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RESEARCH ARTICLE

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Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions

Abstract Blockchain, a peer-to-peer, controlled, distributed database structure, has the potential to profoundly affect current business transactions in the construction industry through smart contracts, cryptocurrencies, and reliable asset tracking. The construction industry is often criticized for being slow in embracing emerging technologies and not effectively diffusing them through its supply chains. Often, the extensive fragmentation, traditional procurement structures, destructive competition, lack of collaboration and transparency, low-profit margins, and human resources are shown as the main culprits for this. As blockchain technology makes its presence felt strongly in many other industries like finance and banking, this study investigates the preparation of construction supply chains for blockchain technology through an explorative analysis. Empirical data for the study were collected through semi-structured interviews with 17 subject experts. Alongside presenting a strengths, weaknesses, opportunities, and threats analysis (SWOT), the study exhibits the requirements for and steps toward a construction supply structure facilitated by blockchain technology.

Keywords blockchain, smart contract, supply chain management, project management, construction

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1 Introduction

1.1 Digital transformation in the architecture, engineering, and construction (AEC) industry

Policymakers view digitalization as a key strategic response to common problems faced by the architecture, engineering, and construction (AEC) industry, such as low productivity, low value for money, poor health and safety quality, and frequent disputes (Linderoth, 2017; Jacobsson et al., 2017; Lavikka et al., 2018). In addition to offering promising opportunities for industry development, such as task automation (Matthews et al., 2015), data-driven decision making (Renz et al., 2016), and collaborative value creation with new forms of interaction, improved information sharing, and transparency among stakeholders (Schober and Hoff, 2016), serious arguments are also presented regarding digitalization to emphasize the widening digital divide between small and large firms (Dainty et al., 2017); to challenge organizational readiness for digitalization in the AEC industry; and to determine whether digitalization has delivered its promises (Khosrowshahi and Arayici, 2012; Miettinen and Paavola, 2014), and highlight the critical issues of data privacy, trust, and intellectual rights in data-rich environments (Sadeghi et al., 2015; Ahmed et al., 2017).

Accordingly, distributed ledger technologies (DLTs), including blockchain, are increasingly explored by practitioners and researchers as a potential solution to many of the challenges, which hamper the performance of the AEC

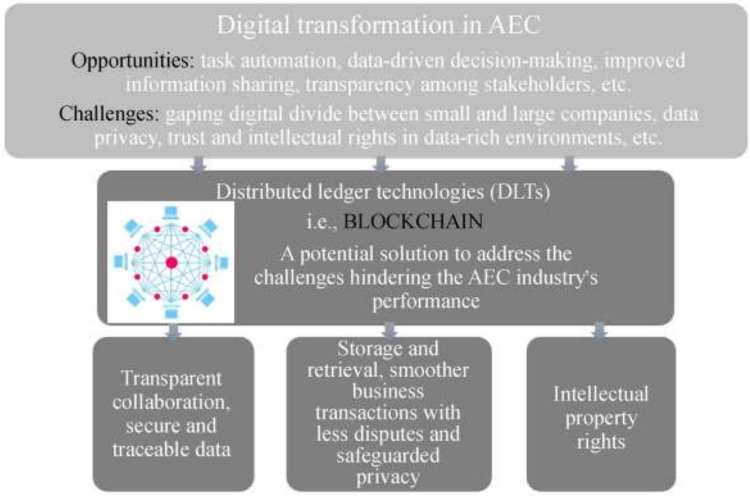

Fig. 1 Role of blockchain technology in the development of the digital transformation in the AEC industry.

industry, such as transparent collaboration, secure and traceable data storage and retrieval, smoother business transactions with less disputes, and safeguarded privacy and intellectual property rights (Li et al., 2018b; Penzes, 2018). Figure 1 shows the role of blockchain technology in the development of digital transformation in the AEC industry.

1.2 Blockchain technology

Blockchain is a peer-to-peer (P2P), distributed data structure that allows transactional data to be recorded chronologically and stored securely (Li et al., 2018a) in a sequence or chain of blocks via cryptography. It is a type of DLT with specific features. Blockchain was introduced in 2008 in a white paper on Bitcoin, the world's first cryptocurrency by Satoshi Nakamoto, a pseudonym for a person and a community (Nakamoto, 2008). A blockchain is basically an encrypted digital ledger that is stored in a public or private network on numerous computers. Blockchains consist of nodes located on those networks that use a common communication protocol; each node on the network stores a copy of the chain, and a consensus mechanism is used to validate transactions to ensure the immutability of the chain, that is, transactions cannot be changed (Bashir, 2017). These nodes contain a copy of encrypted data blocks (records) chained by hash codes to each other (Swan, 2015). Figure 2 shows that each block is connected next to each other, each block is linked to the next block in an irreversible chain, and transactions are blocked together, hence the term "blockchain".

