The Journal of Systems & Software 197 (2023) 111576

Contents lists available at ScienceDirect

The Journal of Systems & Software

journal homepage: www.elsevier.com/locate/jss

A systematic literature review on blockchain governance[☆]

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ARTICLE INFO

Article history:
Received 3 December 2021
Received in revised form 10 November 2022
Accepted 28 November 2022
Available online 1 December 2022

Keywords:
Blockchain
Governance
Systematic literature review
SLR
Distributed ledger technology
DLT

ABSTRACT

Blockchain has been increasingly used as a component to enable decentralisation in software architecture for a variety of applications. Blockchain governance has received considerable attention to ensure the safe and appropriate use and evolution of blockchain, especially after the Ethereum DAO attack in 2016. However, there are no systematic efforts to analyse existing governance solutions. To understand the state-of-the-art of blockchain governance, we conducted a systematic literature review with 37 primary studies. The extracted data from primary studies are synthesised to answer identified research questions. The study results reveal several major findings: (1) governance can improve the adaptability and upgradability of blockchain, whilst the current studies neglect broader ethical responsibilities as the objectives of blockchain governance; (2) governance is along with the development process of a blockchain platform, while ecosystem-level governance process is missing, and; (3) the responsibilities and capabilities of blockchain stakeholders are briefly discussed, whilst the decision rights, accountability, and incentives of blockchain stakeholders are still under studied. We provide actionable guidelines for academia and practitioners to use throughout the lifecycle of blockchain, and discuss future trends to support researchers in this area.

1. Introduction

Blockchain, the technology popularised by Bitcoin Nakamoto (2008), provides decentralised computing and storage infrastructure to build new kinds of trustworthy decentralised applications. Smart contracts are the computer programs ran on blockchain, enabling essential on-chain business logic execution. A substantial number of projects have been conducted to explore how to use blockchain to increase trust in decentralised settings, without central authorities (Bratanova et al., 2019), for instance, healthcare (Zhang et al., 2017), industrial IoT (Miller, 2018), and energy supply (Aitzhan and Svetinovic, 2018).

Although blockchain is considered a viable solution for building decentralised applications, two severe events on the Ethereum[1] and Bitcoin[2] platforms have brought concerns to the community, about whether the decisions for blockchain development and operation are made in a trustworthy way. On 18 June 2016, a decentralised application in Ethereum, Decentralised Autonomous Organisation (DAO), was attacked due to a flaw in smart contract code. The attack caused a loss of over 60 million US dollars. This was remedied via a hard fork to reverse the effect of transactions in the attack (Atzei et al., 2017). However, this rather drastic countermeasure violated the basic property of immutability of historical transactions and deployed smart contracts in blockchain. Another event is the dispute on the block size of Bitcoin, which lasted from 15 August 2015 to 23 January 2016, and resulted in the split of Bitcoin community and ecosystem, also via forking (De Filippi and Loveluck, 2016).

These events have provoked the study of applying governance frameworks to blockchain platforms. However, there is a lack of systematic literature review to understand the state-of-the-art of this research area. Also, the governance of blockchain often involves a large number of participants due to the decentralised nature of blockchain platforms, which calls for software engineering knowledge to operationalise the governance mechanisms. Therefore, we perform a systematic literature review on existing studies to provide an up-to-date and holistic view of this research topic. In this study, we focus on *governance of blockchain*, i.e. the object being governed is the blockchain itself, rather than *governance through blockchain*, i.e., blockchain acts as a means to facilitate governance of other software systems.

The whole study followed Kitchenham's guidelines (Kitchenham and Charters, 2007). The main contributions of this paper are as follows:

- We identify a set of 37 primary studies related to blockchain governance published from 2008 to 3 November 2020. The

☆ Editor: Dr Shane McIntosh.

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1 https://ethereum.org/en/

2 https://bitcoin.org/en/

https://doi.org/10.1016/j.jss.2022.111576
0164-1212/

community can use this set of studies as a starting point to conduct further research on blockchain governance.

- We present a comprehensive qualitative and quantitative synthesis via identified research questions, reflecting the state-of-the-art in blockchain governance with data extracted from the selected studies. Our synthesis covers the following aspects: definition, motivations, objects, process, stakeholders, and mechanisms of blockchain governance.
- We provide insights and research agenda based on our project experiences and SLR results to support further research in the area, which include both high-level governance principles and actionable governance practices.

The remainder of this paper is organised as follows. Section 2 introduces the background knowledge of blockchain and discusses related work. Section 3 introduces the methodology to conduct this study. Section 4 presents the results and our insights. Based on the analysis results, Section 5 discusses how blockchain governance is different from existing governance frameworks. Section 6 provides research agenda for the future studies of this topic. Section 7 analyses the threats to validity of this study. Section 8 concludes the paper.

2. Background and related work

2.1. Blockchain and smart contract

Essentially, blockchain can be considered as a type of distributed ledger technology that can verify and store digital transactions with no central authorities to enhance trust between the interoperating parties (Tschorsch and Scheuermann, 2016). In a blockchain ecosystem, actions within the blockchain platform itself are executed *on-chain*, while the others are regarded as *off-chain* activities. All participants need to agree with the on-chain data states during transaction inclusion and confirmation to achieve trust. Nakamoto assumed that the majority of blockchain nodes are honest to reach consensus through game-theoretic incentives, without a third-party intermediary (Nakamoto, 2008).

The varying data states in a blockchain are carried by identifiable transactions which are contained in the blocks. A list of blocks is linked chronologically to form a chain as the ledger of transactional data. In addition, the perception of *smart contract* improved the computation capability of blockchain networks. Participants can develop customised scripts, then deploy and execute the smart contract on-chain for differential purposes (Omohundro, 2014). After deployment, a smart contract can express triggers, and conditions to enable complex business logic.

Currently, blockchain networks can be categorised into two main groups according to participation permission: permissionless and permissioned blockchains. Permissionless blockchains usually aim to provide a free trading market and thus accept unconditional participation. They have a closed relationship to decentralised finance, where blocks are appended by the elected validators (aka. miners) along with the issuance of on-chain tokens as cryptocurrencies. Permissioned blockchains are usually hosted by one or several cooperating organisations. Hence, they require acceptance from these authorities for participating in the network.

As an emerging technology, blockchain has gained the attraction of researchers in recent years to exploit the features of blockchain itself. For instance, the scalability of blockchain remains a crucial problem that many blockchain platforms (especially permissionless ones) are finding solutions to address low-efficiency issues such as low throughput and high transaction latency (Khan et al., 2021). Meanwhile, many other studies are exploring application domains that use blockchain as a viable infrastructure to set up a decentralised environment. Particularly, there are general works reviewing smart contracts (Leka et al., 2019) and different blockchain applications (Andrian et al., 2018), and also studies diving into specific usage domains such as IoT (Conoscenti et al., 2016; Lo et al., 2019), supply chain Tribis et al. (2018), Queiroz et al. (2020), healthcare (Tandon et al., 2020), agriculture (Bermeo-Almeida et al., 2018), smart city (Ahmed et al., 2020), etc.

2.2. Related work

When selecting the primary studies, we found several papers that conducted surveys or reviews related to blockchain governance. The rest of this section summarises their overview and the differences between these papers and our study. Risus and Spohrer (2017) conducted an SLR to form a general research framework, which included several governance-related research questions. For instance, how public blockchains are affected by ecosystem governance, and what are the differences between outsourcing to blockchain smart contracts and traditional outsourcing regarding governance mechanisms? Politou et al. (2019) focused on the mutability of blockchain, claiming the immutable on-chain records may invade individuals' privacy according to related laws and regulations (e.g. GDPR's "Right to be Forgotten"). They divided the trade-off approaches of blockchain immutability and regulations into two groups: redactable blockchain and storage. Kher et al. (2020) discussed law and governance about cryptocurrencies and initial coin offerings, while Zachariadis et al. (2019) also reviewed the governance issues of blockchain in financial services. Ziolkowski et al. (2020) derived six decision problems in blockchain governance from a literature review and expert interviews. Specifically, the experts are from four types of blockchain-based applications: cryptocurrency, intellectual property rights management, land registries, and supply chain. Three of the identified decision problems are related to existing information system problems (i.e., demand management, data management, and system architecture design and development,), while the others are blockchain-specific (i.e., membership, ownership disputes, and transaction reversal). They analysed the problems in the blockchain domain, and the corresponding solutions for each problem. Smit et al. (2020) focused on decision rights and decision-making process in blockchain governance. They discussed the allocation of decision rights regarding the deployed consensus algorithms, and whether to implement a fork in blockchains. They also compared the differences in decision-making process between private and public blockchains. Li et al. (2020) presented the international specification of blockchain, particularly focusing on the standardisation progress in China.

Compared to the existing studies, our contribution is different in terms of three main aspects (i.e., time frames, methodology, and scope). First, although the related work covered relevant studies in this domain from both industry and academia, most of them did not provide state-of-the-art information. In this SLR, the search time frame is 2008–2020 and the selection set results in 2016–2020 (excluding the papers published from Nov to Dec 2020). Secondly, this study adheres to Kitchenham's standard guideline (Kitchenham and Charters, 2007) as the other two literature reviews, while some related work had no clear or customised methodology, which may cause bias in data extraction and analysis. Regarding the research scope, the related work emphasised a specific aspect of blockchain governance, for instance, mutability, institutional regulations, certain blockchain-based application domains, or the allocation of decision rights. In this study, we comprehend the governance of blockchain based on six research questions (i.e., what, why, where, when, who, and how). Specifically, we analyse the general dimensions based

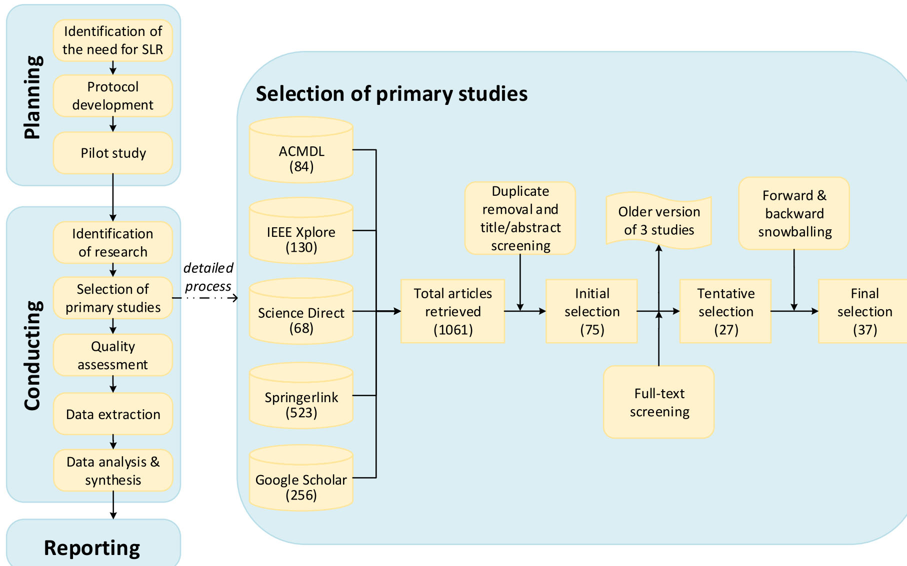

Fig. 1. Systematic literature review steps.

on the definition of blockchain governance extracted from the primary studies. We explore the aims of blockchain governance from the perspective of software quality attributes. We discuss blockchain governance in terms of four objects in the blockchain ecosystem (i.e., data, platform, application, and community). We investigate when to apply governance in the software development process of blockchain. We identify the key stakeholders related to blockchain governance issues. Finally, we present a set of mechanisms for implementing governance for blockchain. In this study, we provide a comprehensive and multidimensional perception of the governance of blockchain.

