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Knowledge diffusion paths of blockchain domain: the main path analysis

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Abstract
Blockchain technology, as a disruptive technology, has received widespread attention in the past few years from all over the world, leading to rapid growth in research outputs. This paper adopts a quantitative method, the main path analysis, to comprehensively and systematically investigate the development trajectories of blockchain. Four different main paths, the global main path, the forward local main path, the backward local main path and the key-route main path are conducted simultaneously. By analyzing these various paths, on the one hand, this paper finds that papers on paths focus on two aspects, cryptocurrencies and blockchain-based applications. On the other hand, this paper discovers several major research areas of blockchain, including internet of things (IoT), healthcare, energy industry, voting, insurance and supply chain management. At the same time, this paper further analyzes the research hotspots, as well as the development trajectories of blockchain in the areas of IoT, healthcare and supply chain management by using the key-route main path analysis. This paper is conductive for both the new and experienced researchers to identify some influential papers and grasp the knowledge diffusion paths in these domains.

Keywords Blockchain · Main path analysis · Internet of things · Healthcare · Supply chain management

Introduction

In the past few years, blockchain, as an emerging technology, has been widely known and understood by both academics and practitioners. The notion of blockchain can be tracked back to 2008 (Nakamoto 2008). It is a public ledger that all transactions will be stored in blocks and then will be linked in chronological order by nodes on the peer-to-peer network. This distributed peer-to-peer linked-structure is able to be independent of trusted third parties, thereby solving the problem of double payment and making the transactions in a more

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transparent way. The key characteristics of blockchain can be described as decentralization, persistency, anonymity and auditability (Zheng et al. 2018).

The first application of blockchain technology is a cryptocurrency called bitcoin, which is a decentralized digital currency. It is usually considered as an important investment and speculative device (Merediz-Sola and Bariviera 2019). Since it was first proposed by Nakamoto (2008), it has attracted widespread attention from a number of researchers and practitioners. Recently, the cryptocurrency market has grown rapidly and a variety of cryptocurrencies have emerged since the advent of bitcoin (Hölbl et al. 2018). The boom in the cryptocurrency market proves the importance of blockchain technology. In addition, the rise of smart contracts provides opportunities for the application of blockchain technology in various fields. For example, Ethereum, a decentralized application platform, allows for running all kinds of applications with the support of smart contracts (Miau and Yang 2018). The advantage of the smart contract is that it has its own code that can be executed automatically without the intervention of third parties. The blockchain-based system supporting smart contracts has broken through the original limitations and made great progress in the development of blockchain. Recently, scholars have gradually realized the potential of blockchain technology in various applications and dedicate to exploring new development opportunities in different areas (Christidis and Devetsikiotis 2016), such as energy (Sikorski et al. 2017), education (Bdiwi et al. 2017), supply chain management (Hackius and Petersen 2017; Subramanian 2017) and internet of things (IoT) (Liao et al. 2017).

With the dramatic growth of the research outputs, many researchers endeavor to review papers about blockchain by concentrating on its concepts, architectures and consensus mechanism (Cao et al. 2017; Zheng et al. 2017). There are also some papers focusing on various applications of blockchain. For example, Casino et al. (2019) conduct a comprehensive literature review of blockchain applications, classifying them into nine different types. In addition, some papers review previous works objectively and comprehensively by using quantitative analysis such as bibliometric method which is an effective way to uncover the development trajectory of a given discipline (Yu et al. 2020). For example, Dabbagh et al. (2019) uncover valuable insights including citation trends, most significant papers and favorite publication venues of the collected papers from 2013 to 2018 by performing a bibliometric analysis. Firdaus et al. (2019) adopt the bibliometric analysis to find the sub areas, key authors, connection of countries and affiliations in this domain. Although these studies provide in-depth insights about blockchain from different perspectives, they all ignore the knowledge diffusion paths of this field. With the dramatic growth of blockchain and a remarkable number of works pouring into academia, it is necessary to identify the development trajectories in a more systematic and comprehensive way.

The main path analysis is a powerful method to capture an overview of a specific field and has attracted the attention from many researchers in recent years. It is based on a citation network of research papers, for the purpose of exploring the knowledge diffusion trajectory. The main path analysis is first proposed by Hummon and Doreian (1989). Three algorithms (node pair projection count, search path node pair, search path link count) and a search approach are presented to calculate the traversal weight of links in citation network and extract the main path respectively. Batagelj and Mrvar (1998) make it possible to analyze the large citation network quickly. Later, Batagelj (2003) proposes a new algorithm named search path count (SPC), showing that SPC has some good properties. Liu and Lu (2012) make a significant contribution by complementing the previous approaches from various angles. Recently, the main path analysis has been used to identify the development trajectory in various fields. For example, Xiao et al. (2014) study the content of main paths of 1880 papers in the field of data quality. Ma and Liu (2016) analyze the main paths of the four popular themes of shareholder activism research from 2003 to 2013. Chuang et al. (2017) explore the development trend of eTourism by this quantitative method. Fu et al. (2019) study the development of IoT through the main path analysis, identifying four branch paths in this domain. Yu and He (2020) study the knowledge diffusion trajectories of the field of energy efficiency based on data envelopment analysis by the main path analysis.

To our knowledge, additional analysis via the main path analysis to present the dynamic development process of blockchain has not been conducted until now. Based on this quantitative method, on the one hand, a set of papers that have made great contributions to blockchain development, as well as interrelationships between them, are able to be identified effectively even though there are a large number of papers in this domain. On the other hand, the trajectories of knowledge diffusion and the evolutionary structure of the blockchain domain can be clearly uncovered through the combination of various main paths. For academia, it can not only help them collect key information effectively but also help them grasp a series of important historical-development events and changes in the focus of blockchain research, thereby providing valuable references for their research. For industrial practitioners, it is able to assist them to understand the application status of the unabated blockchain technology clearly, thus providing solutions for solving technical problems in blockchain domain. Contrary to previous studies that analyze the blockchain domain systematically, this paper has two main advantages. First, in the past, critical papers were usually selected for analysis based on the authors' experience in traditional review papers. However, the main path analysis is a quantitative method used to identify some influential papers, which can eliminate prejudice and makes the analysis objective and fair, and makes it easier to handle thousands of papers. Second, compared with papers that use bibliometric analysis, this paper provides a dynamic process of blockchain development, instead of focusing on static statistical indicators analysis. To illustrate the similarities and differences between the main path analysis and other similar methods such as traditional literature review and bibliometric method, Table 1 is presented for the in-depth comparison.

The rest of this paper is organized as follows. After in "Data and methodology" section briefly introduces the theory of the main path analysis, in "Main path analysis of blockchain" section presents the development of blockchain technology while in "Main path analysis of blockchain in three active areas" section shows the hot topics and knowledge diffusion trajectories of blockchain technology in IoT, healthcare and supply chain management. Then, the last two sections discuss the results and conclude this study, respectively.