The details of a transaction are transmitted to the network for validation and verification when a new transaction is created. If the nodes agree that the transactions in the block are valid in accordance with a governance protocol, then the block is attached to the blockchain, and the copy of each node of the blockchain is

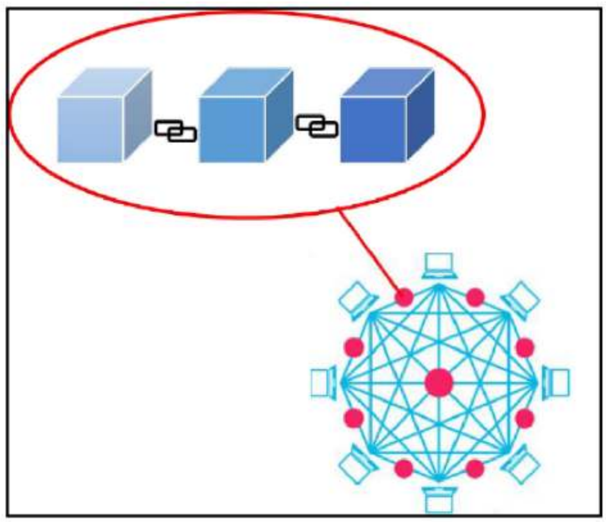

Fig. 2 Encrypted and chained data blocks are distributed over multiple nodes in blockchain.

updated accordingly (Cheng et al., 2017; Karafiloski and Mishev, 2017). The data blocks cannot be changed or deleted by a single actor upon gathering in a chain. No single party or intermediary manages the data, and all parties can see the entire data infrastructure. Each transaction is "permissionless" within the public blockchains, and users can remain anonymous. Usually, the network has an incentive mechanism to encourage participants to join. Examples of public blockchains are Bitcoin and Ethereum. Participants need to obtain an invitation or permission to enter within approved (private) blockchains. A consortium of members (consortium blockchain) or a single entity (private blockchain) manages access. Different types of blockchain are illustrated over the trust and anonymity continua in Fig. 3. The keywords of the blockchain are data security, cryptographic data

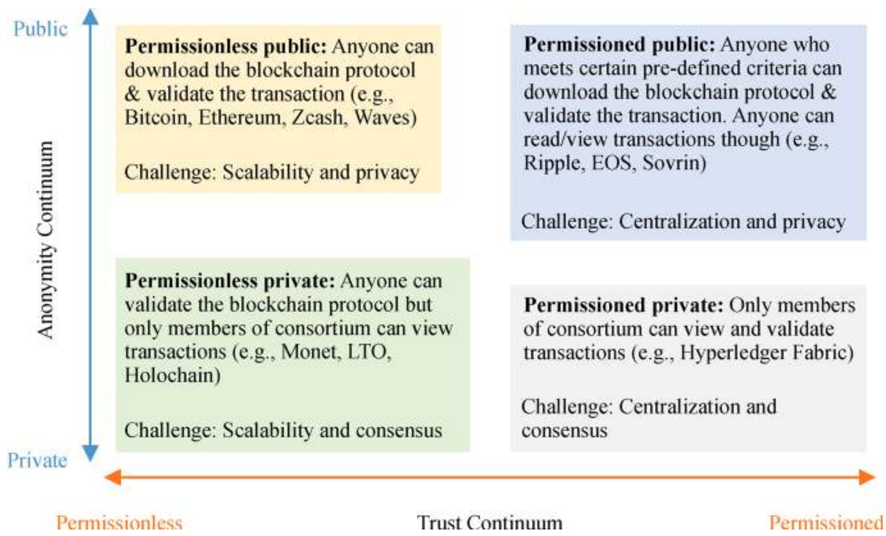

Fig. 3 Types of blockchain by trust and anonymity.

encoding, distributed data storage and consensus mechanisms, anonymity, data auditability/traceability, resilience, and fault tolerance (Hamida et al., 2017).