3. Methodology

In this section, we introduce the methodology of this systematic literature review, which follows Kitchenham's guidelines (Kitchenham and Charters, 2007). Fig. 1 illustrates the steps of this study.

3.1. Identification of the need for SLR

This section describes the motivations of this study.

3.1.1. Crises in blockchain

The topic of blockchain governance has attracted researchers' interest after the negative events mentioned above. In particular, the DAO attack in Ethereum seriously damaged stakeholders' interests as real money was stolen due to software bugs (Atzei et al., 2017). On one hand, the attack raised concerns about blockchain's security whether it is trustworthy to preserve users' data and assets. On the other hand, conducting a hard fork to reverse impacted transactions caused the discussion of whether to preserve the immutability of blockchain under the circumstance that people's money is stolen. Similarly, the debate on Bitcoin's block size is centred on whether to insist on Nakamoto's original design (De Filippi and Loveluck, 2016). The result of two separate Bitcoin forks has influenced people's confidence, since the blockchain community may be fragile. Research interests in the governance of blockchain have been boosted by the discussion on these two events.

3.1.2. IT governance and blockchain governance

Another motivation of this study is that conventional IT governance may not be applicable in the blockchain context. According to Weill (2004), IT governance *"specifies the decision rights and accountability framework to encourage desirable behaviour in the use of IT"*. IT governance is usually applied to better utilise information technology and make profits by providing high-level governance principles and structures within a single organisation. IT governance includes several archetypal approaches, ranging from centralisation to decentralisation. In *business monarchy* and *IT monarchy*, IT-related decisions are made by business executives and IT executives respectively. *Federal system* and *IT duopoly* introduce other executives and business representatives into the decision-making process. A *feudal system* allows each business unit to make separate decisions, whilst individuals can pursue their own IT objectives in *anarchy*. In addition, Weill and Ross (2005) propose three IT governance methods: *decision-making structures* help form decision-making committees within an organisation, *alignment processes* clarify the management techniques in governance decisions and implementation (e.g. investment proposal, exception handling), and *formal communications* provide several ways for involving entities to understand the decisions.

In general, IT governance provides high-level guidance for a single organisation to better leverage information technology and make profits. Nevertheless, there is still a lack of a holistic view to facilitate operational blockchain governance. Blockchain is hard to govern as the code is stand-alone and difficult to update. The decentralised nature of blockchain requires the participation of the majority or even all stakeholders for an update decision to achieve democracy. Consequently, we decide to conduct an SLR to learn the state-of-art of blockchain governance, from which we can extract the actionable mechanisms from current progress in academia.

3.2. Protocol development and pilot study

In this section, we mainly introduce the research questions in our protocol, while the inclusion and exclusion criteria, and quality assessment are demonstrated in subsequent sections. We adopt 5W1H (what, why, where, when, who, and how) as the research questions in our SLR protocol, to holistically examine the adoption, use and design of blockchain governance. Table 1

Table 1
Research questions and motivations.

No	Research question	Motivation
RQ1	What is blockchain governance?	To observe how primary studies define the concept of blockchain governance.
RQ2	Why is blockchain governance adopted?	To understand the forces of blockchain governance.
RQ3	Where is blockchain governance enforced?	To distinguish the key governance objects in blockchain ecosystem.
RQ4	When is blockchain governance applied?	To understand where governance fits in the development process of blockchain.
RQ5	Who is involved in blockchain governance?	To identify the different roles, and their authorities, capabilities and responsibilities in blockchain governance.
RQ6	How is blockchain governance designed?	To explore actionable mechanisms for implementing blockchain governance.

lists the research questions addressed by this study and their motivations.

In RQ1, we extract the definition of blockchain governance from the primary studies. This observation can help explore the fundamental governance dimensions in blockchain. RQ2 identifies the core problems that require proper governance solutions. This research question can help understand the forces and consequences of governance mechanisms analysed in RQ6. RQ3 extends governance to the overall blockchain ecosystem, and identifies the key governance objects. Furthering the point, we can learn how these objects are connected in governance issues. We can learn when governance is applied to the blockchain development process from RQ4. Based on Section 3.1.1, governance plays a significant role in the different phases of development lifecycle, especially in the design phase regarding the initial configuration of blockchain platforms, and the operation phase about how to resolve conflicts between different roles. RQ5 identifies the key roles in governance issues, and analyses how they are involved and interact with each other in these issues. Finally, RQ6 explores the mechanisms and best practices to implement governance for blockchain.

To validate the developed protocol, we conduct a pilot study in which the six research questions are applied to five papers to extract answers. The papers are selected by searching *blockchain governance* via Google Scholar, including (van Pelt et al., 2021; Beck et al., 2018; Allen and Berg, 2020; Katina et al., 2019; Kim, 2020). The pilot study results indicate that our protocol is feasible.

3.3. Identification of research

Blockchain governance was used as the key word, and we also added synonyms, and abbreviations as supplements to include more comprehensive search results, which are shown in Table 3. For *blockchain*, many studies relate cryptocurrencies to this technology and may replace each other in certain cases. In this research, we focus on the blockchain technology itself, and treat cryptocurrency as an application based on it, thus the supplementary terms do not contain any crypto-related words. For *governance*, we only select two cognates to avoid ambiguity and misunderstanding in other synonyms.

We collected the literature from the following sources: (1) *ACM Digital Library*, (2) *IEEEXplore*, (3) *ScienceDirect*, (4) *SpringerLink*, and (5) *Google Scholar*. The selection of data sources was driven by the willingness of searching as many papers as possible to properly perform this systematic literature review. In this regard, the above-selected data sources are all recognised to be the most representative digital libraries for Software Engineering research (Kitchenham and Charters, 2007). The search time frame is set from 1 January 2008 (as the concept of blockchain is popularised in the Whitepaper of Bitcoin Nakamoto, 2008) to 3 November 2020. We designated the search strings for each source for paper collection. Each search string was tested for its appropriateness and effectiveness, and the final search terms for the five sources are presented in Tables 4 to 8.

The original search resulted in 1061 papers: 84 from *ACM Digital Library*, 130 from *IEEEXplore*, 68 from *ScienceDirect*, 523 from *SpringerLink*, and 256 from *Google Scholar*. After the removal of duplicates, and first inclusion/exclusion from the title and abstract, the initial selection set had 75 papers. Then, we conducted a full-text screening and ended up with 27 papers as the tentative selection. After the following snowballing phase, 10 papers were included and the final selection set has 37 papers. The number of papers per source is presented in Table 2.

3.4. Selection of primary studies

We formulated the inclusion and exclusion criteria to conduct selection on collected papers. The drafted criteria were first improved with the pilot study of five studies. Afterwards, four researchers reviewed and updated the criteria. Seven criteria were finalised to determine the eligibility of selected papers. The inclusion criteria are as follows.

- A paper that proposes a solution for governance of blockchain.
- A paper that proposes principles or frameworks for developing governance of blockchain.

The exclusion criteria are as follows.

- Papers that focus on *governance through blockchain* instead of *governance of blockchain*.
- Older version of a study that has a more comprehensive version.
- Papers that are not written in English.
- Papers that are not accessible.
- Survey, review and SLR papers. These studies are selected and identified in a separate subset, to provide a better understanding of state-of-the-art blockchain governance. However, we do not conduct data extraction or synthesis from these studies as they are considered the related work of this study.

Afterwards, we carried out a forward and backward snowballing process, to include any other related studies that might have been missed in the initial search. Hereby, backward and forward snowballing refers to using the references and citations of a paper respectively to find related studies (Wohlin, 2014). Ten studies were included after the snowballing process, which is illustrated in Table 9.

Table 2
Paper selection results.

Sources	ACM	IEEE Xplore	Science Direct	Springer Link	Google Scholar	Total
Count	3	4	1	8	21	37

Table 3
Search terms.

Key term	Supplementary terms
Blockchain	Distributed ledger technology, DLT
Governance	Govern, Governing

Table 4
Search strings and quantity of *ACM Digital Library*.

Search string	`(Title:(blockchain OR ''distributed ledger technology'' OR DLT) AND Title:(governance OR governing OR govern)) OR (Abstract:(blockchain OR ''distributed ledger technology'' OR DLT) AND (Abstract:(governance OR governing OR govern))`
Result quantity	84
Selected papers	**3**

Table 5
Search strings and quantity of *IEEEXplore*.

Search string	`((''Document Title'':blockchain OR ''distributed ledger technology'' OR DLT) AND (''Document Title'':governance OR governing OR govern)) OR ((''Abstract'':blockchain OR ''distributed ledger technology'' OR DLT) AND (''Abstract'':governance OR governing OR govern))`
Result quantity	130
Selected papers	**4**

Table 6
Search strings and quantity of *ScienceDirect*.

Search string	`Title, abstract, keywords: (blockchain OR ''distributed ledger technology'' OR DLT) AND (governance OR governing OR govern)`
Result quantity	68
Selected papers	**1**

Table 7
Search strings and quantity of *SpringerLink*.

Search string	`(blockchain OR ''distributed ledger technology'' OR DLT) NEAR/10 (governance OR governing OR govern)`
Result quantity	523
Remark	The search engine of *SpringerLink* does not support composite logical operators for the title, hence, we decided to search papers in which the word "governance" is closed to "blockchain" within 10 words.
Selected papers	**8**

The overall selection process involved two researchers. A researcher first included and excluded the papers from title and abstract, the results were then screened for full text. The other researcher was responsible to review the results in both phases. Two other researchers were consulted when disagreements happened. The whole collection and selection process is demonstrated in Fig. 1.

Table 8
Search strings and quantity of *Google Scholar*.

Search string	`allintitle: (blockchain OR ''distributed ledger technology'' OR DLT) (governance OR governing OR govern)`
Result quantity	256
Remark	Search title only (*Google Scholar* does not support abstract or keyword search option).
Selected papers	**21**

Table 9
Snowballing result.

Seed paper	Snowballed paper
De Filippi et al. (2020)	De Filippi and Loveluck (2016)
Allen and Berg (2020)	Mosley et al. (2020), Yeung and Galindo (2019)
Hsieh et al. (2017)	Nabilou (2020)
De Filippi and Loveluck (2016)	Mattila and Seppälä (2018), Yeoh (2017), Crepaldi (2019), Azouvi et al. (2019), Wright (2019-2020)
Yeung and Galindo (2019)	Paech (2017)

3.5. Quality assessment

We conducted an assessment of the selected papers to evaluate their quality and finalise the inclusion eligibility (Kitchenham and Charters, 2007; Petersen et al., 2015). Five quality criteria (QC) were developed and each one can be answered by one of three scores: 1 (yes), 0.5 (partially), and 0 (no). The total scores of five QC were calculated and ranked the papers into three categories: good ($4 < score \leq 5$), fair ($2 < score \leq 4$), and fail ($0 \leq score \leq 2$). The studies in *good* and *fair* groups were included while the *fail* papers are excluded in this phase. During the conduction of quality assessment, the 37 papers were all selected as the results are all higher than two scores, which indicates that the selected studies all have fair or good quality. The QC are as follows:

- QC1. Does the study identify a main research purpose? A primary study should have a clear purpose for the investigation of blockchain governance. Please notice if a study fails (i.e., gets a 0 score) at QC1, it will not be included in the subsequent data extraction and synthesis process. Without a main research purpose, a study cannot present novel blockchain governance solutions via a suitable methodology.
- QC2. Does the study clearly define the concept of blockchain governance? The definition can help develop a comprehensive perception of blockchain governance.
- QC3. Does the study describe the methodology clearly? The applied methodology can embody the relevance of a paper to this research.
- QC4. Does the study conduct an evaluation? Are the proposed solutions solid and how to evaluate them? These factors are helpful to design available and applicable governance methods.
- QC5. Does the study discuss any limitations? The discussion on current limitations of blockchain governance can reveal the direction of future studies on this research topic.