Data and methodology

Data collection

As we all know, Web of Science (WoS) is one of the leading and outstanding databases covering about over 10,000 significant journals. In recent years, it is increasingly applied in academic research (Liu 2019; Zhu and Liu 2020). To ensure the quality of the analysis, we chose WoS as the data source. The databases selected in this paper are Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index-Science (CPCI-S) and Conference Proceedings Citation Index-Social Science and Humanities (CPCI-SSH). With reference to the paper that use the bibliometric method to study blockchain (Miau and Yang 2018), the search query

Table 1 Comparison of main path analysis with traditional literature review and bibliometric method

	Traditional literature review	Bibliometric method	Main path analysis
Research object	Papers and patents	Papers and patents	Papers, patents and count decisions
Research with software	No	Yes	Yes
Data size that can be analyzed	Small	Large	Large
Research method	Qualitative	Quantitative	Quantitative
Analysis method	Content analysis	Indicator analysis Visual analysis	Content analysis Visual analysis
Purpose	(1) To summarize the research results of the whole field or a certain aspect of the field from different angles (2) To provide guidelines for future research	(1) To describe characteristics of the data and its changing laws by statistical analysis (2) To explore the intellectual structures, research focus and emerging trends	(1) To reveal the citation relationship between important points (2) To reveal the trajectory of knowledge diffusion to identify the past, current and future development

identified in this paper is as follows: Topic Search (TS) = ("blockchain*" OR "bitcoin" OR "ethereum" OR"cryptocurrenc*" OR "smart contract"). In WoS, the asterisk (*) can search for more related words. The asterisk at the end of "blockchain" takes both "blockchain" and "blockchains" into account when retrieving papers in this domain, and papers containing "cryptocurrency" and "cryptocurrencies" can also be identified based on "cryptocurrenc*". The timespan is set from 2008 to 2019 and we searched on November 10, 2019. In addition, there are no restrictions on document types. In the end, 4337 papers were downloaded from the WoS. After analyzing the content of papers on the main paths of blockchain, several active areas for the application of blockchain technology were identified. The search queries in "Main path analysis of blockchain in three active areas" section for further analysis of blockchain in IoT, healthcare and supply chain management are as follows: TS = ("blockchain*" OR "bitcoin" OR "ethereum" OR "cryptocurrenc*" OR "smart contract") AND TS = ("IoT" OR "Internet of Things"); TS = ("blockchain*" OR "bitcoin" OR "ethereum" OR "cryptocurrenc*" OR "smart contract") AND TS = ("healthcare" OR "health" OR "medic*" OR "medical" OR "medicine" OR "*health*"); TS = ("blockchain*" OR "bitcoin" OR "ethereum" OR "cryptocurrenc*" OR "smart contract") AND TS = ("supply chain" OR "supply chain management"). As a result, 712, 350 and 202 papers were retrieved from the WoS, respectively.

Methodology

Main path is extracted from a citation network which represents citation relationships between a large number of papers (Liu et al. 2019). In a citation network, a node represents a paper and the link between two papers represents the citation relationship, and the arrow represents the direction of knowledge flow and points to the citing paper.

After getting the citation network, various main paths can be drawn based on different algorithms. This paper explains how the main paths are obtained by illustrating a simple citation network. The first step is to transform the citation network into a weighted network. Hummon and Dereian (1989) propose three algorithms for weighting the links: node pair projection count (NPPC), search path node pair (SPNP), search path link count (SPLC). Later, Batagelj (2003) proposes a new algorithm named SPC. There is no significant difference between them and the SPC is chosen in this paper as is recommended by Batagelj (2003). In a citation network, the sources are the nodes that are only cited by other papers but do not cite any papers, and the sinks are the nodes that only cite other papers but do not be cited. The SPC value of a link is defined as how many times this link is traversed from all sources to all sinks in a citation network. In the citation network in Fig. 1, there are two sources, which are A and H, and three sinks, D, G and J. The SPC value of the link A–E is 3 because there are three times that is traversed from two sources to three sinks. In other words, there are three paths that pass through the link A–E, which are A–E–F–D, A–E–F–G and A–E–F–J. The link E–F has the largest SPC value because six paths pass through it, which are A–E–F–D, A–E–F–G and A–E–F–J from source A and H–E–F–D, H–E–F–G and H–E–F–J from source H. After calculating all the links, this simple citation network is fully transformed into a weighted network. The larger the value of the link, the more important it is.

The next step is to extract main paths in the weighted network by using different search algorithms. The forward local main path, searching from sources to sinks, chooses the largest SPC value among all the links emanating from a point. The search will stop until the sink is reached. In Fig. 2, the forward local main path is shown with solid lines. The

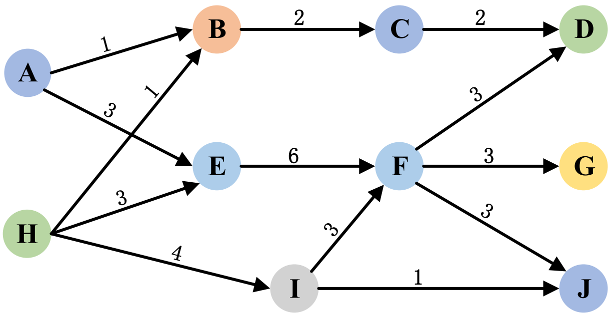


Fig. 1 A simple citation network with SPC values

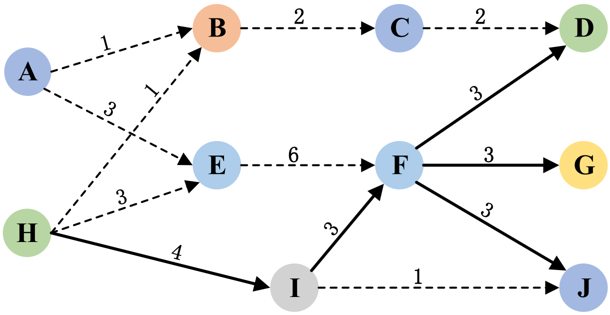


Fig. 2 The forward local main path

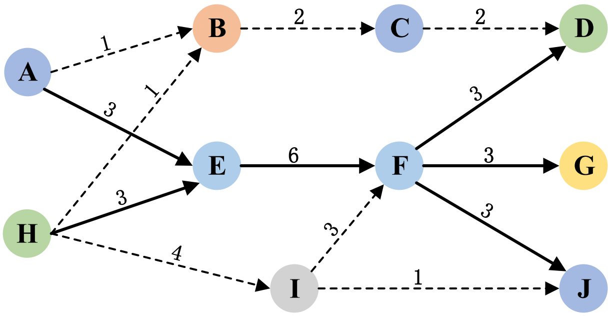


Fig. 3 The backward local main path

process is shown below. First, choosing the link with the largest SPC value among five links emanating from the sources A and H, A–B, A–E, H–B, H–E and H–I, which is the link H–I. Second, the node I is determined as the start point for the next step. The link I–F is selected because its SPC value is greater than the link I–J's SPC value. Third, from the point F, three links are selected because they have the equal SPC value. Finally, the selected links are combined to form the forward local main path.

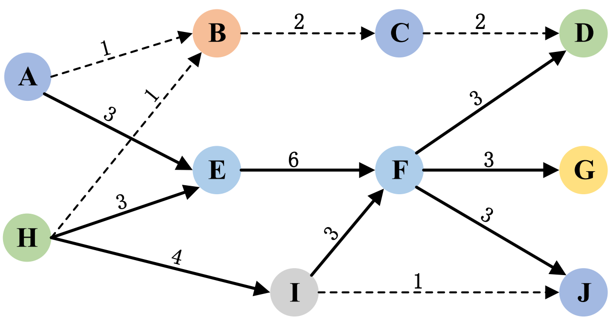
In contrast to the forward local main path, the backward local main path searches from the latest papers to the earlier papers, that is, from sinks to sources. As shown in Fig. 3, the backward local main path in this simple citation network is the combination of paths A–E–F–D, A–E–F–G, A–E–F–J, H–E–F–D, H–E–F–G and H–E–F–J.

The local main path focuses on the local maximum while the global main path focuses on the overall maximum. The global main path is designed to search the path with the largest total number of SPCs. In this simple citation network, the largest value of the path is 12. The paths are A–E–F–D, A–E–F–G, A–E–F–J, H–E–F–D, H–E–F–G and H–E–F–J, with the same results as the backward local main path.