This study presents the findings of a research project that aims to understand the potential and challenges associated with the use of blockchain in the AEC industry by using primary data from 17 expert interviews and secondary information from scientific and gray literature. The strengths, weaknesses, opportunities, and threats (SWOT) analysis are presented and discussed, following a detailed literature review of the blockchain technology and its potential use in the AEC industry. By analyzing the results of the SWOT analysis and considering the potential implementation of the blockchain technology in the AEC industry, a conceptual framework for preparing construction supply chains for blockchain is developed. Furthermore, potential research areas for further development of the implementation of blockchain in the AEC industry are explored.

1.3 Blockchain technology and supply chain management (SCM)

Blockchain deployment outside finance has been largely experimental. However, supply chain management (SCM) is a strong fit for blockchain and will most likely be affected by it, where blockchain may facilitate the main SCM targets of cost (e.g., reduction of regulatory compliance costs and disintermediation of financial intermediaries), speed (e.g., digitalization of physical process), dependability (e.g., blockchain-based digital certification), risk reduction (e.g., only parties mutually accepted in the network can engage), sustainability (e.g., verification of sustainable practices), and flexibility (e.g., proof of provenance) (Kshetri, 2018). In addition to payments and value transactions, some of the main SCM-related practices for blockchain implementation are easing paperwork in SCM transactions with smart contracts, identifying counterfeit products, facilitating origin tracking, and operating the Internet of Things (IoT) in SCM transactions (Hackius and Petersen, 2017). According to Saberi et al. (2019) (p. 2120), “the blockchain technology can highlight and detail at least five key product dimensions: The nature (what it is), the quality (how it is), the quantity (how much of it there is), the location (where it is) and the ownership (who owns it at any moment).” The research in this field has been mostly conceptual to date with reviews, frameworks, and development analyses, mainly in the electric power industry, on blockchain applications to improve security (e.g., IoT and cyber-physical systems communications) and the traditional SCM fields, including logistics (Queiroz et al., 2019).

Blockchain can digitally integrate supply chains (Hofmann and Rüsch, 2017; Korpela et al., 2017). The technology will provoke considerable disruptions and force the SCM field to develop new business strategy models (Queiroz et al., 2019). Different from traditional supply chains, four major entities play roles in blockchain-based supply chains (Steiner and Baker, 2015; Saberi et al., 2019): Registrars, who provide unique identities to actors in the network; standard organizations, who define standards schemes or blockchain policies and technological requirements; certifiers, who provide certifications to actors for supply chain network participation; and actors, including service providers, manufacturers, retailers, and customers, who must be certified by a registered auditor or certifier to maintain the system trust.

Although blockchain can be incorporated in SCM practices, Wüst and Gervais (2018) warn practitioners in SCM to first check and validate the need for a blockchain-based solution. In addition to validating the need for blockchain, other challenges for blockchain in SCM include the following (Casey and Wong, 2017; Levine, 2017; Kshetri, 2018; Sulkowski, 2019): Complex global supply chain environment — the global supply chain operates in an environment where several actors comply with established, old, and diverse laws, regulations, and codes over multiple jurisdictions; integration challenges — implementation of blockchain consists of bringing all the relevant parties together, which can be a difficult undertaking in many cases; and fraudulent and manipulative activities — blockchain helps with virtual validation but not with catching real-life fraudulent activities, where the boundary between the physical and virtual world needs to be controlled as well. For the future research agenda for blockchain in SCM, blockchain best practices, main challenges and strategies used to overcome those challenges, blockchain implementation frameworks for SCM, the level of maturity of economies for blockchain, and the possible blockchain use in green/sustainable SCM can be investigated (Queiroz et al., 2019).

2 Applications of blockchain technology in the AEC industry

The AEC industry has broad and diverse potential applications for blockchain. Given that the technology is still immature, most of the applications in the literature are still conceptually focused on how the blockchain can improve a specific area instead of actual implementations or empirical works (BRE, 2018). Blockchain has been discussed with its immutable, distributed, and decentralized ledger structure as a tool to provide numerous solutions to the industry's challenges (Li et al., 2019a; Li and Kassem, 2019). Some researchers claim that the blockchain technology is a problem-seeking solution (Risius and Spohrer, 2017). Therefore, the industry should ensure that the technology is not applied merely because it is interesting or can solve some of its challenges; the need for implementation of blockchain in construction, and the consideration of potential alternatives should be evaluated thoroughly (Li et al., 2019b). Therefore, the restructuring of these areas and how cultural changes in the industrial sector are to be handled should be prioritized. Decision-making frameworks are available in the literature to support businesses in assessing whether a blockchain or DLT-based solution will be suitable for their needs (Mulligan et al., 2018).

