perishable/non-perishable products being ranked slightly higher. Descriptive framework dominates the third group, making it forth in overall ranking, but first within the group. A large percentage of blockchain studies in supply chain (43.93%) are descriptive in nature. In the application of blockchain in supply chain category (group 4), origin of product received the most attention (41.62%), followed by smart contracts (39.88%) and authenticity (31.21%). Transaction cost has been the most popular topic in the challenges and opportunities group (group 5), followed by security (24.28%). In group 6, execution of contract ranked first, followed by efficiency of data processing (18.50%) and total cost (15.61%).

Table 1 Topics analysed

	Count	*Overall %*	*Rank within the group*	*Overall rank*
Group 1: benefits provided by blockchain				
Transaction related (speed of transaction, transaction authentication, etc.)	78	48.45%	2	2
Trust	76	47.20%	4	4
Transparency/traceability	110	68.32%	1	1
Tracking/monitoring of data or product	77	47.83%	3	3
Fraud protection	45	27.95%	9	14
Security (data integrity, data loss, theft, etc.)	68	42.24%	6	9
Regulatory issues	50	31.06%	8	13
Multi-party acceptance	62	38.51%	7	10
Enhanced information sharing	75	46.58%	5	6
Enhanced information quality	31	19.25%	11	22
Integration, enhancement or automation of DSS	35	21.74%	10	17
Group 2: effects of blockchain on products				
Perishable/non-perishable products	32	19.88%	1	20
High value/low value products	22	13.66%	2	26
Conditions of transport	20	12.42%	3	28
Group 3: methodology				
Literature review	10	6.21%	5	31
Descriptive framework	76	47.20%	1	4
Case study	27	16.77%	3	24
Empirical	18	11.18%	4	29
Theoretical modelling/simulation	33	20.50%	2	18
Strategy	6	3.73%	6	33
Group 4: application of blockchain in supply chain				
IoT	44	27.33%	4	15
Authenticity (product, raw material and distribution)	54	33.54%	3	12
Origin of product	72	44.72%	1	7
Smart contract	69	42.86%	2	8
Group 5: challenges and opportunities				
Privacy	28	17.39%	3	23
Security	42	26.09%	2	16
Latency	13	8.07%	4	30
Transaction cost	55	34.16%	1	11
Group 6: Other business processes				
Scalability	22	13.66%	4	26
Execution of contract and/or business process	33	20.50%	1	18
Efficiency of data processing	32	19.88%	2	20
Total cost	27	16.77%	3	24

Further analyses of the trends among topics within a group and the relationship among the concepts are reported in the following sections:

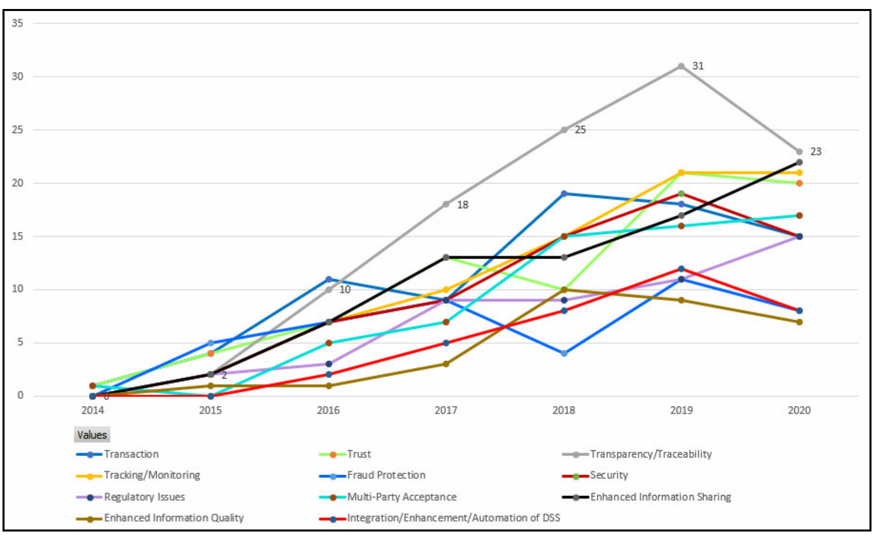
4.2 Analysis of topic groups

4.2.1 Benefits provided by blockchain (group 1)

Figure 2 shows that there is a growing trend among all eleven benefits of blockchain (group 1 in Table 1). However, not all topics have received the same attention. As seen, transparency/traceability has consistently received the highest percentage of coverage since 2016. Note that our data collection ended at the end of March 2020. Hence, the 2020 data marks only one fourth of the articles that would possibly be published in 2020. Even so, there were already 23 articles on transparency/traceability in the first quarter of 2020. If the trend continues, this topic is projected to grow even more by the end of the year.

Similarly, most other topics show an up-ward trend, but the growths in some topics fluctuates. This especially happened in 2018 where the number of articles on fraud, trust, and information sharing dipped before going up.

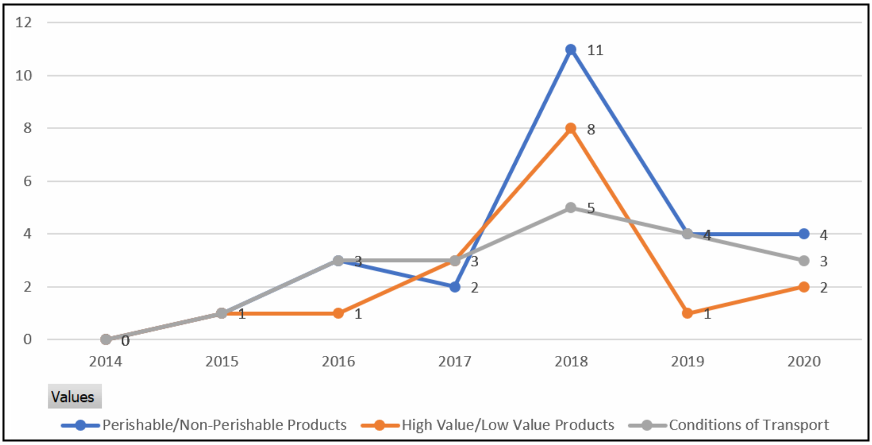
Figure 2 Benefits provided by blockchain (see online version for colours)