For comprehensive analysis, Liu and Lu (2012) propose a new search algorithm, the key-route method. The key-route is the link with the largest traversal weight. The number of the key-route is decided by the author. The more key-routes are chosen, the more details will be shown. This paper chooses two key-routes to illustrate the steps of the key-route method, and the result is shown in Fig. 4. First, it begins with a link which has the largest SPC value. The link E–F is selected at the first step because its SPC value is the largest. Second, either the local method or the global method can be used to search forward from point F and search backward from point E. In this simple citation network, the result of the key-route local main path is the same as the result of the key-route global main path, which are paths A–E–F–D, A–E–F–G, A–E–F–J, H–E–F–D, H–E–F–G and H–E–F–J. Third, select the link with the second largest SPC value. As a result, the link H–I is selected. Then, the paths, which are H–I–F–D, H–I–F–G and H–I–F–J, are determined. After combining all the paths, the key-route main path is determined.

It is worth mentioning that these four paths reveal the knowledge diffusion trajectory from different perspectives, which complement each other and will not be replaced (Lu and Liu 2013). The local main path is to find the most important connections at each juncture. The forward local main path makes it possible for the papers which have many followers appearing on the main path while the backward local main path prefers papers which have drawn inspiration from many previous papers. It focuses only on the local maximum, ignoring the largest accumulated SPC value. To overcome this disadvantage, the global main path, with the highest overall SPC value, is used for analysis simultaneously. It is able to identify the most influential path among all the paths from sources to sinks in a citation network. However, although papers on these three paths provide us in-depth insights, they may not contain all links with the largest traversal weight in the citation network. Therefore, the key-route main path, is applied for further analysis. It is able to provide more important papers, as well as the evolutionary structure of blockchain domain. Based on these four main paths, it is possible to discover the development trajectories more completely.

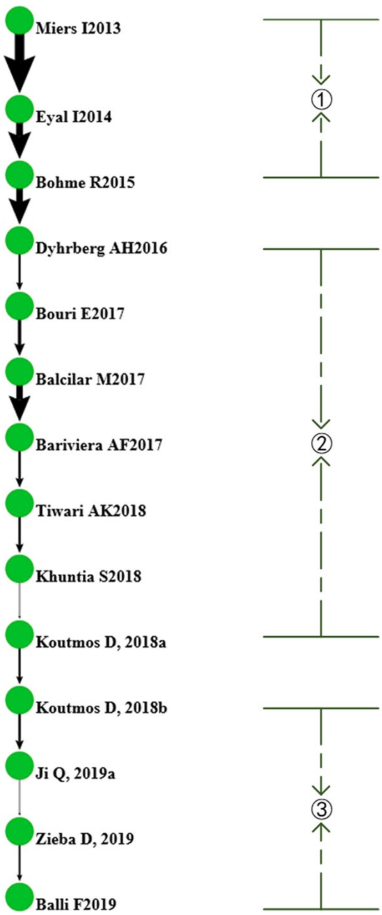
Fig. 4 The key-route 2 main path



Main path analysis of blockchain

Based on the txt format files downloaded from WoS, the citation network is established firstly. From this citation network, the largest subnet is extracted as well as the loop is deleted, getting a directed acyclic citation network of 3136 points and 13,295 links finally. Then, based on SPC algorithm, this directed acyclic citation network is transformed into a weighted network. Finally, with the functions related to main path analysis in the Pajek software, different main paths can be extracted and visualized. In this section, four different paths, which are the global main path, the forward local main path, the backward local main path and the key-route global main path, are selected to uncover the knowledge diffusion trajectory of the blockchain from different perspectives. These paths contain the most important and significant papers in the citation network and complement each other. The main paths drawn from Pajek are shown in Figs. 5, 6, 7 and 8, respectively. In these figures, each node denotes a paper and is labeled with the first author's last name, and capitalization of the first letter of the first name, followed by the publication year. The link presents citation relationship of papers and the arrow shows the direction of the knowledge diffusion. The thicker the link on the path, the more significant it is.

Fig. 5 The global main path



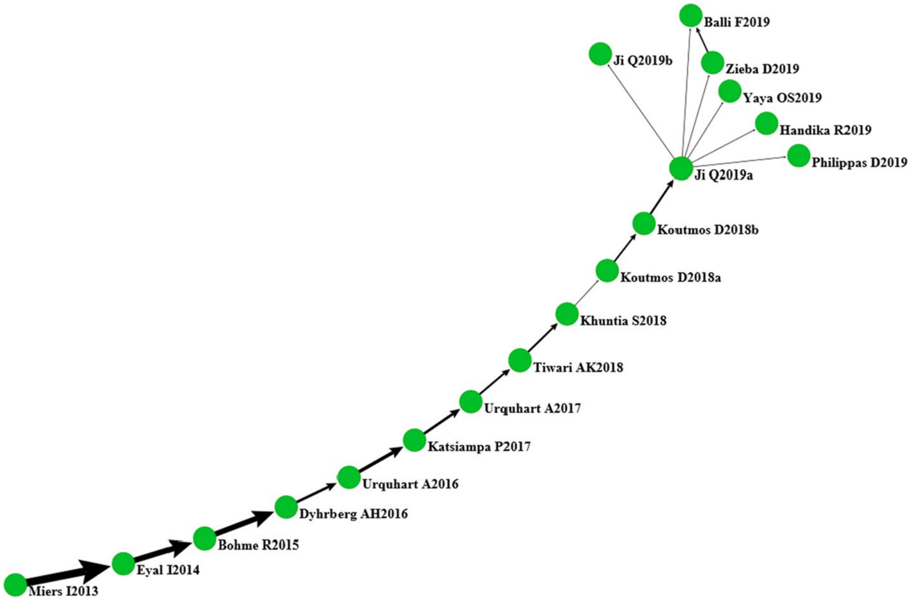


Fig. 6 The forward local main path

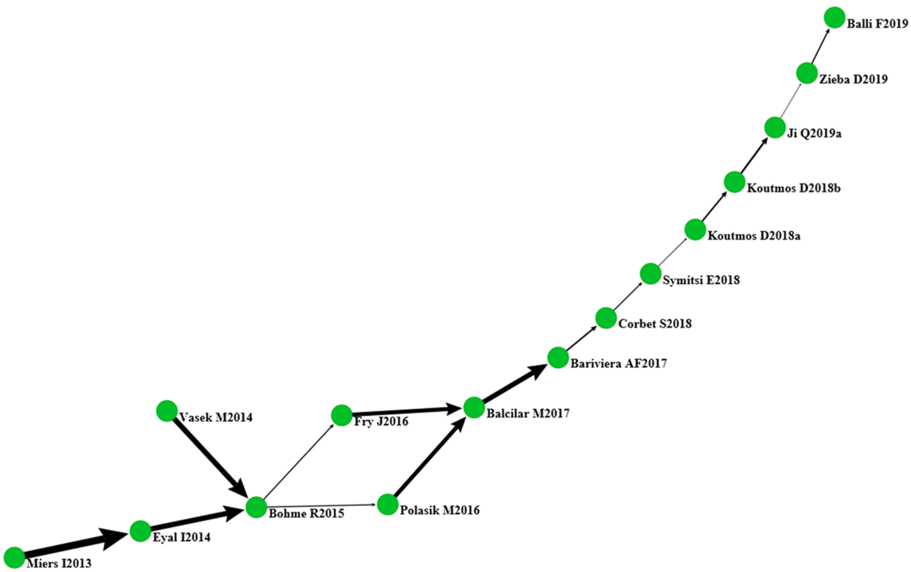


Fig. 7 The backward local main path

Global main path

The global main path of blockchain is shown in Fig. 5. The sum of the SPCs of the links on the global main path is the largest, which reveals the most influential path among the whole