Fig. 2. RQ1: What is blockchain governance?.

3.6. Data extraction and synthesis

We downloaded all selected papers from the search sources for data extraction. A Google sheet was developed to record original data from the papers, including basic information (i.e., title, publication year, search source, type, venue, authors, and affiliation), and the answers of each RQ, while the calculation of QC scores is also included in this sheet. The basic information and quality assessment results of primary studies are presented in Appendix.

Four researchers participated in this phase. First, two researchers are responsible to extract data, and conduct cross-validation to each other's extraction. If there were disagreements on certain data, another two independent researchers were consulted to review the paper and finalise the extraction decisions.

4. Results

In this section, we summarise the extracted results of each research question.

4.1. RQ1: What is blockchain governance?

The first research question is *"What is blockchain governance?"* The motivation is to observe how literature define the concept of blockchain governance. To answer this question, the definition of blockchain governance given by each study is recorded. Fig. 2 is a word cloud showing the frequency of the words, which appear in the original definition of blockchain governance in each study. The top ten appeared words include: *right* (27), *decision* (25), *rules* (24), *platform* (23), *system* (19), *control* (18), *decision-making* (17), *participants* (16), *bitcoin* (13), *community* (13). Further, we found that seven studies adopt theories of governance from other domains, including IT governance (van Pelt et al., 2021; Mattila and Seppälä, 2018; Beck et al., 2018), corporate governance (Allen and Berg, 2020; Hsieh et al., 2017), complex adaptive systems (John and Pam, 2018), and formal political economy (Lee et al., 2020).

To answer RQ1 more accurately, we summarise three categories from the extracted data and their involved dimensions, as shown in Table 10. First, based on the observation that several studies comprehend blockchain governance from the perspective of IT governance, we recap the three dimensions of IT governance (i.e., decision rights, accountability, and incentives) (Weill, 2004) in blockchain governance as follows.

- *Decision Rights*: Decision rights denote the authority, responsibility, and capability of involved individuals in a blockchain that how decisions are made and monitored (Allen and Berg, 2020; van Pelt et al., 2021; Mosley et al., 2020), and which stakeholders' interests should be prioritised (Yeoh, 2017). The allocation of decision rights can also indicate the degree of decentralisation of a blockchain Beck et al. (2018). Ellul et al. (2020) state that no single party can determine the appending transactions, while two other studies also mention all decisions in a blockchain are made by the collective power (Katina et al., 2019; Yeung and Galindo, 2019).
- *Accountability*: Accountability means that those responsible for the different phases of the blockchain lifecycle should be identifiable and answerable for their decisions and the outcomes over a blockchain. Consequently, this governance dimension can ensure the efficient use of resources and monitor the overall performance of a blockchain platform (Katina et al., 2019). Usually, accountability in blockchain is enacted via on-chain smart contracts and off-chain legal agreements (Beck et al., 2018).
- *Incentives*: Incentives are considered to be a motivational factor that influences participants' behaviours (van Pelt et al., 2021), which can be either positive or negative (i.e., rewards for contributions, or sanctions for malicious operations). On one hand, incentives attract individuals to participate in the governance issues (Mattila and Seppälä, 2018; De Filippi and Loveluck, 2016). On the other hand, incentives can guide different stakeholders to make decisions as a whole (Baudlet et al., 2020; Beck et al., 2018; Wright, 2019-2020).

Secondly, considering the different blockchain types, Werner et al. (2020) state that the trust and perceived risks are dependent on the decentralisation level of a blockchain. Thirdly, five studies give the definition of on-chain and off-chain governance (Fan et al., 2020; Reijers et al., 2018; Arribas et al., 2020;

Erbguth and Morin, 2018; Wright, 2019-2020): (1) on-chain governance focuses on the decision-making process that is codified to a blockchain, while subsequent interactions should adhere to these rules of code, and; (2) off-chain governance comprises all other off-chain processes that may influence the development and operation of blockchain.

Insight from RQ1: What is blockchain governance?

Dimensions of blockchain governance: Blockchain governance consists of the three dimensions of decision rights, accountability, and incentives, whereby they should all align with the decentralisation level of deployed blockchains. First, the decision rights of an entity may vary throughout the lifecycle of a blockchain. For example, a user can compete to be a block validator, who is capable to select the transactions for inclusion. Secondly, pseudonymous addresses are a challenge for the identification of accountable entities, particularly in permissionless blockchains. Thirdly, incentives can be realised through both on-chain token distribution and off-chain business agreements.

Definition of blockchain governance: Since there is not a commonly recognised definition of blockchain governance, hereby, we give a high-level definition based on the extracted information as follows. Please note that the definition also considers the following research questions and results.

Blockchain governance refers to the structures and processes that are designed to ensure the development and use of blockchain are compliant with legal regulations and ethical responsibilities. On one hand, blockchain structures are generally determined by the decentralisation level, while the detailed design and implementation of governance solutions are dependent on the actual allocation of decision rights, incentives, and accountability of different stakeholder roles. Note that governance solutions should consider the overall blockchain ecosystem to establish a comprehensive governance structure. On the other hand, processes mean that the coordination between stakeholders throughout the development lifecycles of different governance objects can also embody how governance is realised.

Table 10
Dimensions of blockchain governance definition.

Categories	Dimensions	Primary studies
IT governance	Decision rights	Katina et al. (2019), Allen and Berg (2020), Finck (2018), John and Pam (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Meijer and Ubacht (2018), Hsieh et al. (2017), Reijers et al. (2018), Merrill et al. (2020), Ellul et al. (2020), Yeoh (2017), Mosley et al. (2020), Werner et al. (2020), Erbguth and Morin (2018), Yeung and Galindo (2019), Santos and Kostakis (2018)
	Accountability	Katina et al. (2019), Rikken et al. (2019), Beck et al. (2018)
	Incentives	Baudlet et al. (2020), De Filippi et al. (2020), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Wright (2019-2020)
Decentralisation level	Permissioned	Bao et al. (2019), Werner et al. (2020)
	Permissionless	Werner et al. (2020)
Governance context	On-chain	Fan et al. (2020), Reijers et al. (2018), Arribas et al. (2020), Erbguth and Morin (2018), Wright (2019-2020)
	Off-chain	Fan et al. (2020), Reijers et al. (2018), Arribas et al. (2020), Erbguth and Morin (2018), Wright (2019-2020)

4.2. RQ2: Why is blockchain governance adopted?

The motivation of RQ2 is to understand the main challenges blockchain governance aims to resolve. As illustrated in Table 11, we classify the answers into seven categories: adaptability, upgradability, security, social orders, accountability, privacy, and censorship-resistance (Anon, 2011).

- *Adaptability*: Adaptability is the main motivation for adopting blockchain governance. An effective governance structure can widen the application scenarios of blockchain Katina et al. (2019), Allen and Berg (2020), Rikken et al. (2019), Yeoh (2017). Proper governance can help minimise the risks of different applications, hence blockchain can adapt to the specific needs and restrictions of both public and private sectors, where stakeholders may heavily modify the deployed blockchains (Trump et al., 2018). Atzori (2018) mentions the European Parliament Resolution on virtual currencies (Anon, 2016), which implied the recognition of blockchain and applications from the perspective of institutional regulations. The proposed resolution established a conceptual framework for both regulatory supervision and the development of technical expertise, to ensure timely responses to new challenges or risks. Paech (2017) also states that a governance framework for blockchain financial networks can reduce the cost of adaption to new rules in the subsequent stages.
- *Upgradability*: Upgradability is the second major objective to apply governance in blockchain, which means the capability of being upgraded in functionality by adding or replacing blockchain components. Blockchain intends to provide immutable data storage, nevertheless, such absolute immutability is not desirable as on-chain governance relying on the original code has proved to be insufficient (Erbguth and Morin, 2018). Blockchain platforms should be upgraded

Table 11
RQ2: Why is blockchain governance adopted?

Categories	Primary studies
Adaptability	Katina et al. (2019), Atzori (2018), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), John and Pam (2018), Rikken et al. (2019), Paech (2017), Trump et al. (2018), De Filippi and Loveluck (2016), Fan et al. (2020), Yeoh (2017), Reshef Kera (2020), Mosley et al. (2020), Werner et al. (2020), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Wright (2019-2020)
Upgradability	Baudlet et al. (2020), Nabilou (2020), Finck (2018), DiRose and Mansouri (2018), John and Pam (2018), van Pelt et al. (2021), De Filippi and Loveluck (2016), Fan et al. (2020), Merrill et al. (2020), Ellul et al. (2020), Arribas et al. (2020), Reshef Kera (2020), Erbguth and Morin (2018), Crepaldi (2019), Yeung and Galindo (2019), Azouvi et al. (2019)
Security	De Filippi et al. (2020), van Pelt et al. (2021), Rikken et al. (2019), Paech (2017), Meijer and Ubacht (2018), Trump et al. (2018), Reijers et al. (2018), Ellul et al. (2020), Yeoh (2017), Reshef Kera (2020), Kim (2020), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
Social orders	Bao et al. (2019), De Filippi and Loveluck (2016), Yeung and Galindo (2019), Wright (2019-2020)
Accountability	Howell et al. (2019), Ellul et al. (2020)
Privacy	Yeoh (2017)
Censorship-resistance	Nabilou (2020)

to fix bugs and adopt new practices and behaviours (Baudlet et al., 2020; Nabilou, 2020; van Pelt et al., 2021; Arribas et al., 2020). Specifically, the Bitcoin block size debate is viewed as an example that governance is needed for upgrading blockchain Nabilou (2020), Finck (2018), De Filippi and Loveluck (2016), Fan et al. (2020), Ellul et al. (2020).

- *Security*: Security can ensure that the daily operation of blockchain is in a trustworthy manner, protecting on-chain data and digital assets against malicious attacks (De Filippi et al., 2020). A significant aspect is that the vulnerabilities in code should be mitigated (Rikken et al., 2019). Notably, several studies all mention the Ethereum DAO attack, which was caused by a smart contract bug (Reijers et al., 2018; Crepaldi, 2019; Yeung and Galindo, 2019; Santos and Kostakis, 2018). This attack made the entire Ethereum system stop and ultimately ended up in a hard fork. Such a crisis has affected the reputation of blockchain, and intensified the need for blockchain governance to prevent malicious behaviours and ensure the security of the whole system. In recent years, blockchain is often associated with data violations and cyber crimes as there is a lack of proper governance to manage legal compliance (Paech, 2017; Ellul et al., 2020; Yeoh, 2017).
- *Social orders*: Social orders include pursuing collective goals, and balancing power relations in the decentralised environment of blockchains. A blockchain community consists of multiple types of stakeholders, consequently, governance models are required to maintain social orders among these stakeholders regarding the complex realities (e.g., the variety of human motivations, behaviours, and decisions) (Yeung and Galindo, 2019). De Filippi and Loveluck (2016) discuss that the governance crisis in Bitcoin emphasised the tension and conflict between the decentralised nature of blockchain and a centralised governance model in Bitcoin. In a highly decentralised context (e.g., permissionless blockchains), efficient governance mechanisms should provide stakeholders with transparent criteria for selecting the goals of blockchain protocols (Wright, 2019-2020).
- *Accountability*: In RQ1, accountability is one of the three dimensions adopted from IT governance, and this is considered the consequence brought by governance structures. While in RQ2, two primary studies are identifying this attribute as a motivation of blockchain governance. Howell et al. (2019) state that neither the on-chain ledger nor platform itself is claimed to be possessed by any entity, however, the responsibility is assumed to be taken by a particular party for the ongoing operation. Ellul et al. (2020) mention removing the anonymity of permissionless blockchains requires a regulatory framework in the context of decentralised governance.
- *Privacy*: In a permissionless blockchain network, data are generally transparent and visible to all nodes that participate in the network and all devices with access to those nodes. This might pose a risk in situations where sensitive data should only be visible to selected participants. Governance is expected to protect sensitive data stored in blockchain Yeoh (2017).
- *Censorship-resistance*: Nabilou (2020) states that permissionless blockchains represent a censorship-resistant technique which enables rules as code. Preserving censorship-resistance relies on the collective decisions of all participants. Adopting governance can facilitate the decentralisation in blockchain and hence, retain the censorship-resistant property.