4.2.2 Effects of blockchain on products (Group 2)

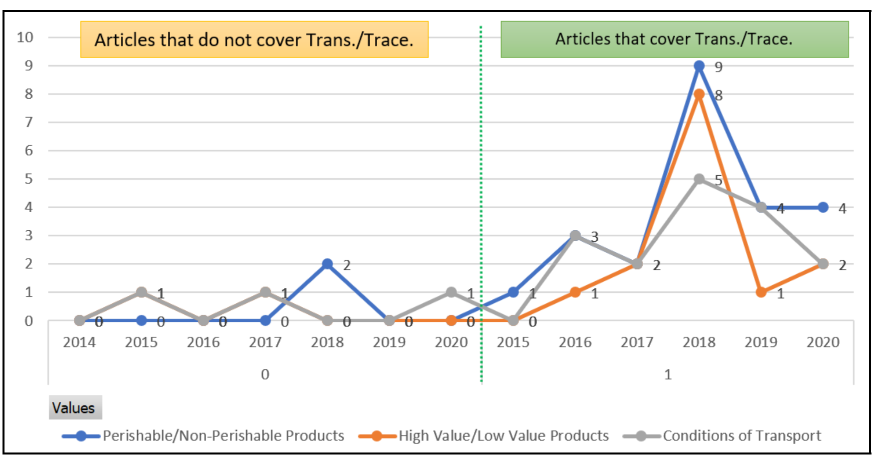
Figure 3 shows the overall trend about products and conditions during the transportation of products (group 2 in Table 1). Surprisingly, there were very few articles that specifically address blockchain for products. Of all three categories of products, perishable/non-perishable products received the most attention, followed by high value/low value products. There was a noticeable spike of publications in 2018, followed by a decline in the topic coverage in 2019.

Figure 3 Products and conditions of transportation – overall trend (see online version for colours)



To further uncover insights in the coverage of topics, data were split into two sets based on the top three topics: transparency/traceability, transaction, and tracking (see Table 1). For example, Figure 4 reports the trend of group 2 topics between non-transparency/non-traceability (left half of the figure), and transparency/traceability articles (right-half of the figure). Figures 5 and 6 show the trends of group 2 topics but for the data splits on transaction and tracking, respectively.

Figure 4 Products and conditions of transportation – transparencies/traceability (see online version for colours)



The purpose of this division of data is to uncover areas of focus (or lack thereof) to develop future research agenda. The upward pattern between 2017 and 2019 was more prevalent in articles covering perishable/non-perishable products that also discussed transparency/traceability (right half of Figure 4), non-transaction related (left half of Figure 5) or non-tracking related topics (left half of Figure 6). Comparatively, all the three product categories received the least attention in articles that do not cover transparency/traceability (Figure 4) with only 0 to 2 articles per year throughout our study period.

Figure 5 Products and conditions of transportation – transaction (see online version for colours)

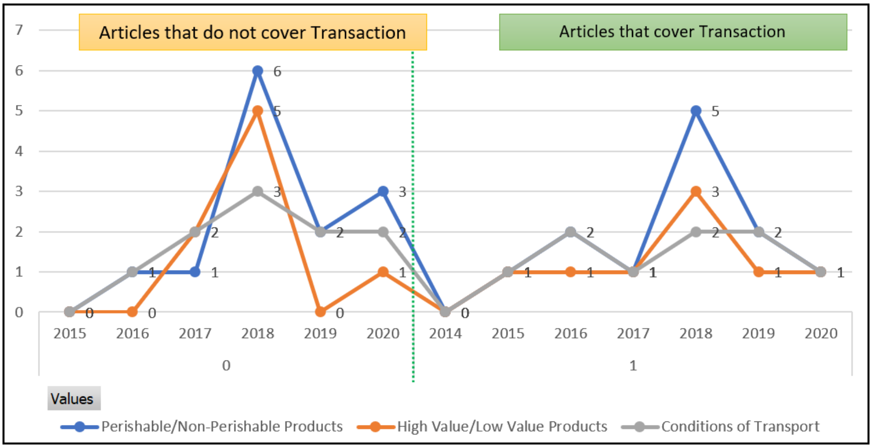
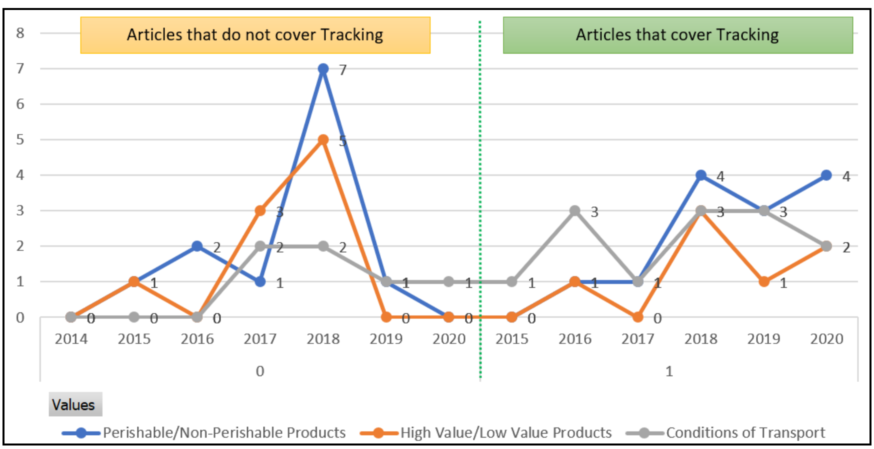


Figure 6 Products and conditions of transportation – tracking (see online version for colours)



4.2.3 Research methodology used by journal articles

Overall, descriptive approach dominates blockchain in supply chain research (see Figure 7), but the growth of modelling/simulation surpassed that of the descriptive framework in the first quarter of 2020. This is typically the case in early phases of an emerging field of research (Filippini, 1997). For a new research area, descriptive articles appear first, with other methodologies picking up momentum at a later stage.