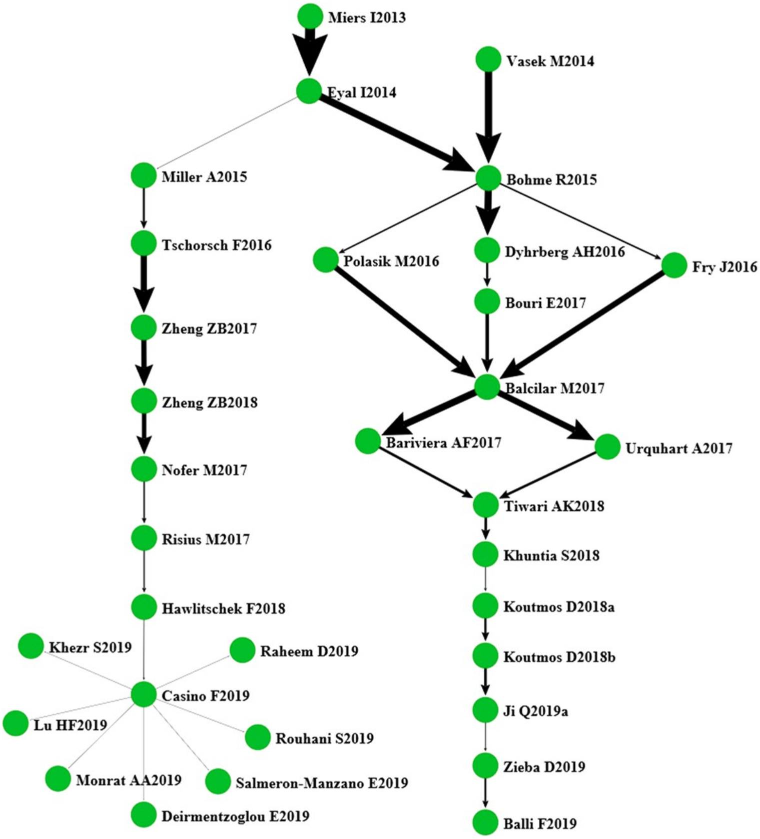


Fig. 8 The key-route main path

paths from sources to sinks in the citation network.

As can be seen from Fig. 5, the development of blockchain can be divided into three stages. Papers in the first stage are Miers et al. (2013), Eyal and Sirer (2014) and Böhme et al. (2015). Miers et al. (2013) is the first paper on the global main path, which lays an important foundation for the development of blockchain. It proposes a distributed e-cash system based on bitcoin, which is zerocoin, to overcome the problem of weak privacy of bitcoin, and to support fully anonymous transactions. In Eyal and Sirer (2014), the conventional opinion that bitcoin's mining algorithm is incentive-compatible is rejected by introducing the selfish mining strategy. This strategy poses a threat to bitcoin and will result in the bitcoin not being a decentralized cryptocurrency. Böhme et al. (2015) systematically and objectively analyze bitcoin, including its design principles, risks, uses, regulatory issues, etc. Papers in the first stage focus on the technical aspect of bitcoin. The privacy and security of bitcoin is the most concern.

However, since Dyhrberg (2016), the development of bitcoin has entered the second stage. Scholars are interested in investigating the financial and economic aspects of bitcoin. Dyhrberg (2016) analyzes the capability of bitcoin as a hedge by adopting the GARCH model, indicating that bitcoin is expected to be a useful tool in portfolio management and will play an important role in financial markets. To complement the research of Dyhrberg

(2016), Bouri et al. (2017) further examine the potential of bitcoin as a diversifier and safe haven, showing that bitcoin can be an effective diversifier, but only in few cases can be a safe haven.

Balcilar et al. (2017), which is one of the most cited papers on the global main path, is the first paper on the path to investigate the impact of traded volume on returns and volatility in bitcoin market. The next two papers, Bariviera (2017) and Tiwari et al. (2018), arrive at the same conclusion that the bitcoin market is information efficient. Contrary to the above two papers examining the effective market hypothesis of bitcoin market, Khuntia and Pattanayak (2018) study the adaptive market hypothesis of bitcoin. Koutmos (2018a) measures the degree of liquidity uncertainty of bitcoin in a new way and tries to explain it from the perspective of market microstructure characteristics.

The third stage of the development of blockchain consists of four papers, which are Koutmos (2018b), Ji et al. (2019a), Zięba et al. (2019) and Balli et al. (2019). With more and more cryptocurrencies pouring into the cryptocurrency market, researchers are interested in examining the connectedness of the cryptocurrency market. Koutmos (2018b) investigates the inter-dependencies between eighteen major cryptocurrencies. The next year, Ji et al. (2019a) study the returns and volatility spillovers between six large cryptocurrencies and identify four factors that affect the cryptocurrency market spillovers. Zięba et al. (2019) adopt the minimum spanning tree method to examine the hierarchical structure of the cryptocurrencies market and then analyze the interdependence between cryptocurrencies by using the vector autoregression model. Balli et al. (2019) show that the degree of economic uncertainty has a negative association with the connectedness of cryptocurrencies.

The global main path denotes that cryptocurrencies, especially bitcoin, have been the focus in the development of blockchain in the past few years. This paper has two main findings. First, papers in the first and second stage focus on bitcoin while papers in the third stage mainly dedicate to examining the connectedness of major cryptocurrencies. With the emergence of more and more types of cryptocurrencies, the object of papers on the global main path has shifted from bitcoin, which is the first application of blockchain technology, to the cryptocurrency market. Second, papers on the first and second stage study bitcoin from different perspectives. In the first stage, the focus of papers is to expose the security shortcomings of bitcoin as a digital currency in the electronic payment system. Later, more and more research has realized the role of bitcoin in the economy and finance in the second stage. They begin to explore the economic and financial aspects of bitcoin, examining the potential of bitcoin to be a financial asset, as well as the characteristic of bitcoin, such as volatility. Subsequently, the information efficiency of bitcoin becomes another focus on the global main path. It is undoubtedly that these 14 papers on the global main path play an important role in the development of blockchain, which depict the most influential knowledge diffusion path of this domain in the past few years.

Forward local main path

The global main path focuses on the largest SPC overall while the forward local main path centralizes on the largest local SPC, which means the link with the largest SPC value is selected at each juncture of knowledge diffusion. As we can see from Fig. 6, many papers are shown at the end of the path, representing the latest research results. Compared to papers on the global main path, three new papers appear at the middle of the path and four new papers appear at the end of the path.

Three new papers appearing at the middle of the forward local main path are Urquhart (2016), Katsiampa (2017) and Urquhart (2017). By employing a set of tests, Urquhart (2016) finds that the bitcoin market is inefficient during the entire period while it is efficient when the entire period is divided into two sub-periods. The next two papers, Katsiampa (2017) and Urquhart (2017), focus on various characteristics of bitcoin. The former investigates the volatility of bitcoin prices by comparing several GARCH models while the latter investigates bitcoin price for clustering.

Compared with the end of the global main path, four new papers appear at the end of the forward local main path. Yaya et al. (2019) investigate the cointegrated relationship between the pricing of bitcoin and the pricing of other cryptocurrencies during two periods, before and after the crash. Handika et al. (2019) is the first paper on the path to study the cryptocurrencies contagion by adopting three different measurement methods, examining whether cryptocurrencies pose risks to Asian financial markets. Philippas et al. (2019) is an empirical work aiming at investigating the impact of the media attention on the jump intensity of bitcoin prices. Ji et al. (2019b) explore the connection relationship between the cryptocurrency market and the commodity markets, showing that cryptocurrencies are integrated within some commodity markets.