Insight from RQ2: Why is blockchain governance adopted?

Human values and broader ethical responsibility: Most identified purposes of blockchain governance are software quality attributes, while some of them can be related to human values in software (Mougouei et al., 2018), for instance, security and privacy. These values reflect the awareness of blockchain's impact on human and society. Furthering the point, blockchain governance can be associated with broader ethical responsibility. Take permissionless public blockchains as an example, some blockchain-based decentralised finance applications are criticised for high energy consumption. Governance issues can be extended to cover this topic for the sustainability of blockchain.

Table 12
RQ3: Where is blockchain governance enforced?

Ecosystem	Primary studies
Platform	Baudlet et al. (2020), Nabilou (2020), De Filippi et al. (2020), Atzori (2018), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), John and Pam (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Lee et al. (2020), Ellul et al. (2020), Yeoh (2017), Arribas et al. (2020), Reshef Kera (2020), Kim (2020), Mosley et al. (2020), Werner et al. (2020), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
Community	Bao et al. (2019), Nabilou (2020), De Filippi et al. (2020), Katina et al. (2019), Atzori (2018), Allen and Berg (2020), DiRose and Mansouri (2018), John and Pam (2018), van Pelt et al. (2021), Rikken et al. (2019), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Lee et al. (2020), Yeoh (2017), Arribas et al. (2020), Reshef Kera (2020), Mosley et al. (2020), Werner et al. (2020), Erbguth and Morin (2018), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
Application	Finck (2018), John and Pam (2018), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Paech (2017), Trump et al. (2018), Merrill et al. (2020), Ellul et al. (2020), Yeoh (2017), Reshef Kera (2020), Mosley et al. (2020), Werner et al. (2020), Santos and Kostakis (2018)
Data	Bao et al. (2019), Atzori (2018), Rikken et al. (2019), Beck et al. (2018), Trump et al. (2018), Yeoh (2017), Mosley et al. (2020), Erbguth and Morin (2018)

4.3. RQ3: Where is blockchain governance enforced?

The motivation of RQ3 is to distinguish the key governance objects within blockchain ecosystem. We summarise four different governance objects as shown in Table 12, including data, platform, application, and community.

The majority of primary studies focus on the governance of blockchain platform itself (89%). In particular, the governance of blockchain should determine how the platform is designed (Howell et al., 2019), for instance, infrastructure configuration (e.g. block size and interval) (DiRose and Mansouri, 2018; Merrill et al., 2020; Azouvi et al., 2019), and consensus protocol (e.g. transaction generation and confirmation process) (Allen and Berg, 2020; John and Pam, 2018; Hsieh et al., 2017). Moreover, governance can facilitate the upgrade of platforms to meet the new requirements according to users' feedback and proposals (Allen and Berg, 2020; Fan et al., 2020; Merrill et al., 2020; Lee et al., 2020; Crepaldi, 2019).

81% of the primary studies discuss governance of the blockchain community. Violations of on-chain governance may cause conflicts in the real-world context (Reijers et al., 2018), consequently, governance of the community places an emphasis on both formal and informal governance processes of different stakeholders and their collaborations via off-chain channels (e.g., Twitter, Reddit and GitHub) (Nabilou, 2020; Allen and Berg, 2020; Hsieh et al., 2017; Fan et al., 2020; Crepaldi, 2019). Governance over community also includes institutional governance which covers the legitimacy of all aspects of the blockchain ecosystem against injustice (John and Pam, 2018). The development and business activities associated with blockchain ecosystem should comply with the regulations issued by the states that the blockchain is expected to deploy (Paech, 2017; Meijer and Ubacht, 2018; Yeoh, 2017).

14 out of 37 primary studies express that governance is required to be enforced over the blockchain applications, where blockchain is exploited as a component to enable decentralised architecture. Consequently, the usage of blockchain in the applications should be governed according to industry regulations and specifications (Merrill et al., 2020; Yeoh, 2017). Specifically, cryptocurrencies are taken as examples that legal solutions should be employed against criminal activities such as money laundering and terrorist financing (Paech, 2017; Ellul et al., 2020).

There are 8 primary studies discussing on-chain data governance. In particular, Atzori (2018) focuses on the data source and quality to ensure the conformance of on-chain data in permissioned blockchains. Once a block is validated and appended to the blockchain, all included data is permanently stored unless human interventions are involved to edit or reverse historical transactions (Rikken et al., 2019; Trump et al., 2018). Stored data should be audited to detect illegal actions (Bao et al., 2019). Violations of regulations such as data protection or child pornography require governance methods to remove relevant transaction records (Erbguth and Morin, 2018).

Insight from RQ3: Where is blockchain governance enforced?

The majority of blockchain governance studies focus on the design of ***platform*** and organisation of ***community*** activities, while less attention is paid to applications and data.

Application: The governance of application mostly discusses cryptocurrency, whereby the influences of other application domains are missing.

Data: Governance over the ***data*** can be enabled throughout ***on-chain data lifecycle***, e.g. checking submitted data through client applications, classifying data based on its degree of sensitivity, adding supernodes with higher level of data access permission.

4.4. RQ4: When is blockchain governance applied?

The motivation of RQ4 is to understand when governance is applied in the development process of blockchain. Currently, there is not a commonly recognised lifecycle for the development

Table 13
RQ4: When is blockchain governance applied?

Categories	Primary studies
Planning	Baudlet et al. (2020), Nabilou (2020), De Filippi et al. (2020), Katina et al. (2019), Atzori (2018), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), John and Pam (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Lee et al. (2020), Yeoh (2017), Mosley et al. (2020), Werner et al. (2020), Crepaldi (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
Analysis	Baudlet et al. (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Meijer and Ubacht (2018), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Mosley et al. (2020), Crepaldi (2019), Azouvi et al. (2019), Wright (2019-2020)
Design	Baudlet et al. (2020), Nabilou (2020), Allen and Berg (2020), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Trump et al. (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Reijers et al. (2018), Merrill et al. (2020), Kim (2020), Mosley et al. (2020), Werner et al. (2020), Erbguth and Morin (2018), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019)
Implementation	Nabilou (2020), De Filippi et al. (2020), Finck (2018), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), De Filippi and Loveluck (2016), Reijers et al. (2018), Lee et al. (2020), Ellul et al. (2020), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019)
Testing	van Pelt et al. (2021), Merrill et al. (2020), Arribas et al. (2020), Reshef Kera (2020)
Operation	Bao et al. (2019), Baudlet et al. (2020), Nabilou (2020), De Filippi et al. (2020), Atzori (2018), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Paech (2017), Trump et al. (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Reijers et al. (2018), Merrill et al. (2020), Ellul et al. (2020), Kim (2020), Mosley et al. (2020), Werner et al. (2020), Erbguth and Morin (2018), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
Termination	Nabilou (2020), De Filippi et al. (2020), Finck (2018), Howell et al. (2019), Reijers et al. (2018)

process of blockchain platforms. To answer this question, we adopt the software development process (Anon, 2017a) to analyse and synthesise extracted data, as shown in Table 13.

During the development of a blockchain, governance is instrumentally embedded with the settings and design of on-chain rules, which are considered *endogenous governance* (Allen and Berg, 2020). In the *planning* phase, the founding members should make institutional arrangements in the first place, for instance, the initial distribution of decision rights (Howell et al., 2019). Besides, the blockchain type should also be determined according to the desired decentralisation level, for the subsequent identity verification process (Hsieh et al., 2017). In the *analysis* phase, finalising the governance decisions usually depends on the coordination of relevant entities via voting (Baudlet et al., 2020; De Filippi et al., 2020; Allen and Berg, 2020). Afterwards, specific on-chain rules are arranged in the *design* phase. For instance, Proof-of-Work and various incentive mechanisms are usually integrated into permissionless blockchains, to align the different interests of stakeholders and prevent uncooperative behaviours which may harm the platform (Nabilou, 2020). Regarding the *implementation* phase, forking is viewed as a special form to implement new functionalities in blockchain Finck (2018), DiRose and Mansouri (2018), Mattila and Seppälä (2018). Further, in the *testing* phase, implemented codes need to be deployed to the testnet for a certain time period before officially in use (Merrill et al., 2020).

Subsequently, governance during the *operation* of a blockchain usually happens when human interventions are required to deal with emergencies (De Filippi et al., 2020), for instance, violations of laws (Ellul et al., 2020), software bugs (Yeung and Galindo, 2019), or disputes between different entities (Erbguth and Morin, 2018). Such interventions are regarded as *exogenous governance*, which provides formal mechanisms for stakeholders to express their ideas on the future direction of a blockchain platform (Allen and Berg, 2020). In these cases, proposals are submitted to change the status quo and introduce new policies to a blockchain, which then starts a new epoch of development process from the *planning* phase (Lee et al., 2020; Mosley et al., 2020; Crepaldi, 2019; Azouvi et al., 2019).

Finally, five primary studies mention various forms of activities that might lead to the *termination* of a blockchain platform. Specifically, if the requirements cannot be satisfied, an entity can always choose *exit or voice*. *Voice* means proposing or voting for new improvement proposals, while *exit* refers to leaving the blockchain Nabilou (2020), De Filippi et al. (2020), Finck (2018), Howell et al. (2019), Reijers et al. (2018).

Insight from RQ4: When is blockchain governance applied?

Full development lifecycle: The primary studies present a relatively complete development lifecycle except for the *termination* phase. When a blockchain project fails, all involved stakeholders have to leave the blockchain platform. At this point, blockchain governance needs to guide how to distribute the resources to protect the rights and interests of stakeholders.

Lifecycle of other governance objects: The current studies mainly focus on the governance process of blockchain platform, while further refinement is needed to extend the analysis to other governance objects in blockchain ecosystem (e.g., data, application, community), to understand how governance fits in their development processes.

4.5. RQ5: Who is involved in blockchain governance?

The motivation of RQ5 is to identify the stakeholders who are related to the governance of blockchain and how they are involved. We present the identified stakeholders in Table 14.