Blockchain is not an independent solution; it is a data-recording infrastructure that can help support the digital transformation of the construction industry in connection with other technologies, such as building information modeling (BIM), the IoT, and smart contracts (Li et al., 2019a; Li and Kassem, 2019). Blockchain essentially works as a transparent layer underneath the transactions associated with those technologies. Some of these potential areas of application for the industry are facilitating collaboration and trust among stakeholders, P2P commercial transactions, digital passports, proof of ownership and rights, supply chain traceability, smart contracts, tokenization of value and assets, accelerated planning and design processes, digital twins, decreased transactional and financial costs, proof of provenance, reduced human errors and improved IoT applications, formation of decentralized autonomous organizations (DAOs), and easier/less costly insurance arrangements (Heiskanen, 2017; Kinnaird and Geipel, 2017; Turk and Klinc, 2017; Li et al., 2018a; 2018b; Penzes, 2018; Qian and Papadonikolaki, 2019). Li et al. (2019a) conducted a systematic literature review on conceptual models and practical use cases regarding blockchain and digital ledger solutions in the built environment, discretized in the areas of smart energy, smart cities/sharing economy, smart government, smart homes, intelligent transport, BIM in construction management, business models, and organizational structures. Blockchain can also solve some crucial problems and barriers to BIM, especially about confidentiality, disintermediation, provenance tracking, multiparty aggregation, inter-organizational recordkeeping, nonrepudiation, traceability, data ownership and intellectual rights, and change tracing (Klinc et al., 2017; Turk and Klinc, 2017). Wang et al. (2017) suggested blockchain-enabled applications to enhance the existing processes of contract management, SCM, and equipment leasing.

In addition to those potential applications, many emerging challenges during the adoption of blockchain in the AEC industry have also been highlighted as follows (Bocek et al., 2017; Koutsogiannis and Berntsen, 2017; Kshetri, 2017; Li et al., 2018b; 2019a): Authentication of data input in the immutable blockchain structure, legal gaps, unreliable and insufficient bandwidth capacity, human errors in coding of smart contracts, potentially enabling unethical and criminal activity, blockchain interoperability issues, significant energy consumption requirements by the nodes, exchange rate volatility in the cryptocurrencies, lack of organizational readiness, resistance to change, and insufficient skilled human resources for blockchain. Potential applications versus challenges facing the adoption of blockchain for the AEC industry are shown in Fig. 4. The discussions associated with potential applications and challenges for blockchain in the AEC industry overlap well with the general blockchain in SCM discussions, particularly at a large scale, with some minor differences relating to the specificity of the AEC industry, such as the apparent focus on the BIM processes as the virtual replica of an asset, the emerging digital twins concept, and data management/resilience issues in the industry, which are widely discussed and popular topics in the AEC domain.

To date, the real-world application of blockchain in the AEC industry, and consequently, the number of empirical outcomes associated with it has been limited. It is used to store sensor data from buildings in a trustworthy and

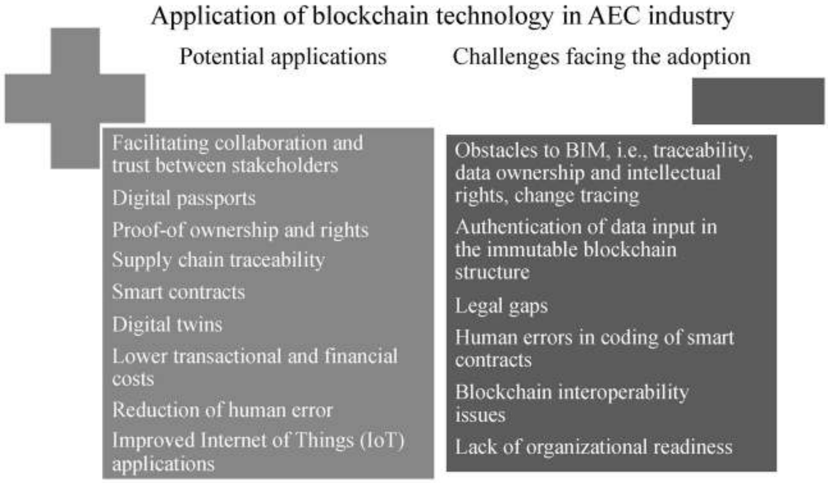

Fig. 4 Potential applications versus challenges facing the adoption of blockchain technology in AEC.