Descriptive frameworks for non-transparency related articles in Figure 8 show a similar pattern as the one in the overall trend, but less so for the transparency related articles. Modelling/simulation began to receive momentum in recent years (after 2018) by articles that discussed transaction related topic (Figure 9).

For articles discussing tracking (see Figure 10), a separate pattern emerges. The use of descriptive frameworks grew before 2018 in articles discussing non-tracking topics. But, the interest in descriptive framework methodology remained unchanged since 2016 for articles that cover tracking. Similarly, empirical studies grew for non-tracking articles, but less so for tracking articles.

Figure 7 Methodology – overall trend (see online version for colours)

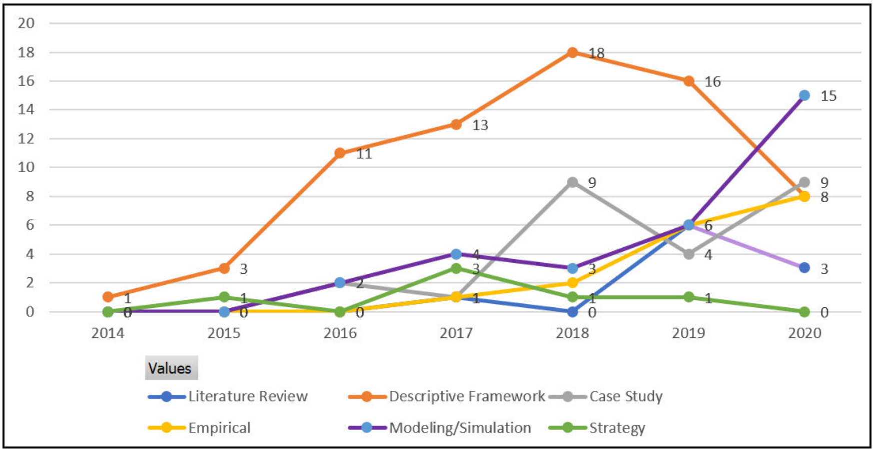
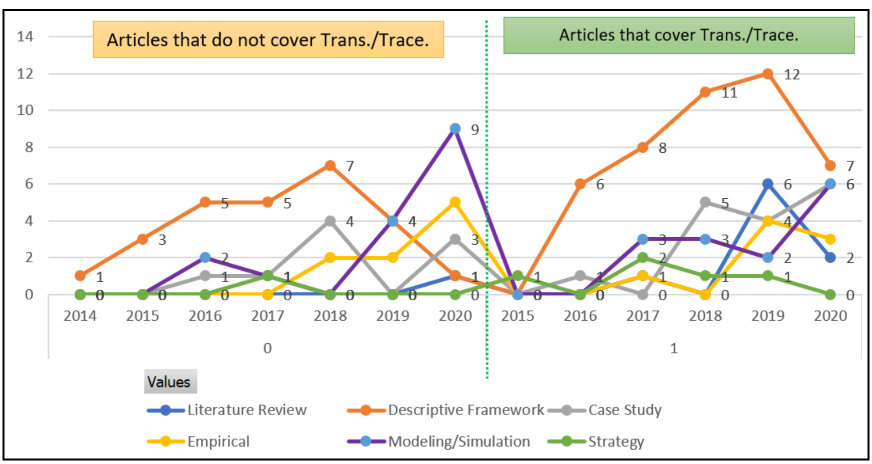


Figure 8 Methodology – transparency/traceability (see online version for colours)



Putting it all together, interest in modelling/simulation, in general, grew after 2018. But most interestingly, that is also the year when interest in descriptive frameworks began to wane. The growth of empirical studies continues to lag behind descriptive framework and modelling/simulation approaches. According to Filippini (1997), this indicates that blockchain research in supply chain is yet to move towards a more mature stage of adoption.

Figure 9 Methodology – transaction (see online version for colours)

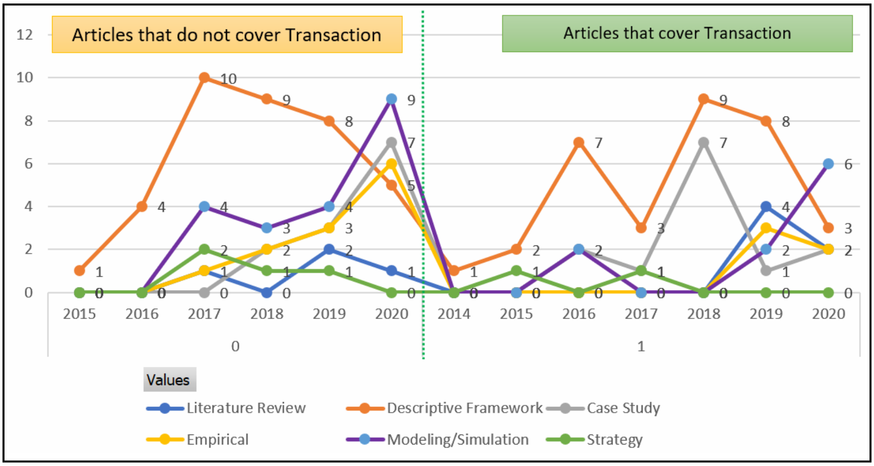
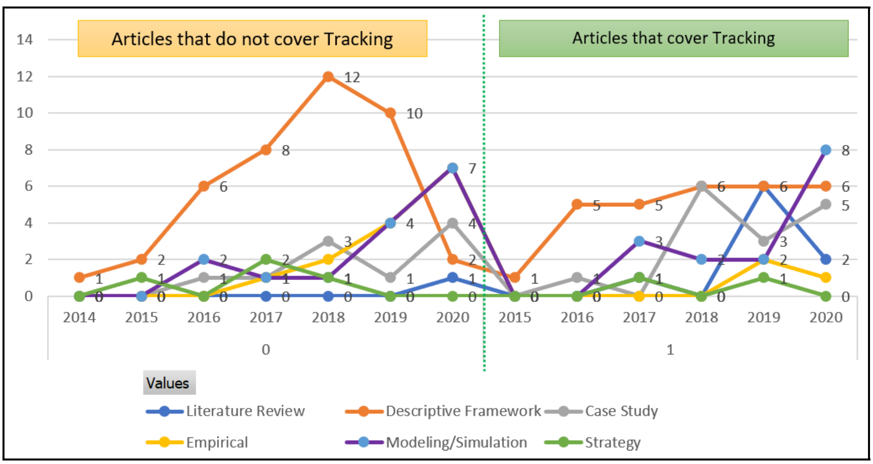