Although the majority of papers on these two paths, the global main path and the forward local main path, are in common, there are two new findings through the analysis of the latter path. First, two new papers at the middle of the forward local main path focus more on characteristics of bitcoin, price volatility in Katsiampa (2017) and price clustering in Urquhart (2017). Second, the research at the end of the path is more diversified. These papers mainly focus on two themes. One focuses on investigating the relationship between various cryptocurrencies while the other concentrates on examining the relationship between the cryptocurrency market and other markets. Papers focusing on the first theme, which are Ji et al. (2019a), Zięba et al. (2019) and Balli et al. (2019), study the inter-dependence between different types of cryptocurrencies. Papers focusing on the second theme, including Handika et al. (2019) and Ji et al. (2019b). The former studies the inter-market relationship between the cryptocurrency market and the Asian financial markets while the latter analyzes the relationship between commodity markets and the cryptocurrency market. This phenomenon indicates that the focus of the research has shifted to the relationship of various markets, and this is beyond the previous focus, cryptocurrencies.

Backward local main path

Compared with the above two paths, the backward local main path searches from sinks to sources, that is, tracking back to the earliest papers and finding roots of the latest papers. In Fig. 7, the main difference between these three paths is the papers at the beginning and the middle of the path.

On the backward local main path, five additional papers are uncovered, which are Vasek et al. (2014), Fry and Cheah (2016), Polasik M2016 (Polasik et al. 2015), Corbet et al. (2018) and Symitsi and Chalvatzis (2018). The above two paths show that Böhme et al. (2015) conduct a comprehensive review absorbing the findings of Eyal and Sirer (2014). However, the backward local main path finds another significant paper, Vasek et al. (2014), which studies the DDoS attacks on the bitcoin ecosystem. After Böhme et al. (2015), a bifurcation appears on the backward local main path. Polasik M2016 (Polasik et al. 2015) investigates two aspects of bitcoin, the role of payment and the role of investment. The focus of this empirical work is to explain the price of bitcoin in terms of its popularity and transaction volume. Fry and Cheah (2016) test the presence of negative bubbles in the cryptocurrency market using an econophysics model. Finally, these two papers merge again to Balcilar et al. (2017).

Two new papers, Corbet et al. (2018) and Symitsi and Chalvatzis (2018), only appear on the backward local main path. The former investigates the relationship between the major three cryptocurrencies, which are bitcoin, ripple and lite, and other financial assets. The latter studies the return, volatility and shock spillover effects between bitcoin and energy and technology companies.

Based on the above analysis, two characteristics are founded on the backward local main path. First, the path ignores investigating the potential of bitcoin to be a financial asset that is mentioned in the above two paths. That is the reason why various paths are selected to analyze simultaneously. They complement each other and are able to comprehensively uncover the development of blockchain. In contrast, this path has investigated the relationship of trade volume and the bitcoin price or returns and volatility. Second, two papers, Polasik M2016 (Polasik et al. 2015) and Corbet et al. (2018), appearing at the beginning and the middle of the path respectively, propose new idea earlier. Some papers at the end of the forward local main path do their research based on these ideas.

Key-route main path

The key-route main path is able to provide more detailed information and the evolutionary structure of blockchain domain. The larger number of key-routes will reveal more information about the domain. The key-route main path is selected for further analysis in this part to fully understand the field of blockchain. This paper chooses the global method and selects 10 key-routes for the best result. The key-route main path is shown in Fig. 8.

Figure 8 presents the key-route main path consisting of 33 significant papers. It is clear that there are two main streams of the development of blockchain from 2008 to 2019. The right side of the path is a combination of the above three paths. Specifically, the first half of the path is similar to the first half of the forward local main path, while the rest of the path is more similar to the second half of the backward local main path. However, all the papers on the right side of the key-route main path is more like the papers on the global main path.

Papers on the left side of the path have not appeared on the above three paths. Miller et al. (2015) first propose some modifications to the reward structure to address issues caused by mining coalitions, including both the mining pools and hosted mining. Three papers, Miers et al. (2013), Eyal and Sirer (2014) and Miller et al. (2015) dedicate to exposing the existing problems of bitcoin and proposing the corresponding solutions.

The following two papers, Tschorsch and Scheuermann (2016) and Zheng et al. (2017), respectively, conduct a survey on digital currencies including bitcoin, and focus on presenting the characteristics, consensus algorithms, challenges and future trends of blockchain technology. Since then, subsequent papers have shifted their focus to blockchain technology instead of cryptocurrencies. Zheng et al. (2018) extend the Zheng et al. (2017) by introducing several representative applications of blockchain technology, which are finance, IoT, security and privacy, reputation system and public and social service. Nofer et al. (2017) divide the applications of blockchain into two broad categories, financial applications and non-financial applications, expanding the areas of application beyond financial market. Risius and Spohrer (2017) propose a research framework based on selected 69 papers, describing the current research status and future directions of blockchain technology in detail. Hawlitschek et al. (2018) concentrate on the topic of trust in blockchain technology and investigate the effect of blockchain technology on the trust in sharing economy. Near the end of the path, Casino et al. (2019) comprehensively review previous research efforts on various applications of blockchain technology, providing a guide for future research for scholars and practitioners.

The above-mentioned studies mainly focus on different aspects of blockchain technology, ranging from the theory of blockchain technology to blockchain-based applications. At the end of the left path, there is a trend to extent the previous research to multiple directions. Based on Casino et al. (2019), most of the ending papers focus on a particular application. These papers are discussed in detail below.

In the context of blockchain technology, papers related to data management, supply chain management and internet of medical things in healthcare are investigated in Khezr et al. (2019). Deirmentzoglou et al. (2019) centralize on the security of blockchain, listing several popular attacks against common consensus protocols and corresponding countermeasures. Rouhani and Deters (2019) is the first paper to comprehensively summarize related papers on the subject of smart contracts, including its history, supporting platform, programming languages, security, performance and seven different categories of applications for smart contracts. Lu et al. (2019) analyze four parts of blockchain technology that can be applied in the oil and gas industry, which are trading, management and decision making, supervision and cyber security. Monrat et al. (2019) is a comparative study that studies the applications, future challenges and opportunities of blockchain, aiming to provide some efficient suggestions for exploring potential research directions. Contrary to the aforementioned papers, Salmerón-Manzano and Manzano-Agugliaro (2019) carries out a quantitative method, the bibliometric analysis, to analyze the research trends of the smart contracts from different angles. Raheem et al. (2019) discuss the possible aspects where the blockchain technology can be used to improve the food system.

The key-route main path indicates that there are two main streams in the development of blockchain, which are obviously different from each other. Papers on the left path focus on various aspects of blockchain itself and its applications in different areas while the right path focuses on cryptocurrencies, especially bitcoin, the first application of blockchain. The focus of the left path has shifted from the general knowledge of blockchain technology to blockchain-based applications. On the one hand, some papers on the left path discuss this disruptive technology from technological perspective. These papers mainly discuss the characteristics, architecture, consensus algorithms or possible technical challenges of blockchain technology, which paves the way for a deeper understanding of this innovation. On the other hand, some papers on the path uncover the state-of-the-art research on various blockchain-based applications. It is worth mentioning that papers at the end of the path target a specific aspect of blockchain, such as smart contract, or a particular application, such as healthcare. The right path is almost the combination of the above-mentioned three paths, shifting from bitcoin to the cryptocurrency market. In addition, by analyzing the key-route main path, this paper summarizes several major research areas of blockchain, which are IoT, healthcare, energy industry, voting, insurance, and supply chain management. Papers on the two sub-paths complement each other, comprehensively depict the knowledge diffusion path of blockchain technology and also clearly reveal the divergence and convergence structure in this field.