- *Project team*: 27 out of 37 primary studies consider the project team as a key stakeholder in blockchain governance. In general, the project team is responsible for both technical implementations codified to the blockchain and other real-world arrangements (Howell et al., 2019). First, developers maintain the code of a blockchain platform that any upgrades to the blockchain are implemented by them (Finck, 2018). Specifically, three studies mention the concept of *benevolent dictator*, which indicates that the core developers (e.g. Nakamoto who invented Bitcoin) of a blockchain platform usually have more decision rights than the other roles to overcome emergency situations (DiRose and Mansouri, 2018; Beck et al., 2018; Santos and Kostakis, 2018). Secondly, foundations provide financial support to the invention and development process, hence, they can also affect the governance decisions of blockchain platforms (Allen and Berg, 2020). According to Reijers et al. (2018), the Ethereum Foundation had a significant influence in regards to the responses to the "DAO attack". In addition, three studies (Hsieh et al., 2017; Ellul et al., 2020; Erbguth and Morin, 2018) point out that the project team should select a person as the lead who is responsible and accountable for the team decisions and handles legal issues. van Pelt et al. (2021) have a similar suggestion of hiring legal professionals for blockchain firms.
- *Node operator*: 28 out of 37 primary studies view node operators as the main stakeholders in blockchain governance. First, the most discussed node operators are block validators (also known as *miners* in blockchain-based decentralised finance). They are responsible for the generation and inclusion of new blocks (i.e., the data entries of a blockchain), and ensure security by participating in the consensus mechanism (Mattila and Seppälä, 2018; Hsieh et al., 2017). Secondly, full node operators maintain the storage of all historical ledger data, and they can decide to support the blockchain platform upgrades by installing the latest version (Allen and Berg, 2020). Moreover, special node operators with particular decision rights can be either predetermined in design or selected during operation (Baudlet et al., 2020; DiRose and Mansouri, 2018; Reijers et al., 2018; Mosley et al., 2020). For example, Dash allows stakeholders who own more than 1000 Dash tokens to be the *masternodes*, who can vote for the future direction of Dash blockchain Mosley et al. (2020).
- *User*: In the governance of blockchain, users are critical as they eventually determine whether a blockchain platform can survive. For instance, when a hard fork occurs, a blockchain splits into two versions. Users need to decide which version they will continue to use (Finck, 2018; Lee et al., 2020). Besides, users can provide feedback to the project team about encountered problems during the usage of the blockchain platform (Finck, 2018). Furthermore, regarding the close connection between permissionless blockchain and decentralised finance, seven studies mention token holders in blockchain governance, as listed in Table 14. In certain blockchain platforms, token holders can submit proposals that outline potential directions while other token holders can vote for the proposal (Fan et al., 2020; Merrill et al., 2020; Mosley et al., 2020). Please note that users are not necessarily *end-users*, since blockchain-based applications may provide certain services to the end-users, while hiding the complexities of blockchain. End-users may not send transactions by themselves. Consequently, they do not participate in governance-related issues. In this case, the *users* involved in blockchain governance could be considered the application providers discussed below.
- *Application provider*: As blockchain-based applications are considered a critical part of the blockchain ecosystem, the application providers also participate in the governance of blockchain. For instance, financial systems may influence the underlying blockchain platforms of decentralised finance via interactions or competition (Allen and Berg, 2020; Paech, 2017). Cryptocurrency exchanges also play a significant role that they need to decide which coin (token) to support in the case that the related blockchain platform conducts a hard fork (Finck, 2018). Similar providers include custodian, wallet provider, and bank (Nabilou, 2020; De Filippi et al., 2020; Allen and Berg, 2020; Paech, 2017).
- *Regulator*: Regulators include governments, courts, and third-party auditors, who ensure that all decisions and activities within the blockchain ecosystem comply with related laws and policies. Governments can affect the governance decisions made by other stakeholders by introducing new legal restrictions and constraints (De Filippi et al., 2020; Trump et al., 2018). Examples include regulations of tax or against criminal behaviours like money laundering, where courts are also involved (Paech, 2017; Yeoh, 2017; Erbguth and Morin, 2018). Meanwhile, auditors are responsible to record all required information for future investigation (Ellul et al., 2020).
- *Indirect stakeholders*: In addition to the above stakeholders, we categorise the following three types as *indirect stakeholders*, including media, researchers, and environmentalists. They can all influence or contribute to the blockchain governance decisions while do not participate in the operation of a blockchain platform. Media and environmentalists can both make social pressure which may affect stakeholders' decisions (Nabilou, 2020; De Filippi et al., 2020; Allen and Berg, 2020; Hsieh et al., 2017). Whilst, van Pelt et al. (2021) mention that researchers contribute to the

Table 14
RQ5: Who is involved in blockchain governance?

Stakeholders		Primary studies
Project team		Nabilou (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), John and Pam (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Ellul et al. (2020), Yeoh (2017), Arribas et al. (2020), Werner et al. (2020), Erbguth and Morin (2018), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
	Developer	Nabilou (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), John and Pam (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Arribas et al. (2020), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
	Foundation	Nabilou (2020), Allen and Berg (2020), Beck et al. (2018), Howell et al. (2019), Hsieh et al. (2017), Reijers et al. (2018), Yeoh (2017), Werner et al. (2020), Santos and Kostakis (2018)
	Project lead	Hsieh et al. (2017), Ellul et al. (2020), Erbguth and Morin (2018)
	Legal professional	van Pelt et al. (2021)
Node operator		Bao et al. (2019), Baudlet et al. (2020), Nabilou (2020), De Filippi et al. (2020), Atzori (2018), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), Mattila and Seppälä (2018), Rikken et al. (2019), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Ellul et al. (2020), Arribas et al. (2020), Kim (2020), Mosley et al. (2020), Erbguth and Morin (2018), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
	Block validator	Baudlet et al. (2020), Nabilou (2020), De Filippi et al. (2020), Atzori (2018), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), Mattila and Seppälä (2018), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Merrill et al. (2020), Arribas et al. (2020), Crepaldi (2019), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
	Full node operator	Bao et al. (2019), Nabilou (2020), Allen and Berg (2020), Finck (2018), Mattila and Seppälä (2018), Rikken et al. (2019), Howell et al. (2019), Paech (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Ellul et al. (2020), Kim (2020), Erbguth and Morin (2018), Crepaldi (2019), Yeung and Galindo (2019), Wright (2019-2020)
	Special node operator	Baudlet et al. (2020), DiRose and Mansouri (2018), Reijers et al. (2018), Mosley et al. (2020)
User		Baudlet et al. (2020), Nabilou (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Paech (2017), Meijer and Ubacht (2018), Hsieh et al. (2017), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Lee et al. (2020), Mosley et al. (2020), Werner et al. (2020), Yeung and Galindo (2019), Santos and Kostakis (2018), Wright (2019-2020)
	Token holder	De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), Fan et al. (2020), Merrill et al. (2020), Mosley et al. (2020), Werner et al. (2020), Santos and Kostakis (2018), Wright (2019-2020)
Application provider		Nabilou (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Beck et al. (2018), Howell et al. (2019), Paech (2017), Hsieh et al. (2017), Arribas et al. (2020), Santos and Kostakis (2018)
	Exchange	Nabilou (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), Howell et al. (2019), Paech (2017), Santos and Kostakis (2018)
	Custodian	Nabilou (2020), De Filippi et al. (2020)
	Wallet provider	Nabilou (2020), De Filippi et al. (2020), Allen and Berg (2020)
	Bank	Paech (2017)
Regulator		Bao et al. (2019), De Filippi et al. (2020), Katina et al. (2019), Atzori (2018), Allen and Berg (2020), John and Pam (2018), Paech (2017), Meijer and Ubacht (2018), Trump et al. (2018), Hsieh et al. (2017), Ellul et al. (2020), Yeoh (2017), Arribas et al. (2020), Reshef Kera (2020), Erbguth and Morin (2018)
	Government	De Filippi et al. (2020), Atzori (2018), Allen and Berg (2020), John and Pam (2018), Paech (2017), Meijer and Ubacht (2018), Trump et al. (2018), Hsieh et al. (2017), Ellul et al. (2020), Yeoh (2017), Reshef Kera (2020), Erbguth and Morin (2018)
	Auditor	Bao et al. (2019), Ellul et al. (2020)
	Court	Erbguth and Morin (2018)

(*continued on next page*)

Table 14 (*continued*).

Stakeholders	Primary studies
Media	Nabilou (2020), De Filippi et al. (2020), Hsieh et al. (2017)
Researcher	van Pelt et al. (2021)
Environmentalist	Allen and Berg (2020)

blockchain technology by conducting academic studies. Researchers usually do not count themselves as the stakeholders within the blockchain community, whilst their studies indeed help form governance models and frameworks for blockchain platforms.

Insight from RQ5: Who is involved in blockchain governance?

Direct stakeholders: The project team, node operators, users, application providers, and regulators can directly participate in the decision-making process of a blockchain. In addition to the high-level overview of these roles in blockchain governance from the primary studies, a mapping of each role with each of the governance dimensions analysed in RQ1 (i.e., decision rights, accountability, and incentives) can further refine their capabilities and responsibilities in blockchain governance.

Indirect stakeholders: Indirect stakeholders may be more inclusive when considering other blockchain governance objects discussed in RQ3. For instance, in on-chain data governance, the rights of data subjects should be protected when their data is stored on-chain, even though they are not using the blockchain platform.

4.6. RQ6: How is blockchain governance designed?

The final research question is to explore actionable mechanisms for implementing blockchain governance. As illustrated in Table 15, the governance mechanisms can be classified into two categories: process mechanisms and product mechanisms. Hereby, process mechanisms describe the steps of blockchain development via the governance meta-rules. Whilst, product mechanisms include the features of a blockchain, as the outcomes of software development process.

The extracted process mechanisms are summarised as follows.

- *Improvement proposal*: 20 primary studies mention improvement proposals. An improvement proposal is created to address unexpected exceptions and changing requirements in permissionless blockchains. Two well-known examples are the Bitcoin improvement proposal and Ethereum improvement proposal (Baudlet et al., 2020). The project team can collect the feedback regarding the future roadmap of a blockchain platform from other blockchain stakeholders (e.g., Ethereum Request for Comment (Rikken et al., 2019)) via offline seminars, online posts and mailing lists. Usually, there is a valid period for a proposal, expired proposals cannot be processed anymore (Baudlet et al., 2020).
- *Institutional oversight*: 12 papers discuss institutional oversight for blockchain, which depends on the governments and related organisations. First, laws and policies for blockchain governance should be issued and enforced by the states. De Filippi et al. (2020) state that blockchain needs to adapt constitutional safeguards from centralised coordinating authorities. The practical examples include legally mandated mutability (Finck, 2018; Trump et al., 2018), and finance-related laws regarding the decentralised finance applications (Paech, 2017; Yeoh, 2017). Secondly, authorities can assign specific roles to participate in the governance of blockchain. For instance, Atzori (2018) propose a permissioned network where only the trust service providers, which are appointed by European governmental agencies, can become transaction validators. Thirdly, in certain emergency cases, regulators should be capable to stop all on-chain business via extreme methods like blocking data transmission at network layer (Paech, 2017; Ellul et al., 2020). In addition, auditing the historical data of a blockchain is necessary to ensure the legitimacy of on-chain business activities (Ellul et al., 2020; Bao et al., 2019). Finally, since on-chain smart contracts are hard to update due to the immutability, off-chain contracts or agreements are required in a business relationship, to flexibly make changes to the "non-smart" parts (Paech, 2017).
- *Testing environment*: Testnet and sandbox are two techniques providing separate running programs for testing new codes or functionalities without influencing the actual business activities in blockchain platforms (Merrill et al., 2020; Arribas et al., 2020; Reshef Kera, 2020).

The extracted product mechanisms are listed as follows.

- *Voting*: *Voting* is commonly used as a conflict resolution method to finalise governance decisions in permissionless blockchains, which can be held either on-chain or off-chain. Specifically, node operators and users are the dominant roles in a voting process (Baudlet et al., 2020; Finck, 2018; DiRose and Mansouri, 2018; Mattila and Seppälä, 2018), to support or veto particular on-chain activities (e.g., the acceptance of proposals (Beck et al., 2018; Meijer and Ubacht, 2018; De Filippi and Loveluck, 2016), audit of historical transactions (Bao et al., 2019), and the election of particular roles Allen and Berg, 2020). Besides, different variants are proposed to ensure on-chain voting is viable and fair. Finck (2018) discusses *carbonvote* in which votes are counted regarding the tokens owned by voted individuals. Fan et al. (2020) propose a *cross-chain voting* scheme for new blockchain platforms via distributing tokens in other famous public blockchains, whereby token holders can vote for the new policies of this new blockchain. Wright (2019-2020) analyses quadratic voting, which can capture the preferences of votes via quadratically-increased tokens required for each additional vote. Mosley et al. (2020) mention restricting IP spoofing to ensure the integrity of on-chain voting systems. In permissionless blockchains, different stakeholders can participate in a voting process, but a major challenge is that individuals lacking technical expertise can also influence the result (Rikken et al., 2019).

Table 15
RQ6: How is blockchain governance designed?