Figure 10 Methodology – tracking (see online version for colours)



4.2.4 Applications of blockchain in supply chain

Blockchain is used in supply chain to a) provide authenticity of raw material, product or distribution, b) verify the origin of products, c) use IoT technology, and d) support smart contracts. The trend in these four topics is plotted in Figure 11. As can be seen, growth in all the four areas exhibits a similar pattern with a slight exception of smart contracts, where it received a higher rate of interest after 2018.

Figure 11 Applications of blockchain in supply chain (see online version for colours)

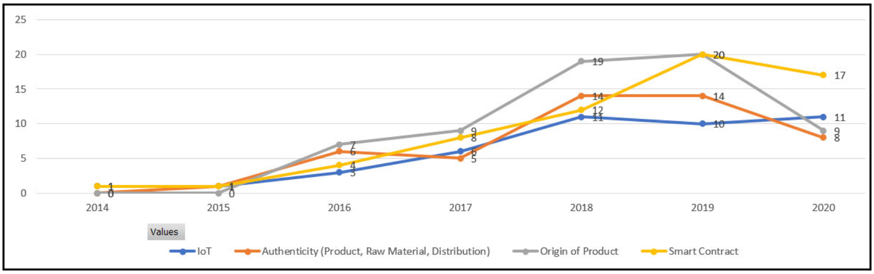
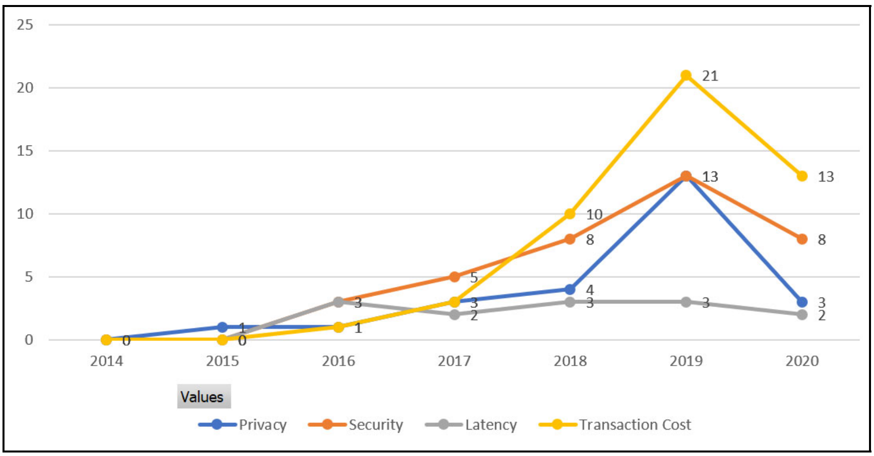


Figure 12 Challenges – overall trend (see online version for colours)



4.2.5 Challenges

There is a recent up-tick in articles that discuss transaction cost, security, or privacy (Figure 12) but interest in latency is flat. As seen in Figure 13 a near identical pattern emerges for articles covering transparency/traceability. However, there is marginal growth of interest in all four topics in non-transparency/non-tracking articles. The patterns of interest are quite similar between transaction and non-traction related articles with transaction cost receiving the most attention, followed by security and privacy (Figure 14). A similar trend is observed when splitting data by tracking (Figure 15). Transaction cost dominates both tracking and non-tracking related articles, but security ranks second for non-tracking related articles and third for tracking related articles. Interest in security for non-transaction and non-tracking articles started to grow since 2015, nearly two years sooner as compared to articles discussing transaction related issues or tracking. It is interesting to note that latency generally received very little interest compared to the other three areas.

Figure 13 Challenges – transparency/traceability (see online version for colours)

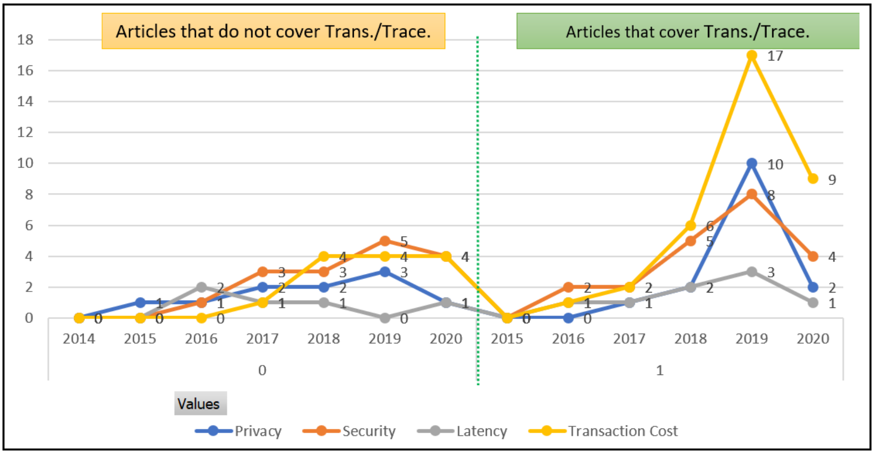
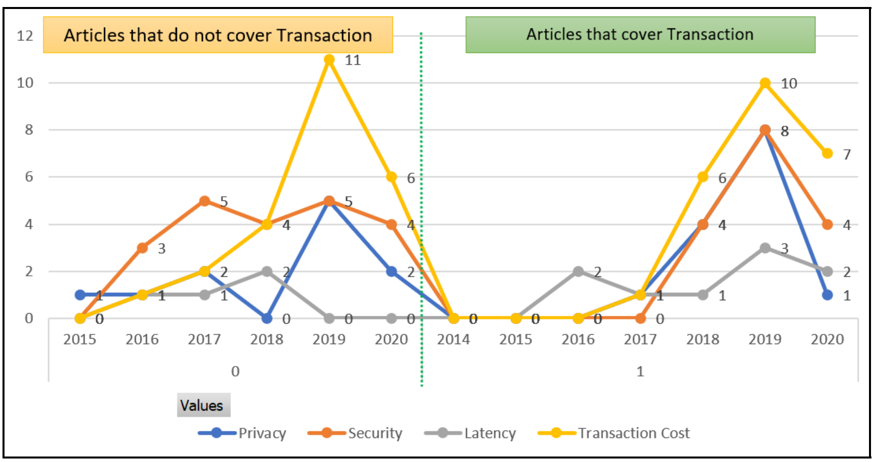