Main path analysis of blockchain in three active areas

By analyzing papers on the key-route main path of blockchain, several active applications are identified, including IoT, healthcare, energy industry, voting, insurance, and supply chain management. In this section, we choose three popular areas of IoT, healthcare and supply chain management from these active areas for further analysis. In order to make all the links with the largest traversal weight, that is, all the most important citations in the development process of blockchain in different areas, appear on the path at the same time, only the key-route main path is considered in this section. Also, more details can be uncovered by setting the number of key-routes. In addition, the knowledge diffusion structure—divergence and convergence structure, can also be presented by this path. Through analyzing the evolutional structure, we can clearly understand how different ideas are consolidated and how different new ideas are inspired as time passes in the process of knowledge dissemination.

Similar to the process of extracting main paths in blockchain domain, we first establish a citation network for each of the three application areas. Based on each citation network, we further extract the largest subnet, remove its loop and weight the largest subnet, and then set the number of key-routes to 2 to form the key-route main paths of three areas with the Main Paths function in Pajek. Since blockchain technology in these areas has just begun to develop in the past few years, the length of the paths is not long.

The key-route main path of blockchain in IoT

IoT, which is a network of various devices that connect with each other, has contributed a lot to the development of the society (Pohrmen et al. 2019; Fu et al. 2019). The advent of blockchain technology has brought new opportunities. Nowadays, the integration of blockchain technology and IoT is becoming a hot topic and has received much attention in academia. For example, Xu et al. (2019) propose a blockchain-enabled computation offloading method for the IoT, for the purposed of minimizing task offloading time and energy consumption, as well as achieving load balance and data integrity. Dwivedi et al. (2019) present a modified blockchain model suitable for IoT devices, which is able to enhance the security and privacy of the data. With the rapid growth of related research achievements in the past few years, in this part, the key-route main path is conducted to better understand the current research trends of blockchain technology in IoT. As shown in Fig. 9, these representative papers on the path present the development process of the blockchain-based approaches in IoT.

The path begins with two branches and emerges to the work of Ali MS2019. Four papers appearing on the left branch mainly focus on enhancing the security and privacy of the IoT through integrating blockchain technology. For example, the first paper of the left branch, Zhang and Wen (2015), proposes an e-business model for IoT with the support of blockchain technology, where people can use a new crypto coin, IoT coins, to gain access to the encrypted IoT data. To enhance the security of energy transactions in the industrial IoT, Li ZT2018 (Li et al. 2017a) proposes an energy trading system based on blockchain. Zheng et al. (2017) systematically introduce theoretical knowledge of blockchain technology, stating that blockchain-based applications have received wide attention recently and there is a growing trend in IoT, financial services, and other fields. Based on Zheng et al. (2017), Zheng et al. (2018) further summarize previous papers that address two aspects of blockchain technology that can improve the IoT, which are e-business on the IoT, as well as safety and privacy.

In addition to emphasizing the improvement in security and privacy, papers on the right branch focus on access control and management of data as well. Ouaddah et al. (2016, 2017) introduce a framework, Fair Access, that gives users an opportunity to maintain

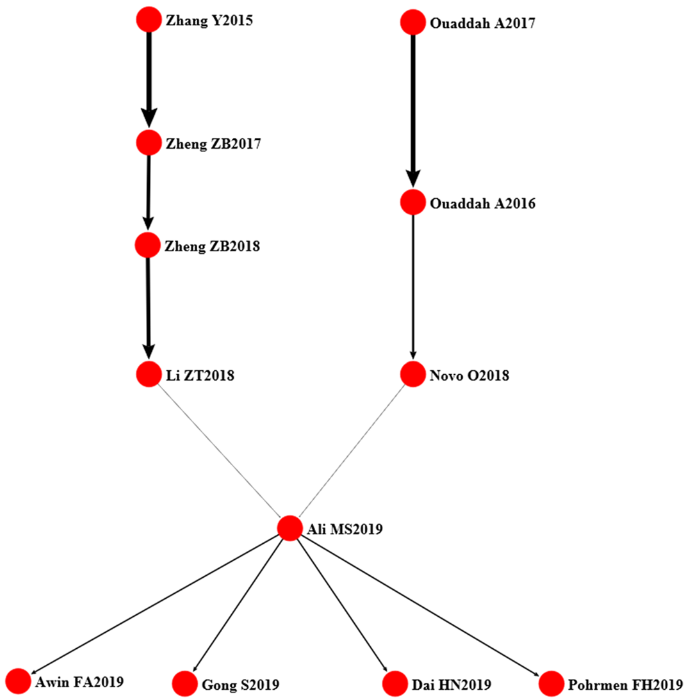


Fig. 9 The key-route main path of blockchain in IoT

ownership of their IoT data and control their data by themselves instead of trusted third parties. Novo (2018) proposes a distributed access control system for managing numerous IoT devices efficiently based on blockchain technology and smart contracts.

Ali MS2019 is a significant review paper that merges two branches. It conducts a comprehensively survey on the state-of-the-art efforts of blockchain in IoT, including privacy, trustless, security, identity and data management and monetization of IoT data (Ali et al. 2018). After this paper, four papers appear at the end of the path. Dai et al. (2019) provide in-depth insights on the integration of blockchain technology with the industrial IoT, including its general architecture, various applications and issues. To improve the management of devices in smart cities and protect the devices from attacks, a device management architecture is proposed based on the blockchain technology in Gong et al. (2019). Awin et al. (2019) discuss the benefits and impacts of blockchain technology incorporated into the cognitive radio-based IoT systems. Pohrmen et al. (2019) investigate the impact of blockchain technology on the security aspect of IoT and depict the evolution of the architectures of IoT.

There are two findings through the analysis for the key-route main path in IoT. First, papers on the left show that the privacy and security of data is a main concern while papers on the right focus on access control and management. Second, the review paper, Ali et al. (2018), has the ability to bring different ideas together and integrate branches. It can be illustrated by Ho et al. (2017), which investigates the role of review papers, indicating that review papers' role in integrating multiple perspectives. With many problems exploring in the traditional architecture, the IoT, under the context of blockchain technology, provides opportunities for the users to manage access controls and master their ownership of their data effectively.

The key-route main path of blockchain in healthcare

One field that could benefit from blockchain technology that researchers have been focusing on is healthcare (Shuaib et al. 2019). In recent years, many studies have been conducted on the combination of blockchain and healthcare. For instance, Shen et al. (2019) propose a new data-sharing scheme called MedChain to improve the efficiency and security of healthcare data sharing. An mHealth system vis blockchain technology, aiming to enable compatibility of security and scalability of the medical data, is designed in Motohashi et al. (2019). To get an overview of the state-of-the-art research about blockchain in healthcare, the key-route main path is conducted in this part. From Fig. 10, obviously, there are two separated paths.

The first paper on the left path, Liu (2016), is the knowledge base for the development of blockchain technology in healthcare. In this paper, some approaches and suggestions about various aspects of the medical records are proposed by adopting the blockchain technology, big data analysis or tokenization. The next two papers, Xia et al. (2017) and Ahmed (2019), focus on the medical data and medical images respectively. Xia et al. (2017) design MeDShare, a system which is based on blockchain technology, to enhance the security of sharing medical information among untrusted cloud service providers. Ahmed (2019) proposes a framework called iChain using blockchain technology, to protect the sensitive digital images in healthcare domain from the false image injection attack. The remaining two papers on the left path conduct surveys from different perspectives. McGhin et al. (2019) study literatures related to blockchain technology in healthcare industry, identifying the current research focus and pointing out future research opportunities. Aggarwal et al. (2019) aim to summarize the latest research on the broad use of blockchain technology, in particularly, classifying current literatures on the application of blockchain technology in the medical field into four categories, which are record management, access control policy, data sharing and storage.