Governance mechanisms		Primary studies
Process mechanisms	**Improvement proposal**	Baudlet et al. (2020), Nabilou (2020), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Meijer and Ubacht (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Lee et al. (2020), Mosley et al. (2020), Crepaldi (2019), Santos and Kostakis (2018), Azouvi et al. (2019), Wright (2019-2020)
	Institutional oversight	Bao et al. (2019), De Filippi et al. (2020), Atzori (2018), Finck (2018), Rikken et al. (2019), Paech (2017), Meijer and Ubacht (2018), Trump et al. (2018), Ellul et al. (2020), Yeoh (2017), Werner et al. (2020), Erbguth and Morin (2018)
	Law enforcement	De Filippi et al. (2020), Finck (2018), Paech (2017), Trump et al. (2018), Ellul et al. (2020), Yeoh (2017)
	Role assignment	Atzori (2018), Ellul et al. (2020), Yeoh (2017)
	Auditing	Bao et al. (2019), Ellul et al. (2020)
	Emergency stop	Paech (2017), Ellul et al. (2020)
	Off-chain contract	Paech (2017)
	Testing environment	Merrill et al. (2020), Arribas et al. (2020), Reshef Kera (2020)
Product mechanisms	**Voting**	Bao et al. (2019), Baudlet et al. (2020), De Filippi et al. (2020), Allen and Berg (2020), Finck (2018), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Meijer and Ubacht (2018), De Filippi and Loveluck (2016), Fan et al. (2020), Reijers et al. (2018), Merrill et al. (2020), Mosley et al. (2020), Crepaldi (2019), Wright (2019-2020)
	Carbonvote	Finck (2018)
	Cross-chain voting	Fan et al. (2020)
	Quadratic voting	Wright (2019-2020)
	IP restriction	Mosley et al. (2020)
	Forking	Nabilou (2020), De Filippi et al. (2020), Finck (2018), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), De Filippi and Loveluck (2016), Reijers et al. (2018), Lee et al. (2020), Ellul et al. (2020), Yeung and Galindo (2019), Santos and Kostakis (2018), Azouvi et al. (2019)
	Consensus protocol	Baudlet et al. (2020), Allen and Berg (2020), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Rikken et al. (2019), Beck et al. (2018), Howell et al. (2019), Trump et al. (2018), Hsieh et al. (2017), De Filippi and Loveluck (2016), Reijers et al. (2018), Kim (2020), Santos and Kostakis (2018)
	Role election	Baudlet et al. (2020), DiRose and Mansouri (2018), Hsieh et al. (2017)
	Incentive mechanism	Baudlet et al. (2020), Nabilou (2020), Allen and Berg (2020), DiRose and Mansouri (2018), van Pelt et al. (2021), Mattila and Seppälä (2018), Beck et al. (2018), Howell et al. (2019), Hsieh et al. (2017), De Filippi and Loveluck (2016), Merrill et al. (2020), Mosley et al. (2020), Werner et al. (2020), Yeung and Galindo (2019), Wright (2019-2020)
	Token burner	Merrill et al. (2020), Mosley et al. (2020), Wright (2019-2020)
	Platform modularisation	Baudlet et al. (2020), Rikken et al. (2019), Howell et al. (2019), Trump et al. (2018), Merrill et al. (2020)
	Participation permission	van Pelt et al. (2021), Beck et al. (2018), Hsieh et al. (2017)
	Transaction filter	Atzori (2018), Mattila and Seppälä (2018)

- *Forking*: After the voting for an improvement proposal from all related stakeholders, forking is conducted to implement accepted proposals in permissionless blockchains. It consists of two types of upgrade: (1) soft forks refer to backward-compatible software upgrades to a blockchain platform; (2) hard forks mean backward-incompatible upgrades that all stakeholders need to discard the previous version (Nabilou, 2020; Finck, 2018; DiRose and Mansouri, 2018; Mattila and Seppälä, 2018; Reijers et al., 2018; Ellul et al., 2020). Please note that there is also a special situation of forking: a subset of stakeholders are not satisfied with a particular governance decision, hence, they leave the current blockchain platform and then perform a hard fork to establish a separate blockchain instance as a means of veto De Filippi et al. (2020).
- *Consensus protocol*: The consensus protocol specifies how participants behave when interacting with a blockchain platform. The on-chain protocol is autonomously executed by blockchain stakeholders (Rikken et al., 2019). Reijers et al. (2018) discuss that consensus protocols can be regarded as a shared concept of authority within a blockchain platform. Allen and Berg (2020) state that the consensus protocols in permissionless blockchains can maintain and protect the platform by coordinating self-interested behaviours. Specifically, the definition of the authority, capability and responsibility of different roles is viewed as a significant part of the consensus protocol. For instance, in Dash blockchain, applying for *masternode* requires the ownership of at least 1000 dash tokens, to express the importance of a participant in the blockchain platform (DiRose and Mansouri, 2018). Baudlet et al. (2020) adopt importance scores calculation in the election of *honorary masternode*. These special node operators can vote for improvement proposals. Kim (2020) proposes a consensus mechanism in which the honest nodes can collaborate to defend the attack from malicious nodes.

- *Incentive mechanism*: In addition to consensus protocols, the incentive mechanisms, along with the inherent token distribution in permissionless blockchain platforms, are regarded as motivational factors for stakeholders to participate in governance-related activities (Nabilou, 2020; Allen and Berg, 2020; Howell et al., 2019; Yeung and Galindo, 2019). The embedded incentive mechanisms are usually based on game-theoretic insights, to encourage the operation of consensus protocol regarding the election of block validators (Baudlet et al., 2020; DiRose and Mansouri, 2018; Mattila and Seppälä, 2018; De Filippi and Loveluck, 2016). Furthermore, incentive mechanisms also include negative incentives, for instance, preventing or punishing violations based on stakeholders' behaviours. The blockchain community can burn a service provider's staked tokens via voting, if the terms of service are not fulfilled (Merrill et al., 2020). In Dash blockchain, proposing an improvement amendment costs 5 Dash tokens to restrict the spams (Mosley et al., 2020).
- *Platform modularisation*: Five studies mention that blockchain platforms need to perform modularisation to achieve flexible replacement of on-chain components, especially in permissionless blockchains. In particular, the movement from Proof-of-Work consensus protocol to Proof-of-Stake can adjust the allocation of decision rights, avoid energy consumption, and also address the scalability issues (Baudlet et al., 2020; Howell et al., 2019). The replacement of deployed smart contracts can improve the adaptability toward changes in application domains (Rikken et al., 2019). Similarly, the community can vote to adjust the infrastructure settings of a blockchain platform (e.g., block size, block interval) (Merrill et al., 2020). Finally, government agencies should be allowed to edit blockchain platforms under certain conditions to ensure conformance to laws (Trump et al., 2018).
- *Participation permission*: In certain blockchain networks, especially permissioned blockchains, new users are verified before joining the systems (van Pelt et al., 2021; Beck et al., 2018; Hsieh et al., 2017).
- *Transaction filter*: Transactions are the data entries of a blockchain platform, while block validators are viewed as having the capability to manually filter the transactions to ensure data source and quality (Atzori, 2018; Mattila and Seppälä, 2018).

Note that most primary studies distinguish governance of permissioned blockchains from permissionless blockchains. The major difference between these two types of blockchain is that permissioned ones may have clear authorities dominating the blockchain platform (van Pelt et al., 2021; Yeoh, 2017), and such difference leads to various best-practices for governance. Specifically, governing permissioned blockchains can refer to existing centralised decision-making models as only a few stakeholders are involved (Nabilou, 2020). Consequently, *participation permission* is usually applied in this type of blockchain platform to ensure security and privacy. Further, the roles in a permissioned blockchain are more of assigned than elected according to entities' off-chain positions. On the contrary, governance is more complex in permissionless blockchains where there is a higher level of decentralisation (Finck, 2018). In this case, effective negotiation and voting schemes are significant for the stakeholders to reach agreements for governance decisions, for instance, to finalise improvement proposals for the upgrade directions of a blockchain. *Platform modularisation* can be considered as an evolved version of *forking* to implement the accepted proposals. *Forking* may result in backward-incompatible upgrades, and split the overall blockchain ecosystem, while *platform modularisation* can achieve smoother adjustment and upgrades. In addition, *consensus protocols* and *incentive mechanisms* can manifest how the project teams regulate other stakeholders' behaviours, and value their contributions in permissionless blockchains. Other governance mechanisms (e.g., auditing, testing environment) are neutral, and can be applied to either blockchain type.

In addition to the above-extracted mechanisms, seven studies propose governance frameworks for blockchain platforms, as checkboxes to guide the future design and testing of blockchain. Katina et al. (2019) propose seven interrelated elements (philosophy, theory, axiology, methodology, axiomatic, method and applications), while Allen and Berg (2020) provide a descriptive framework to understand exogenous and endogenous governance in blockchain. John and Pam (2018) and van Pelt et al. (2021) both study on-chain and off-chain development processes to realise governance. Beck et al. (2018) formulate a blockchain governance framework that is centred on the three dimensions of decision rights, accountability, and incentives adopted from IT governance. Howell et al. (2019) focus on the membership and transacting relationships, and Werner et al. (2020) develop a taxonomy of platform governance for blockchain. Note that most frameworks discuss different blockchain decentralisation levels, while Allen and Berg (2020) focus on permissionless blockchains, Katina et al. (2019) and John and Pam (2018) do not explicitly refer to any specific blockchain type or decentralisation level.

Insight from RQ6: How is blockchain governance designed?

Source code management: The transparency degree of source code may affect the governance of blockchain. Currently, the code of many permissionless blockchain platforms (e.g., Bitcoin, Ethereum) are visible to the public, to accept contributions and also regulate the development process. Nevertheless, such openness allows the copy of code and hence, reduces the difficulty of *forking* to compete with the original blockchain.

Infrastructure design: Although the primary studies emphasise the decision-making process of blockchain upgrades (e.g., *improvement proposal* and *voting*), and regulation of human behaviours (e.g., *consensus protocol* and *incentive mechanism*), the design of infrastructure can also manifest governance. For instance, *sharding* means that a blockchain can be divided into multiple shards to process transactions in parallel, which includes how on-chain users are partitioned into different shards and how data is stored.

5. Discussion

Based on the research question results and our insights, in this section, we briefly discuss the relationship between blockchain governance and traditional governance theories. From RQ1 and RQ6, we have learned that blockchain governance is closely connected to IT governance, since the fundamental governance dimensions of IT governance can be adopted to blockchain governance. Further, we extended our review to existing governance frameworks and standards. We adhered to a previous study on data governance for platform ecosystem process management (Lee et al., 2018) for the choice of extant governance frameworks and standards. The selected literature are IT governance (Weill and Ross, 2004; Cobit, 2012), data governance (Ballard et al., 2014; Anon, 2017b), and platform ecosystem governance (Tiwana et al., 2010). According to S7 (Allen and Berg, 2020), we included corporate governance, and VISA (Inc., 2020) was selected since it is often compared to permissionless blockchains regarding financial transactions. Based on two primary studies (De Filippi and Loveluck, 2016; van Pelt et al., 2021), we selected open-source software (OSS) governance (O'mahony and Ferraro, 2007; De Laat, 2007).

IT governance (Weill and Ross, 2004; Cobit, 2012) ensures the design and use of information technology are aligned with the enterprises' organisational goals, while data governance (Anon, 2017b) focuses on how organisations/enterprises evaluate, direct, and monitor the use of data. Platform ecosystem governance (Tiwana et al., 2010) can provide platform-agnostic guidance on platform decision-making based on different environmental dynamics. As for corporate governance, VISA (Inc., 2020) emphasises the code of conduct to regulate employees' behaviour, and hence, to gain the trust of clients. OSS governance (O'mahony and Ferraro, 2007; De Laat, 2007) can be adopted to analyse the development and production process of software, where diverse volunteer contributors are included.