Figure 14 Challenges – transaction (see online version for colours)



4.2.6 Other business processes

Interest in the total cost and scalability topics continues to grow across the years (Figure 16). But, separate patterns emerge when the overall trend is analysed against the top three ranked topics, namely transparency, transactions, and tracking. Generally, researchers did not pay much attention to non-transparency/non-traceability topics (left half of Figure 17). This provides a unique opportunity for future research. Figure 18 shows that, after 2018, scalability was not much discussed in articles covering non-transaction topics. Figure 19 shows that there is a delayed interest in all areas for articles that cover tracking. The upward trend started for tracking related articles in 2017. But, for non-tracking articles, it began in 2015. Interest in all new areas of focus is high for both non-tracking and tracking articles. However, this phenomenon is not observed for transparency (Figure 17) and transaction (Figure 18). It can be seen that the interest in these areas has not picked up momentum for non-transparency related articles.

Figure 15 Challenges – tracking (see online version for colours)

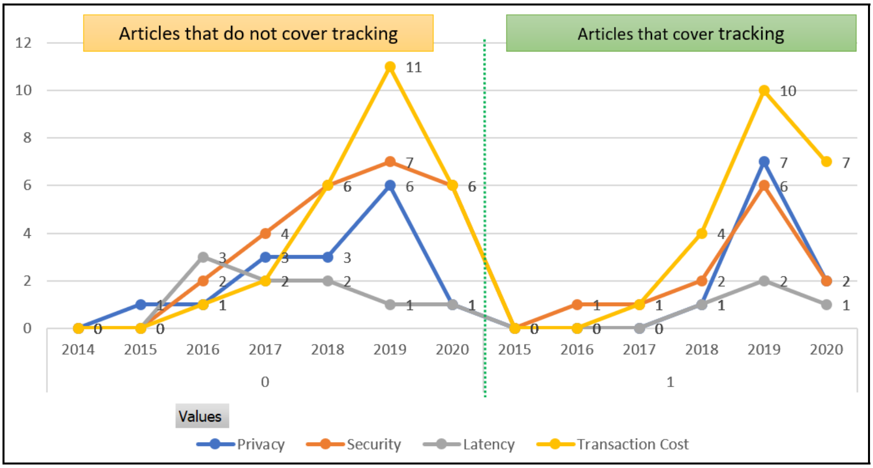
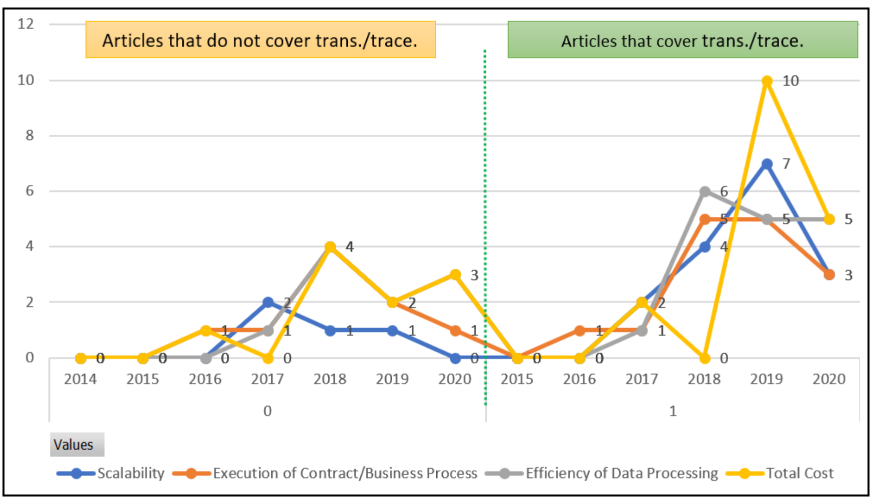


Figure 17 New areas of focus – transparency/traceability (see online version for colours)



4.3 Association analysis

The previous section presented research trends for the top three topics: transparency/traceability, transaction related issues, and tracking in relation to the remaining 27 topics. It shows that multiple topics are frequently covered in the same article. Although our work extends beyond the traditional frequency count into trend analysis, the unit of analysis is still individual topics in articles. In other words, topics are treated independently from each other to uncover insights regarding popularity of topics. Despite an improvement over simple frequency count of topics, trend analysis does not account for relationships among topics in the same article. Therefore, it cannot easily answer the question about how and to what extent topics are studied together in the same article. This is a common problem in many literature review articles that stopped at frequency and trend analysis. Being able to identify topic relationships allows researchers to see what topic combinations have been well-studied and where the new directions might be for the field. This offers a renewed contribution for researchers looking for the maturity of topics as the basis to build sound theories, and identifying new research topics.