The right path consists of six representative papers. At the beginning of the right path, it is no doubt that the link is the thickest, indicating that Azaria et al. (2016) is the most cited paper on the main path. During the development of blockchain technology in the aspect of medical records in healthcare, it is the first paper to provide specific solutions and introduce a fully prototype. It plays an important role in the application of blockchain in electronic medical records. The next year, Kuo et al. (2017) analyze the benefits, categories of applications, challenges and corresponding solutions of blockchain technology in biomedical/health care applications. To improve the security and scalability of clinical data sharing, Zhang et al. (2018) propose a blockchain-based architecture, FHIRChain, and apply it to create a FHIRChain-based decentralized app. Kleinaki et al. (2018) propose a notary service based on blockchain technology to meet the requirements for the integrity and non-repudiation of the data which are retrieved from the medical knowledge databases. At the end of the right path are two papers, Verde et al. (2019) and Mayer et al. (2019). In Verde et al. (2019), potential applications of blockchain technology in radiology departments are discussed. By systematically analyzing previous papers which are related to the integration of blockchain technology and electronic health records, some potential challenges and issues, as well as benefits are identified in Mayer et al. (2019).

Fig. 10 The key-route main path of blockchain in healthcare

Applying blockchain technology in the area of healthcare has attracted wide attention in recent years. The key-route main path of blockchain technology in healthcare indicates that the security and privacy of the medical information is the main focus. Some practical solutions are proposed to overcome the limitation of the traditional framework, such as MeDShare in Xia et al. (2017) for addressing the problem of data sharing and access control, MedRec in Azaria et al. (2016) for managing the medical information, FHIRChain in Zhang et al. (2018) for electronic health record integration and iChain in Ahmed (2019) for improving the security of medical records images.

The key-route main path of blockchain in supply chain management

Due to the advantages of the blockchain technology such as its trustworthiness, it has the potential to disrupt the supply chain (Saberi et al. 2019). Nowadays, many efforts have been made to explore where the blockchain may disrupt this field. For example, Longo et al. (2019) develop a software connector that connects an Ethereum-like blockchain with different information systems of enterprises so that information can be safely shared between partners. With the support of the blockchain technology, a solution is proposed for shipment supply chain management via smart containers (Hasan et al. 2019). By integrating blockchain and IoT technology, a system is introduced in Tsang et al. (2019) for effective and efficient food traceability and enhancing quality assurance. To further investigate the development of blockchain technology in supply chain management area, the key-route main path is performed in this part. Figure 11 shows the path of this domain, consisting of 15 significant papers.

There are two streams on the key-route main path, as we can see from Fig. 11. Three papers, which are Chen et al. (2017), Nakasumi (2017) and Kshetri (2018), are the common knowledge base of the two streams. Chen et al. (2017) propose a supply chain quality management framework by using blockchain technology. In this framework are four layers with different functions: IoT sensor layer used to gather and record the product quality information, logistics, assets and transaction information; data layer used to share the information with enterprises in the supply chain; contract layer used to secure data and control quantity and business layer consisting of enterprises used to make decisions to work efficiently. A solution using blockchain technology is proposed in Nakasumi (2017) to solve the problems such as double marginalization and information asymmetry facing the companies in the supply chain. Kshetri (2018) assesses the effect of blockchain technology on various supply chain management objectives, such as cost and speed, and particularly emphasizes the importance of the integration of the IoT and blockchain technology.

In the remaining papers, five papers appear on the left while seven papers appear on the right. The left stream consists of five papers, which are Toyoda et al. (2017), Kamble et al. (2019), Queiroz and Wamba (2019), Hughes et al. (2019) and Wang et al. (2019a). In Toyoda et al. (2017), a product ownership management system is proposed

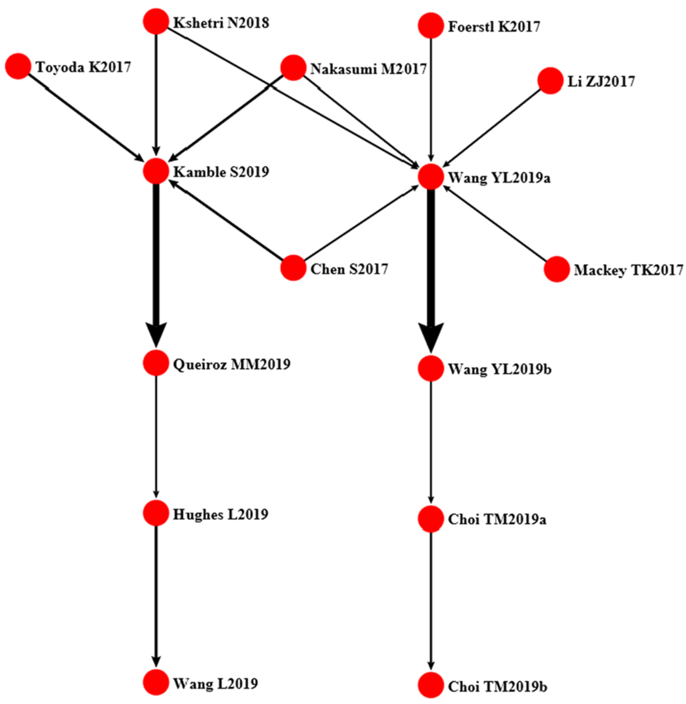


Fig. 11 The key-route main path of blockchain in supply chain management

to make the tags which are cloned by the counterfeiters meaningless by adopting blockchain technology, and specific implementation process and corresponding algorithms are described in this paper. Instead of focusing on the pros and cons of blockchain technology in supply chain, Kamble et al. (2019) propose an integrated model which identifies the factors that influence the adoption of blockchain technology by collecting the data from 181 supply chain practitioners in India. Influenced by Kamble et al. (2019), Queiroz and Wamba (2019) conduct an empirical research, investigating the blockchain adoption behavior of individual level in India and the USA, and the results are consistent with that of Kamble et al. (2019). In addition, there exist different adoption behaviors between India and the USA. Hughes et al. (2019) divide the blockchain theme into eight categories and consider that the most frequent applications of blockchain are smart contract, as well as supply chain management and logistics. The blockchain-based supply chain exists tremendous business development potential. Wang et al. (2019a) investigate a case study of BubiChain loyalty point platform, which is able to satisfy different motivations of customers, not just economic needs.

The right stream uncovers the development of blockchain technology in supply chain from different perspectives. It is clear that several papers are referred simultaneously by Wang YL2019a at the beginning of the path. Li et al. (2017b) propose a physical distribution framework using blockchain technology to improve the efficiency and transparency of the information in supply chain. Foerstl et al. (2017) aim to uncover the effect of the purchasing and supply management decisions on the supply chain and in turn the effect of the supply chain on the purchasing and supply management policies. Mackey and Nayyar (2017) identify five categories of technology to address fake medicines in pharmaceutical industry and consider that blockchain technology, as a potential revolutionizing technology, will ensure the transparency and validity of the medicines in supply chain. Wang YL2019a is a significant review paper. It discusses the motivations, the possible areas, the challenges and the opportunities of blockchain technology in supply chain, aiming to provide both scholars and practitioners with guidelines for the future research on the supply chain management with the support of blockchain technology (Wang et al. 2019b). Wang YL2019b (Wang et al. 2019c) analyzes main aspects of the supply chain can be improved by blockchain technology and identifies some areas where the blockchain technology is likely to penetrate. Choi et al. (2019) conduct the mean–variance analysis for exploring air-logistics related risks. By adopting the blockchain technology to improve the information flow and sharing, the visibility of both supply and demand has been enhanced. Choi and Luo (2019) is a theoretical work to analyze the conditions for achieving a win–win situation for social welfare and supply chain benefits.