In IT governance and corporate governance, there is a clear source of authority, which is similar to the governance of permissioned blockchains. The governance structure usually has an explicit hierarchy, where the top executives can determine the governance mechanisms and other organisational or business policies and strategies (e.g., role assignment, and participation permission discussed in Section 4.6). This embodies a low decentralisation level. Data governance, OSS governance, and platform ecosystem governance all involve multiple organisations and a trusted agent among these organisations. This situation is similar to the governance of permissionless blockchains where blockchain stakeholders need to trust the code developed by the project team. Besides, the high decentralisation level of permissionless blockchains embeds certain governance aspects in the original design. For instance, incentive mechanisms and consensus protocols are the two core mechanisms for on-chain governance, motivating and regulating stakeholders' behaviour when they use blockchains. Although these mechanisms are designed and implemented by the project team, other stakeholders can determine the upgrade directions of a blockchain via voting, which highlights the notion of democracy in the decentralised environment of permissionless blockchains. In general, the governance of blockchain can refer to existing governance theories to obtain an initial understanding of governance structures, while it also needs further investigation for a comprehensive governance guideline that involves different decentralisation levels, and novel governance mechanisms to orchestrate diverse stakeholders.

6. Research agenda

In this section, we provide a research agenda of this topic as future study directions based on the performed SLR and our insights. Generally, the research agenda can be categorised into two main groups: high-level governance principles and best governance practices.

6.1. High-level governance principles

Future studies can propose governance principles to provide systematic guidance to blockchain practitioners and the broader community.

First, based on *social orders*, *human values and broader ethical responsibility*, and *law enforcement* discussed in RQ2 and RQ6, further study is required to ensure the blockchain ecosystem is compliant with legal regulations and ethical responsibilities. The governance of blockchain needs to comply with the legal regulations which set the minimum standards of human behaviours, which are dependent on where a blockchain platform is deployed. Researchers need to analyse the regulations issued by different countries and how to codify the rules into blockchain platforms. Further, future studies can focus on how to preserve human values and even manage broader ethical responsibilities which denote the maximum standards of human behaviours. For instance, how to develop blockchain as a responsible technology via proper governance approaches, to gain trust from diverse stakeholders?

Secondly, in RQ3, the governance of blockchain covers four objects: the platform itself, blockchain-based applications, on-chain data, and off-chain community, while RQ4 focuses on the development lifecycle of blockchain platform. Future studies can explore the governance processes throughout the blockchain ecosystem, by analysing the lifecycles of other governance objects.

Thirdly, future studies can integrate the governance dimensions adopted from IT governance (discussed in RQ1), and different blockchain stakeholders (identified in RQ5). Further refined research questions include: What decision rights are allocated to different stakeholders? How to ensure they are accountable? How are they incentivised? The mapping between blockchain stakeholders and their decision rights, accountability, and incentives is significant to derive the responsibility assignment matrix from the governance perspective.

Based on the SLR results and this research agenda, we propose a framework consisting of six high-level principles for blockchain governance, to support better governance processes in blockchain and blockchain-based applications. The principles are evaluated via case studies on five blockchain platforms. Please refer to Liu et al. (2022c) for a deeper dive on this work.

6.2. Best governance practices

Further research can investigate the actionable governance solutions for the design and operation of blockchain.

In RQ6, multiple governance mechanisms are identified and discussed. Based on the results, we summarise a list of best practices of blockchain governance.

- *Determine governance structures and authorities.* Permissioned blockchains have a clear governance structure that can map to the off-chain institutional hierarchy. Whilst, permissionless blockchains will usually face the dilemma that they claim to be democratic to attract participation, nonetheless, there are still authorities possessing certain additional decision rights. For instance, regulators may conduct audits or suspend the blockchain platform. In either decentralisation level, determine the governance structures can help properly allocate the decision rights and establish effective and efficient accountability process.
- *Reach consensus by selecting block validators.* Blockchain's integrity and consistency are ensured via consensus across all participants. Selecting block validators to append new blocks is a universal solution in different blockchain platforms. The validators are assigned by the authorities in permissioned blockchains, and selected by the codified criteria in permissionless blockchains.

Table 16
Pattern language overview (Liu et al., 2022a).

Name	Summary
Sharded chain	A blockchain platform can be divided into multiple shards to process transactions in parallel.
Scam list	The blockchain addresses of the entities who are deemed malicious are labelled, and listed to warn all stakeholders.
Token locker	A certain amount of blockchain tokens are locked for a specified time period, to secure the token holders' behaviour.
Network freezer	The blockchain platform is frozen that all on-chain business is suspended.
Carbonvote	Votes for improvement proposals are counted according to the tokens held by blockchain addresses.
Quadratic voting	For a blockchain account, submitting n votes for an improvement proposal costs n^2 tokens.
Liquid democracy	A stakeholder can delegate the voting rights to other stakeholders, and revoke the delegation to directly vote for improvement proposals.
Cross-chain token voting	Specific token holders in a blockchain platform can vote for governance-related issues of another blockchain platform.
Protocol forking	The software upgrades of a blockchain platform are implemented as forks of the blockchain.
Social contract	A social contract is deployed to select the future maintainers of a blockchain platform.
Digital signature	Transactions are digitally signed by users, to identify the transaction sources. The digital signature can be verified by other stakeholders.
Transaction filter	A filter can be utilised to examine the submitted transactions, to ensure the validity of transaction format/content.
Log extractor	Log extractor allows application providers to extract DApp usage information from blockchain.

- *Drive stakeholders' behaviours by providing incentives.* Incentives can attract participation and drive stakeholders' behaviours in on-chain activities. Contributions to blockchain operation will be rewarded by cryptocurrencies in many permissionless blockchain platforms. In addition, this practice can be extended to the penalties of violations, to restrict stakeholders' behaviours.
- *Ensure upgradability while avoiding affecting blockchain's properties.* A blockchain platform needs upgrades to implement new functionalities, and conform to industry specifications and legal regulations. Forking is a reluctant action that may affect the fundamental properties of blockchain, e.g., immutability. Decoupling and modularising the architectural components of a blockchain platform can help achieve smooth on-chain protocol replacement and upgrade instead of forking.
- *Preserve democracy by casting votes.* In many permissionless blockchain platforms, referendums are held by the blockchain project team to finalise improvement proposals. Token holders are allowed to vote to preserve democracy, since they are regarded the contributors to blockchain operation. Note that additional rules may be applied to the voting, to preserve other attributes, e.g., security, fairness, and participation rate, etc.

Future studies can review existing blockchain platforms, to summarise the reusable process and patterns for blockchain governance. A pattern collection and related decision models are required to analyse the trade-offs when leveraging different governance approaches. Based on the SLR results and the experience of designing the blockchain governance framework, we present a list of patterns for blockchain governance in Table 16. Please refer to Liu et al. (2022a) for more details of the pattern collection.

Furthering the above remark, practitioners need to consider how blockchain systems are designed to enable proper governance. A governance-driven software architecture can help architects operationalise governance approaches in the future design and development of blockchain-based systems. Based on the results of this study and our subsequent works (Liu et al., 2022c,a), we present a simplified governance-driven blockchain software architecture in Fig. 3, by adopting and extending an existing blockchain reference model (Anon, 2022), and integrating the pattern collection into this model. Note that the reference architecture elaborates and refines the platform layer and data layer discussed in RQ3. The architecture consists of infrastructure layer, platform layer, API layer, user layer, and cross-layer functions. Specifically, each blockchain node implements the platform layer and API layer locally, while the infrastructure layer and cross-layer functions are distributed among all nodes. Please refer to Liu et al. (2022b) for more details of the reference architecture.

We also notice that many primary studies do not evaluate the governance mechanisms discussed in RQ6. This is understandable since blockchain governance is difficult to quantify. We suggest that future studies can propose proper evaluation methods for blockchain governance solutions. For instance, a maturity model can serve as a benchmarking tool to understand the degree of governance in certain blockchain platforms.

Table 17
Selected primary studies.

ID	Ref.	Title	Author	Year	Source
S1	Bao et al. (2019)	An Auditable and Secure Model for Permissioned Blockchain	Bao et al.	2019	ACM
S2	Baudlet et al. (2020)	The Best of Both Worlds: A New Composite Framework Leveraging PoS and PoW for Blockchain Security and Governance	Baudlet et al.	2020	IEEE
S3	Nabilou (2020)	Bitcoin Governance as a Decentralised Financial Market Infrastructure	Nabilou	2020	Google Scholar
S4	De Filippi et al. (2020)	Blockchain as a Confidence Machine: The Problem of Trust & Challenges of Governance	Filippi et al.	2020	Science Direct
S5	Katina et al. (2019)	Blockchain Governance	Katina et al.	2019	Google Scholar
S6	Atzori (2018)	Blockchain Governance and The Role of Trust Service Providers: The TrustedChain Network	Atzori	2018	Google Scholar
S7	Allen and Berg (2020)	Blockchain Governance: What We can Learn from the Economics of Corporate Governance	Allen and Berg	2020	Google Scholar
S8	Finck (2018)	Blockchain Governance (from *Blockchain Regulation and Governance in Europe*)	Finck	2018	Google Scholar
S9	DiRose and Mansouri (2018)	Comparison and Analysis of Governance Mechanisms Employed by Blockchain-Based Distributed Autonomous Organisations	DiRose and Mansouri	2018	IEEE
S10	John and Pam (2018)	Complex Adaptive Blockchain Governance	John and Pam	2018	Google Scholar
S11	Santos and Kostakis (2018)	The DAO: a million dollar lesson in blockchain governance	Santos and Kostakis	2018	Google Scholar
S12	van Pelt et al. (2021)	Defining Blockchain Governance: A Framework for Analysis and Comparison	Pelt et al.	2020	Google Scholar
S13	Mattila and Seppälä (2018)	Distributed Governance in Multi-sided Platforms: A Conceptual Framework from Case: Bitcoin	Mattila and Sepp̀aĺa	2018	Springer Link
S14	Azouvi et al. (2019)	Egalitarian Society or Benevolent Dictatorship: The State of Cryptocurrency Governance	Azouvi et al.	2018	Springer Link
S15	Rikken et al. (2019)	Governance Challenges of Blockchain and Decentralised Autonomous Organisations	Rikken et al.	2019	Google Scholar
S16	Beck et al. (2018)	Governance in the Blockchain Economy: A Framework and Research Agenda	Beck et al.	2018	Google Scholar
S17	Howell et al. (2019)	Governance of Blockchain and Distributed Ledger Technology Projects	Howell et al.	2019	Google Scholar
S18	Paech (2017)	The Governance of Blockchain Financial Networks	Paech	2017	Google Scholar
S19	Meijer and Ubacht (2018)	The Governance of Blockchain Systems from an Institutional Perspective, a Matter of Trust or Control	Meijer and Ubacht	2018	ACM
S20	Trump et al. (2018)	Governing the Use of Blockchain and Distributed Ledger Technologies: Not One-Size-Fits-All	Trump et al.	2018	IEEE
S21	Hsieh et al. (2017)	The Internal and External Governance of Blockchain-based Organisations: Evidence from Cryptocurrencies (from *Bitcoin and Beyond*)	Hsieh et al.	2017	Google Scholar
S22	De Filippi and Loveluck (2016)	The Invisible Politics of Bitcoin: Governance Crisis of a Decentralised Infrastructure	Filippi and Loveluck	2016	Google Scholar
S23	Fan et al. (2020)	MULTAV: A Multi-chain Token Backed Voting Framework for Decentralised Blockchain Governance	Fan et al.	2020	Springer Link
S24	Reijers et al. (2018)	Now the Code Runs Itself: On-Chain and Off-Chain Governance of Blockchain Technologies	Reijers et al.	2018	Springer Link
S25	Merrill et al. (2020)	Ping-Pong Governance: Token Locking for Enabling Blockchain Self-governance	Merrill et al.	2020	Springer Link
S26	Lee et al. (2020)	The Political Economy of Blockchain Governance	Lee et al.	2020	Google Scholar
S27	Wright (2019-2020)	Quadratic Voting and Blockchain Governance	Wright	2019	Google Scholar
S28	Ellul et al. (2020)	Regulating Blockchain, DLT and Smart Contracts: a Technology Regulator's Perspective	Joshua et al.	2020	Springer Link
S29	Yeoh (2017)	Regulatory Issues in Blockchain Technology	Yeoh	2017	Google Scholar

(*continued on next page*)

7. Threats to validity

According to SLR guidelines (Kitchenham and Charters, 2007; Zhou et al., 2016), threats to validity may be introduced during the review process and affect the whole study. In this section, we identify the threats to four different types of validity (i.e., construct validity, internal validity, external validity, and conclusion validity), and discuss the strategies we adopted to minimise their influences.