Figure 18 New areas of focus – transaction (see online version for colours)

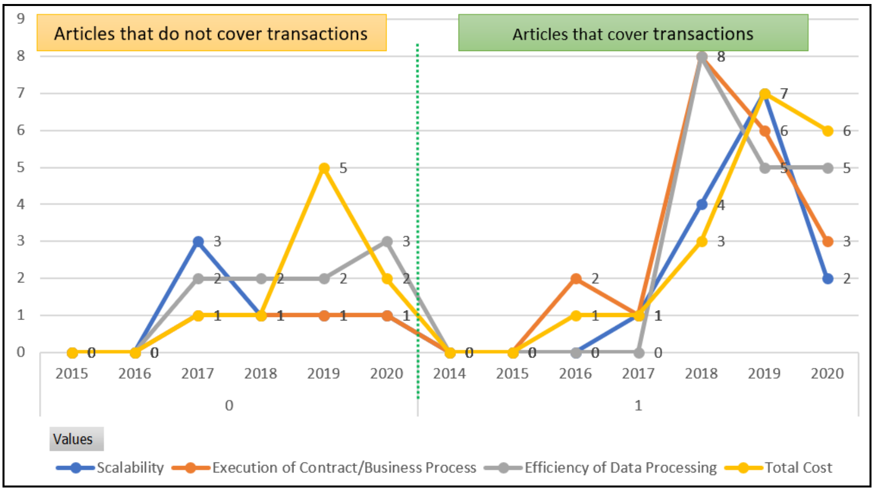
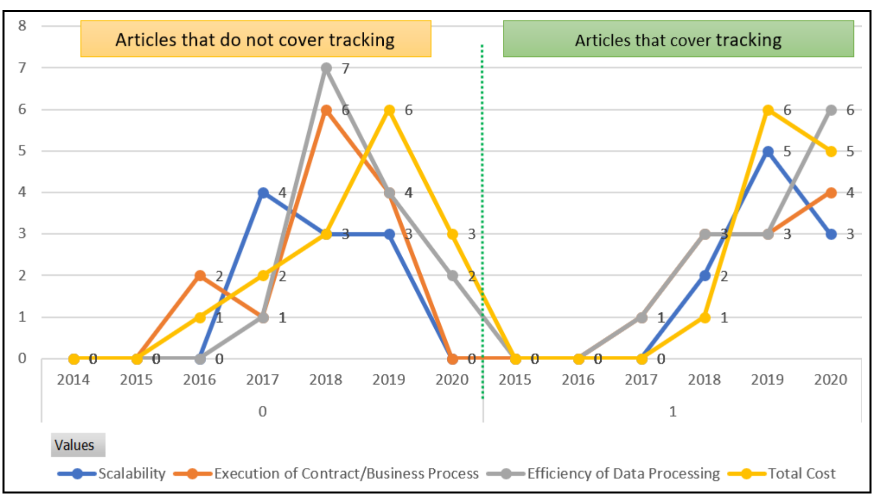


Figure 19 New areas of focus – tracking (see online version for colours)



In this section we focus on the pattern of how multiple topics are studied in the same article through a co-occurrence (or association) analysis. To uncover trends of co-occurrence among the topics identified, we report findings from an association analysis using the popular machine learning algorithm called apriori. The results are reported in the form of association rules, where rule quality is measured in common performance metrics, including support, confidence and lift ratio.

Table 2 Final association rules

Rule no.	*Left-hand side (lhs)*	*Right-hand side (rhs)*	*supp*	*conf*	*cov*	*lift*	*cnt*
1	{Transparency/traceability, origin of product}	{Authenticity}	0.277	0.727	0.382	2.330	48
2	{Transparency/traceability, authenticity}	{Origin of product}	0.277	0.923	0.301	2.218	48
3	{Authenticity}	{Origin of product}	0.283	0.907	0.312	2.180	49
4	{Origin of product}	{Authenticity}	0.283	0.681	0.416	2.180	49
5	{Transaction, transparency/traceability}	{Origin of product}	0.202	0.714	0.283	1.716	35
6	{Regulatory issues}	{Transaction}	0.202	0.700	0.289	1.553	35
7	{Authenticity, origin of product}	{Transparency/ traceability}	0.277	0.980	0.283	1.541	48
8	{Multi-party acceptance}	{Transaction}	0.249	0.694	0.358	1.538	43
9	{Transaction}	{Multi-party acceptance}	0.249	0.551	0.451	1.538	43
10	{Transparency/traceability, tracking/monitoring}	{Origin of product}	0.243	0.636	0.382	1.529	42
11	{Authenticity}	{Transparency/ traceability}	0.301	0.963	0.312	1.514	52
12	{Multi-party acceptance}	{Security}	0.208	0.581	0.358	1.477	36
13	{Security}	{Multi-party acceptance}	0.208	0.529	0.393	1.477	36
14	{Tracking/monitoring, origin of product}	{Transparency/ traceability}	0.243	0.933	0.260	1.468	42
15	{Transparency/ traceability}	{Origin of product}	0.382	0.600	0.636	1.442	66
16	{Origin of Product}	{Transparency/ traceability}	0.382	0.917	0.416	1.442	66
17	{Transparency/traceability, Origin of product}	{Tracking/monitoring}	0.243	0.636	0.382	1.430	42
18	{Transaction, origin of product}	{Transparency/ traceability}	0.202	0.897	0.225	1.411	35
19	{Tracking/monitoring}	{Origin of product}	0.260	0.584	0.445	1.404	45
20	{Origin of product}	{Tracking/monitoring}	0.260	0.625	0.416	1.404	45
21	{Security}	{Transaction}	0.243	0.618	0.393	1.370	42
22	{Transaction}	{Security}	0.243	0.538	0.451	1.370	42
23	{Smart contract}	{Trust}	0.237	0.594	0.399	1.353	41
24	{Trust}	{Smart contract}	0.237	0.539	0.439	1.353	41
25	{Tracking/monitoring}	{Transparency/ traceability}	0.382	0.857	0.445	1.348	66
26	{Transparency/ traceability}	{Tracking/monitoring}	0.382	0.600	0.636	1.348	66

Notes: supp –support, conf – confidence, cov – coverage, lift – lift ratio, cnt – record count (no. of articles).