The path denotes that the improvement of information transparency is an important aspect of the application of blockchain in supply chain management. Some problems caused by opaque information, such as double payment and counterfeiting, often arise in traditional supply chain management. With the improvement of transparency, the risk will be mitigated for companies to some extent. The individual blockchain adoption behavior is at the central of the left path (Kamble et al. 2019; Queiroz and Wamba 2019) while the right path endeavors to explore the possible aspects that blockchain can be used in supply chain management. Another important finding is that there exists a theoretical work to do the research by establishing a model from the mathematical perspective. With the support of blockchain, the efficiency and transparency will be improved and several frameworks proposed in the papers on this path can be helpful for both the scholars and practitioners.

Discussion

Blockchain is a disruptive technology that exerts a far-researching influence on our social life. It has attracted widespread attention in recent years. Confronted with massive papers studying blockchain technology, this paper adopts a quantitative method, the main path analysis, to identify some significant papers and investigate development trajectories of blockchain domain. This paper totally analyzes seven different main paths. Four main paths depict the development of blockchain technology from different angles and three key-route main paths uncover the knowledge diffusion trajectories of applications of blockchain technology, which are IoT, healthcare and supply chain management. The common feature between these paths is that the links above the paths are heavier than the links at the bottom of the paths. This is because early papers have relatively high citations. The papers closing to the end of the main paths receive wide attention recently, indicating that they are significant at the present. As time goes by, the later papers existing on the paths still need to be verified.

Through analyzing several main paths of blockchain domain, which are obtained from the citation network formed by 4337 papers, this paper finds that (1) the forward local main path, the backward local main path and the global main path have some common papers, which proves the importance of these papers in the development of blockchain domain, and there is no much significant difference between each other, (2) these three different paths mainly focus on the early application of blockchain technology, that is, cryptocurrencies. The objection of the research has shifted from bitcoin to the cryptocurrency market. Papers at the end of the main paths concentrate on investigating the relationship between several influential cryptocurrencies. The forward local main path is able to show more directions of the latest research, finding that scholars are interested in investigating the relationship between the cryptocurrency market and other markets, (3) the key-route main path enables to show more details, revealing two separated streams of the development in the area of blockchain. One is to study the cryptocurrencies, which is similar to the above mentioned three main paths, while the other focuses on various applications of blockchain technology. Recently, people have become more and more interested in studying the foundation of the digital currencies, blockchain technology, and there has been growing interest in applying blockchain technology in a wide range of applications, which has potential to change various domains. In addition, the structure of continuous divergence and convergence makes us see the interrelationships between important papers intuitively. (4) the most active research areas of blockchain technology on these main paths are IoT, healthcare, energy industry, voting, insurance, and supply chain management.

After identifying the most popular applications of blockchain technology, this paper further analyzes three areas among them, which are IoT, healthcare and supply chain management, by conducting the key-route main path. The results are as follows. (1) Although the number of papers relating blockchain technology in these domains is growing rapidly, this integration is still in fancy and the length of the main paths is not long. As more and more papers are added to this citation network, the results may be changed quickly and papers on these main paths should be verified in time. (2) IoT is one of the most popular areas. The most two concerned aspects of blockchain technology in IoT are the privacy and security of data, as well as access control and management. The blockchain technology enables to manage the device data in a more secure and effective way. (3) The review paper has potential to integrate different branches, as is illustrated in the key-route main path of blockchain in IoT. (4) Papers on the main path of blockchain in healthcare mainly focus on enhancing the aspect of electrical health records in healthcare domain. (5) There are two main streams in the area of supply chain management. One focuses on investigating blockchain adoption behavior and the other concentrates on exploring the influence of blockchain technology on supply chain management. The blockchain will be beneficial in identifying counterfeits, enhancing information transparency and improving quality or risk management under the context of supply chain.

This paper dedicates to demonstrating how to integrate various main paths to analyze the knowledge diffusion of blockchain domain. Through connecting a series of important historical-development events in chronological order, the trajectories of knowledge flow are clearly presented. The results of these paths enhance our ability to capture how the research focus has shifted, and which research can leave a footprint in the course of blockchain development and which research has become a hot spot currently. It is not difficult to see that studies focusing only on bitcoin have gradually faded out the view of the researchers, though it has attracted the most attention at first. As time passes, the cryptocurrency market is relatively more popular currently, which can be analyzed further in the future. The key-route main path enables us to grasp more information about the blockchain, indicating that the research on the blockchain technology itself and its applications is of vital importance. The blockchain technology is immature and has some limitations. In the future, the challenges faced by blockchain such as scalability still need to be addressed to make blockchain technology more efficient and durable. It is foreseeable that research on blockchain-based applications will continue to be rich. In addition to the active areas mentioned in this paper, due to the inherent excellent characteristics of blockchain, the symbiotic relationship between it and other fields will become increasingly connected.

Conclusion

The last few years has witnessed a growing interest in blockchain from scholars, resulting in many outputs. It is necessary to conduct a systematic and comprehensive review of this domain by adopting a quantitative method. This paper presents several different main paths of the domain of blockchain and its applications in IoT, healthcare and supply chain management for exploring their knowledge diffusion trajectories. After building the citation network which consists of 4337 papers, four different main paths are extracted based on SPC algorithm to investigate the past, present and future of blockchain technology. By analyzing four different paths, major applications of blockchain technology are identified. This paper further deeply investigates the hotpots and development trajectories in three active areas, IoT, healthcare and supply chain management by adopting the key-route main path analysis.

By analyzing four different paths of blockchain, this paper finds that the boundaries of research on blockchain are obvious in the past few years. One is to study the cryptocurrencies, shifting from bitcoin to the currency market. The other focuses on blockchain itself and various blockchain-based applications. Due to the inherent nature of this new technology, scholars across a wide range of disciplines try to integrate it into various areas. This paper identifies several major research areas of blockchain, which are IoT, healthcare, energy industry, voting, insurance and supply chain management. Based on three blockchain application areas, this paper finds that the security and privacy of data is the main concern in both the areas of IoT, healthcare. The former focus on the device data and the latter focuses on electronic medical records. And the integration of blockchain with supply chain management dedicates to improving the information flow in the supply chain.

To our knowledge, few papers adopt the main path analysis to track the main idea flow of blockchain and blockchain in the areas of IoT, healthcare and supply chain management. The main paths uncover the dynamic development process along the timelines, which provide a systematic and effective way for readers to fully grasp the knowledge diffusion trajectories of these domains. Although this paper intends to investigate more detailed information about blockchain technology, some limitations remain. Firstly, this paper may miss some important and related papers because the database used in this paper is only the WoS. Papers about these domains are not full and the results of the main path analysis may change when the number of papers changes. Secondly, owing to the characteristics of the citation network, the relevancy between a citing paper and a cited paper is assumed to be equal, which is contrary to the reality. To fill this gap, the difference of the relevancies between citing-cited pair of papers should be considered in applying the main path analysis. Thirdly, though review papers play an important role in the development of these domains, it remains controversial whether to remove review papers for main path analysis.

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