Table 17 (*continued*).

S30	Arribas et al. (2020)	Sandbox for Minimal Viable Governance of Blockchain Services and DAOs: CLAUDIA	Arribas et al.	2020	Springer Link
S31	Reshef Kera (2020)	Sandboxes and Testnets as "Trading Zones" for Blockchain Governance	Kera	2020	Springer Link
S32	Kim (2020)	Strategic Alliance for Blockchain Governance Game	Kim	2020	Google Scholar
S33	Mosley et al. (2020)	Towards a Systematic Understanding of Blockchain Governance in Proposal Voting: A Dash Case Study	Mosley et al.	2020	Google Scholar
S34	Werner et al. (2020)	Towards a Taxonomy for Governance Mechanisms of Blockchain-based Platforms	Werner et al.	2020	Google Scholar
S35	Erbguth and Morin (2018)	Towards Governance and Dispute Resolution for DLT and Smart Contracts	Erbguth and Morin	2018	IEEE
S36	Crepaldi (2019)	Why Blockchains need the Law Secondary Rules as the Missing Piece of Blockchain Governance	Crepaldi	2019	ACM
S37	Yeung and Galindo (2019)	Why do Public Blockchains Need Formal and Effective Internal Governance Mechanisms	Yeung and Galindo	2019	Google Scholar

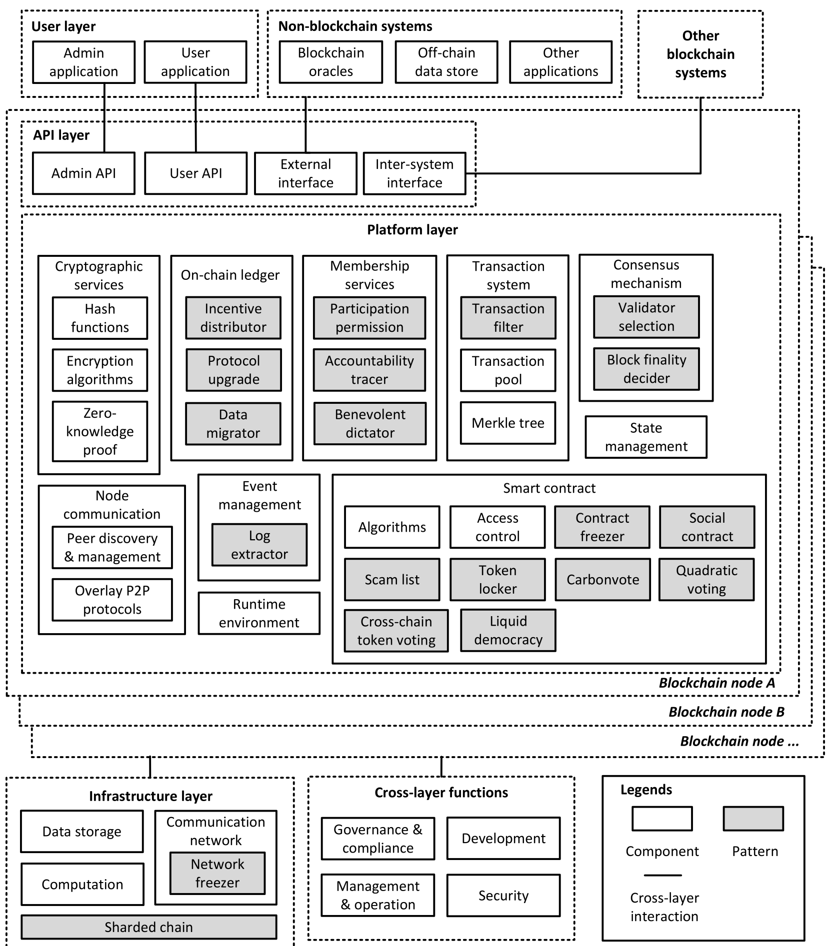

Fig. 3. Governance-driven blockchain software architecture (Liu et al., 2022b).

Construct Validity: The threat to construct validity would be the incompleteness of search strings, the ambiguity of the term *blockchain governance*, and the possible effects on study collection. Originally, we intended to include the synonyms of governance in the search strings, such as rule, administration, supervision, management, etc. These words indeed enriched the search results, nevertheless, we found that these synonyms brought ambiguity to the topic of blockchain governance. Consequently, to avoid misunderstanding, we chose a conservative strategy: only use two cognates of governance (i.e., govern, governing) as keywords. Regarding the ambiguity of *blockchain governance*, the initial retrieved articles included many studies about *governance through blockchain*. We mitigated this threat by applying the inclusion and exclusion criteria discussed in Section 3.4, and conducting title, abstract, and full-text screening in the selection process.

Internal Validity: Publication bias and inadequate size of samples may introduce threats to internal validity. Publication bias means that most studies with evaluation have positive results over negative results. Papers that have significant or positive results may have a higher possibility to be accepted than those

Table 18
Study quality assessment results.

ID	Ref.	QC1	QC2	QC3	QC4	QC5	Sum
S1	Bao et al. (2019)	1	0.5	1	1	1	4.5
S2	Baudlet et al. (2020)	1	1	1	0.5	1	4.5
S3	Nabilou (2020)	1	0.5	1	0.5	0.5	3.5
S4	De Filippi et al. (2020)	1	1	0.5	0	0	2.5
S5	Katina et al. (2019)	1	1	1	0	0	3
S6	Atzori (2018)	1	1	1	0	0	3
S7	Allen and Berg (2020)	1	1	1	0	0	3
S8	Finck (2018)	1	1	1	0	0	3
S9	DiRose and Mansouri (2018)	1	0.5	1	0	0	2.5
S10	John and Pam (2018)	1	1	1	0	0	3
S11	Santos and Kostakis (2018)	1	0.5	1	0	0	2.5
S12	van Pelt et al. (2021)	1	1	1	1	1	5
S13	Mattila and Seppälä (2018)	1	0.5	1	0	0	2.5
S14	Azouvi et al. (2019)	1	0.5	1	1	0.5	4
S15	Rikken et al. (2019)	1	0.5	1	1	1	4.5
S16	Beck et al. (2018)	1	1	1	1	1	5
S17	Howell et al. (2019)	1	1	1	1	0	4
S18	Paech (2017)	1	0.5	1	0	0	2.5
S19	Meijer and Ubacht (2018)	1	1	0.5	1	1	4.5
S20	Trump et al. (2018)	1	1	0	0	0.5	2.5
S21	Hsieh et al. (2017)	1	1	1	1	0.5	4.5
S22	De Filippi and Loveluck (2016)	1	1	0.5	0	0	2.5
S23	Fan et al. (2020)	1	1	1	1	0	4
S24	Reijers et al. (2018)	1	1	1	0	0	3
S25	Merrill et al. (2020)	1	1	1	1	0.5	4.5
S26	Lee et al. (2020)	1	1	1	1	0.5	4.5
S27	Wright (2019-2020)	1	1	0.5	0	0.5	3
S28	Ellul et al. (2020)	1	0.5	1	0.5	0	3
S29	Yeoh (2017)	1	0.5	1	0.5	1	4
S30	Arribas et al. (2020)	1	0.5	0.5	1	0	3
S31	Reshef Kera (2020)	1	0.5	1	1	1	4.5
S32	Kim (2020)	1	0.5	1	1	0	3.5
S33	Mosley et al. (2020)	1	0.5	1	1	1	4.5
S34	Werner et al. (2020)	1	0.5	1	0.5	1	4
S35	Erbguth and Morin (2018)	1	1	1	0	0	3
S36	Crepaldi (2019)	1	1	1	0	0	3
S37	Yeung and Galindo (2019)	1	1	1	0	0	3

with null or negative results, which might lead to a biased publication tendency. We carefully reviewed all included studies to mitigate the effects of this threat. Regarding the inadequate size of primary studies, we included book chapters and papers from online archives as they are all searched by Google Scholar. Four researchers reviewed these studies to ensure that they adhered to the predefined protocol.

External Validity: Threat to external validity refers to the restricted time span in our protocol. We searched papers published from 1 Jan 2008 to 3 Nov 2020. We chose 2008 as Bitcoin was proposed this year, which has boosted the development of blockchain. However, the history of blockchain technology can trace back to 1979 (Sherman et al., 2019). The excluded studies published before 2008 may affect the generalisability of our result.

Conclusion Validity: Threats may be introduced due to the bias in study selection and data extraction phases. During the inclusion and exclusion of searched studies, we found that a set of studies focusing on cryptocurrency governance, which is understandable as decentralised finance is the first well-known application of blockchain technology. We excluded some of them based on our predefined protocol, if the study is mostly discussing financial issues without proper design or process solution, tools or toolkit for the governance of blockchain. Bias in the data extraction phase happens as two researchers conducted the extraction from assigned studies and cross-validated each other's results. However, the extraction situation may vary, considering the different experiences and knowledge reserves of the researchers. For instance, whether framework development should be regarded as a governance solution for blockchain and reported in the paper. Another two independent researchers were consulted to reduce the biased influences in this procedure.

8. Conclusion

The importance of proper governance for blockchain is increasingly recognised in both industry and academia. To understand the state-of-art in this domain, a systematic literature review is performed in this paper. We collected 1061 papers and selected 37 of them as primary studies for this in-depth review based on a predefined protocol. After data extraction and synthesis, we present our study results and insights in this paper, aiming to provide guidance to researchers and practitioners for future studies in blockchain governance.

The primary studies reveal that the current main goals of governance are the adaptability and upgradability of blockchain and governance methods mainly focus on the planning and operation of blockchain platforms. From the extracted data, a common combination of governance mechanisms is the series of *improvement proposal*, *voting*, and *forking* to upgrade the blockchain platform. Meanwhile, the design and operation of *consensus protocol* and *incentive mechanism* are significant to on-chain autonomous governance by regulating stakeholders' behaviours. As blockchain governance is an ongoing topic, we provide the research agenda for future directions, including refining the lifecycle of different governance objects, studying the mapping between stakeholders and their decision rights, accountability, and incentives, and also analysing the legal regulations and ethical responsibilities. We plan to refine the governance-driven blockchain software architecture in the future.

CRediT authorship contribution statement

Yue Liu: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Qinghua Lu:** Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Liming Zhu:** Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Hye-Young Paik:** Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Mark Staples:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

The SLR protocol is available on Google Docs.[3] The extracted data is shown in Table 17, and the quality assessment results are demonstrated in Table 18. These information is also available as a Google Spreadsheet.[4]

[3] https://docs.google.com/document/d/1ZAMWbTj1OIqkIOtafqli6sa73oqhR1u5/edit?usp=sharing&ouid=101956301517606860290&rtpof=true&sd=true

[4] https://docs.google.com/spreadsheets/d/1X4mqQLibO1bhsCcDebpGY0QCSjLai-Yl/edit?usp=sharing&ouid=101956301517606860290&rtpof=true&sd=true

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