Support of an association rule refers to the proportion of records that contains both the antecedent and consequent parts of the rule in the same record. For example, if 0.6 is the support for rule {transparency/traceability} → {transaction}, this means that 60% of the published articles study both transparency/traceability and transaction. *Confidence* is a measure of the likelihood of seeing the consequent part of a rule when one sees the antecedent part. Using the above example, a confidence of 0.7 means 70% chance of seeing transaction topic discussed in the same article when one sees transparency/traceability. *Coverage* is basically the support calculated for the antecedent part of a rule. *Lift ratio*, on the other hand, measures whether the antecedent and consequent parts are independent from each other. An association rule with the lift ratio of one mean that the antecedent part and the consequent part are independent from each other. The higher the lift ratio, the more both parts are dependent on each other.

The analysis initially generated 55 association rules. The final set consisted of 26 rules (see Table 2) after running through Fisher's exact test with Bonferroni adjustment (Hahsler and Hornik, 2007). The mean support, confidence, coverage and lift values are 0.2675, 0.7126, 0.3871, and 1.574 respectively.

The network diagram in Figure 20 is a directed graph that shows how the topics are related in association rules. The colour and size of the circles together with the arrows are the three key elements of the diagram. The colour refers to the lift ratio. The darker the colour, the higher the lift ratio is. The size of the bubble refers to the support value. Again, the bigger the bubble, the larger the support value is. The labels (e.g., R31) are the internal reference of the topic in the original dataset. For example, R31 refers to the origin of product. Each arrow points from the left-hand-side (LHS) of the rule to the right-hand-side (RHS).

Section 1 in Table 3 shows that four rules with very high lift ratios are related to origin of product (R31), authenticity (R30) and transparency/traceability (R08). Since two of these rules (rules 2 and 3) also have high confidence (0.923 and 0.907, respectively), associations between {transparency/traceability, authenticity} and {origin of product}, and between {authenticity} and {origin of product} are strong. Note that the antecedent part of rule 2 includes two topic categories. If considering only one of them, its association with the consequent part would not be high. For example, association between {transparency/traceability} and {authenticity} has a confidence lower than 0.5. If we consider only {origin of product} and {authenticity}, the confidence is 0.681. By considering both topic categories in the antecedent for rule 2, the confidence jumps to more than 0.9. This shows that the association between the two topics combined in the antecedent part and the consequent part is stronger than the association of either topic in the antecedent for its association with the consequent part.

Despite the high degree of association among the above topics, only a few articles study the relationships among these topics. The high lift ratios indicate that the relationships among these categories are consistent (i.e., strong dependency on each other), but the number of articles supporting these relationships (as measured in support) is still not large.

Rules that cover the largest proportions of articles (rules 16, 25, 15, and 26 in Section 2 of Table 3) centre around a similar set of topics with one new addition – tracking/monitoring (R09). Rules 16 and 25 also have moderate to high confidence values, indicating both strong support and confidence are present in these rules. When articles study {origin of product} and {track/monitoring}, it is most likely that they also discuss the {transparency/traceability} issues.

Figure 20 Network diagram (see online version for colours)

Putting both sections of Table 3 together, knowledge about the product [origin of product (R31), authenticity (R30) and transparency/traceability (R08) and tracking/monitoring (R09)] is maturing because of the strong association among these topic areas. It also points to the lack of strong association among other remaining topics or between the above topics and other remaining topics. This is shown in Figure 20. For example, trust (R07) and smart contract (R32) are by themselves in the lower-right corner of the chart. This indicates that they only have a weak association among themselves, but not with other topic areas. This could provide opportunities for future research. For example, several characteristics built into blockchain (e.g., consensus model, encryption and one-way hash) are likely to foster a sense of security, thereby building consumer trust on the authenticity of product and product origin. As a result, the linkage between trust and these other topic areas naturally fit together. Another somewhat isolated cluster of topics includes multi-party acceptance (R13), security (R11) and transaction related issues (R06). Similarly, research opportunities exist to link these to other topics. For example, security in transactions is only one possible appeal for multi-party acceptance of the blockchain technology. Transparency/traceability, fraud protection, enhanced information sharing, etc. could also entice acceptance of BC among supply chain partners. Furthermore, regulatory issues (R12) are only associated with transaction (R06).

It could also be linked to other areas, such as tracking/monitoring, and information quality.

Table 3 Rules sorted by criteria

Rule no.	*lhs*		*rhs*	*supp*	*conf*	*cov*	*lift*	*cnt*
1 Rules with highest lift ratios								
1	{Transparency/traceability, origin of product}	=>	{Authenticity}	0.277	0.727	0.382	2.330	48
2	{Transparency/traceability, authenticity}	=>	{Origin of product}	0.277	0.923	0.301	2.218	48
3	{Authenticity}	=>	{Origin of product}	0.283	0.907	0.312	2.180	49
4	{Origin of product}	=>	{Authenticity}	0.283	0.681	0.416	2.180	49
2 Rules with highest support values								
16	{Origin of product}	=>	{Transparency/ traceability}	0.382	0.917	0.416	1.442	66
25	{Tracking/monitoring}	=>	{Transparency/ traceability}	0.382	0.857	0.445	1.348	66
15	{Transparency/traceability}	=>	{Origin of product}	0.382	0.600	0.636	1.442	66
26	{Transparency/traceability}	=>	{Tracking/monitoring}	0.382	0.600	0.636	1.348	66

5 Discussion and conclusions

Our findings about the trends and the co-occurrence analysis of the topics covered by published research show that certain topics are highly associated with each other. By computing three aspects of association, namely support (proportion of records that support the relationship), confidence (the likelihood of a relationship between two sets of topics) and lift ratio (the interdependence between two sets of topics), we identified the following trends of co-occurrence among research topics:

5.1 Research innovation through established work

Even though associations may not always be high on all three counts, we see that {transparency/traceability}, {authenticity} and {origin of product} are frequently studied together. Association rules involving only two or three of these topics usually have high support, confidence and lift values. This evidence is important for several reasons. First, such a strong association is the prerequisite to establish meaningful construct relationships in a theory. Our findings provide a basis for further theory refinement and expansion. Second, the strong relationships from our findings will also serve as the basis for testing causality, moderation and/or mediation. For example, trust in product authenticity or origin of product may grow when transparency/traceability is in place. In this case, transparency/traceability could be the catalyst or moderator for consumers to perceive a high level of product authenticity. Third, the existing strong relationships among topics offer researchers opportunities to expand into other topics of interest by building incremental theory improvement into new areas.

5.2 Research innovation through the new-found paths

Our work highlights areas that are beginning to receive attention. For example, the association between {transaction} and {regulatory issues} are taking shape with association rule 6 having a medium level of support, confidence and lift as compared to other rules. However, the confidence of rule 6 is about 0.7 meaning that every time regulatory issues are discussed, there is a 70% chance that transaction related issues are also discussed. In other words, despite a medium confidence of this rule, regulatory issues are discussed together with some other topics. The reason they do not show up in the top 26 rules is because the associations between regulatory issues and other topics are still low. This is an opportunity for future researchers to extend the association of regulatory issues with other topics. For example, regulations of energy use could have an impact on the type of consensus model in block chain, number of miners, smart contracts, pricing, and IoT leading to social-economic impacts (Rao and Clarke, 2020).

Similarly, {trust} and {smart contract} are the isolated pockets of knowledge with little association with other topics. Although blockchain via smart contracts engenders trust, the association between smart contracts and other topics (such as security, speed, multi-party acceptance, and information sharing) is still low. This does not mean there is no research on such topics together. The lower values of the parameters indicate that there are not enough studies to associate smart contracts with other topics. Therefore, these areas of 'gap' could also be possible ideas for future research.

The trend analysis offers other types of insights as well. Charts show crowded areas such as transparency/traceability in blockchain benefits, descriptive frameworks in methodology, and transaction costs in blockchain challenges. Although these crowded areas do not necessarily suggest no more research is needed in those areas, they point out current interest in blockchain related research.

5.3 Research innovation through the paths that have not been travelled

Network diagram in Figure 10 is an informative overview of the 'gap' in existing research. For example, multi-party acceptance, information sharing, latency, execution of contract/business processes, and scalability are among the areas that have received little attention. Some of these topics have not been discussed often as compared with other topics (e.g., only 13 articles covered latency, and 22 on scalability as shown in Table 1). Also, popular topics do not have a large number of associations with other topics. For example, information sharing, multi-party acceptance and execution of contract/business processes show little association with a popular topic such as transparency/traceability.

Our work offers several forms of theoretical and practical contributions. First, the majority of literature surveys take a single-topic approach. In that they analyse the published literature by assuming little or no correlation among the topics discussed in an article, or assuming that each article covers a single topic. In addition to providing empirical evidence that blockchain articles in supply chain usually cover more than one topic per article, we examine topic co-occurrence through association analysis. With the knowledge of how topics are studied together, we offer researchers directions to study meaningful relationships among their topics of interest and other related areas. This is especially important to further theoretical contributions, since "relationships, not lists [of variables], are the domain of theory" [Whetten, (1989), p.492]. Second, even existing relationships among key topics shown in our findings are useful to start or solidify a theory. In supply chain management one key aspect of a viable theory is the ability to withstand refutation. This is referred to as 'falsifiability', which largely concerns about robustness of relationships among variables (Handfield and Melnyk, 1998). Our work shows topic relationships measured through three relationship indicators, namely support, confidence and lift ratio. As a result, it offers researchers ways to extend their interest based on the sure associations among topics. Similarly, relationships with high confidence values offer stronger evidence to test causality. Third, our focus on several key elements of Supply chain 4.0 offers researchers key insights on moving into these new areas of supply chain management. This is a unique direction in supply chain literature. Fourth, trend analysis presented here will help researchers identify areas that lack the focus, in terms of benefits provided by blockchain, effects of blockchain on products, methodology, applications, and challenges and opportunities.

6 Future directions

Both service and manufacturing industries are moving towards pull environment by using the available information to provide location specific product or services in a timely manner. This requires mass customised smart products that can collect, store and transmit data in real time. To assure customers about product sourcing and authenticity, it also needs an integrated supply chain network for real time data processing and decision making. Industry 4.0 and its associated SC is a move in this direction and blockchain is one of the enabler technologies. Significant research opportunity exists to properly integrate BC in SCM. Our research identifies the following areas for further investigation.

As discussed earlier, the number of descriptive studies is trending down. As the blockchain technology is maturing, more case and empirical studies are needed to authenticate the challenges and opportunities it presents. For example, although privacy issues in blockchain certainly deserve further investigations, not everyone is equally concerned about it. Privacy concerns may be affected or even ignored when some form of incentives (vendor coupons, access to information, discounts, etc.) are given, or when the BC is open to trusted partners only.

Using trends and co-occurrence relationships identified in the previous sections, mathematical/simulation models could be built to develop a theoretical base, and to move blockchain research in the supply chain to the next stage of maturity. This is an important direction towards building social science theories, where constructs and their relationships are key building blocks. Our trends analysis could help researchers to gauge the maturity of constructs for such a theory. Investigations into co-occurrence relationships could demonstrate support for construct relationships.

Topics that are extremely important for successful implementation of blockchain in Supply chain 4.0, such as smart contract, IoT, and origin of product have not received the much needed attention. As a result, their associations with other topics are not strong enough. This means that they either are not discussed together with other topics often, or the same topics, by themselves, are not covered often. There is only scant evidence of the relationship between these topics with other areas. More research is needed to understand the impact of such co-occurrences on the overall implementation of blockchain in the supply chain.

Trend analysis shows many potential areas for future research, e.g., the left half of Figure 4 shows that for perishable/non-perishable products or high value/low value products, conditions of transport are not studied much in non-transparency/non-traceability papers. Case studies investigating the importance of transport conditions for certain products (susceptible to fraud and/or temperature, pressure during their transport) will lead to a better understanding of the importance of smart products and IoT.

Further studies are also needed to examine cost implications of using blockchain technology. With an increased data needs of Supply chain 4.0, cost of transaction goes up. However, there is a dearth of research that examines total cost (including transaction cost) of implementing blockchain and the related benefits. For a successful penetration of blockchain technology in supply chains, practitioners need to be convinced that their benefits outweigh the cost implementation.

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