distributed way (Graphic, 2016). Tapscott and Vargas (2019) provided actual examples of blockchain use in the AEC industry over transaction registration at legally binding moments and building component specification recording on blockchain within a large-scale development project in the Netherlands. Penzes (2018) describes some early examples of blockchain application in the AEC industry over the TATA Steel Corporation's blockchain pilot for structural steel custody and audit trail in SCM, alongside some start-ups with smart contract provisions for the industry. Arup's recent report entitled *Blockchain and the Built Environment* also presents examples of some early piloting efforts in the field over recording land registry data, circular economy transactions at city scale, key site communication documents, BIM transactions, and material/component supply trails on blockchain (Arup, 2019). Ethereum, which is a cryptocurrency and a public/permissionless blockchain platform, through which developers can create decentralized applications, can host BIM applications (Salmon, 2015). The use of blockchain in co-housing projects has also been proposed (Lohry and Bodell, 2015). Li et al. (2019a) demonstrated blockchain's suitability for some supply chain payment mechanisms such as project bank accounts (PBAs). Hultgren and Pajala (2018) investigated how the technology could facilitate supply chain transparency and material traceability in the construction industry. There are also some blockchain-focused initiatives aimed to increase the adoption and investigation of the technology by the AEC industry, such as the Construction Blockchain Consortium and the Foundation for International Blockchain and Real Estate Expertise.

The study addressed the following research question: How can the construction industry leverage the potential of blockchain technology across its supply chain? Accordingly, the study sets the following research objectives:

- To understand the main strengths, weaknesses, opportunities, and threats of deploying blockchain technology in construction; and
- To develop a conceptual framework for the transformations (e.g., in skills, procurement, and business models) needed in the demand and supply chain of construction to deploy the blockchain technology.

3 Research method

The study is based on an interpretative research philosophy and critical realism to understand how the blockchain technology could affect construction and facilitate SCM (Maxwell and Mittapalli, 2010). Critical realism is coherent with mixed approaches, acknowledges the difficulty of the absolute objectivity of information, and seeks to ensure contextual validity (Shannon-Baker, 2016). The study is therefore explorative in nature with the aim of developing avenues for future research and implementation for blockchain-based SCM in the AEC industry. The sequential phases of the adopted research methodology are presented in Fig. 5.

Qualitative primary and secondary data are two main sources of information for this study. The primary data were collected through semi-structured interviews with 17 subject experts. The interviewees were selected on the basis of their expertise on the subject. Insights were obtained from diverse professional backgrounds. The sampling criteria include the following: (a) familiarity with the blockchain technology, (b) engagement with the digital technologies in construction, and (c) professional experience in the AEC or technology space. The participants' geographic location was not limited. The interviewees were contacted and recruited through professional connections, snowballing effect sampling, and social media contacts.

Table 1 provides a description of the interviewees'

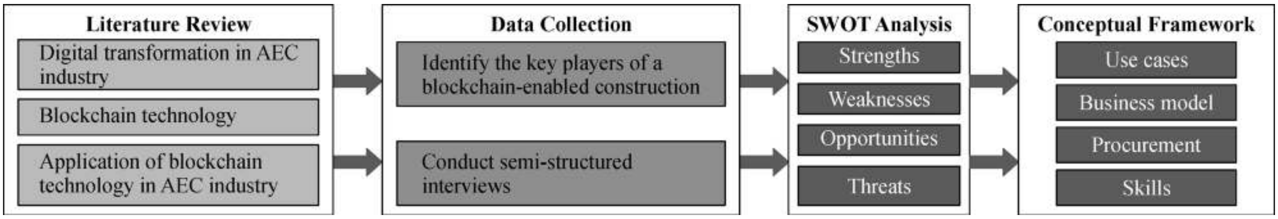

Fig. 5 Sequential phases of the adopted research methodology.

Table 1 Identifiers (ID) and profiles of interviewees and interview details

ID	Position	Organization	Industry	Location	Interview type	Interview duration (min)
1	Director	BIM Consultancy	Construction	London, UK	Face-to-face	38
2	Director	Entrepreneur	Technology	London, UK	Face-to-face	35
3	Founder	Nonprofit	Construction	Washington DC, USA	Face-to-face	50
4	Principal	Architecture & Law	Construction	London, UK	Face-to-face	42
5	Reader	University	Higher education	Cardiff, UK	Face-to-face	75
6	Consultant	AEC Consultancy	Construction	Berlin, Germany	Face-to-face	52
7	Consultant	AEC Consultancy	Construction	Glasgow, UK	Face-to-face	58
8	Consultant	AEC Consultancy	Construction	Manchester, UK	Face-to-face	60
9	Director	Law Consultancy	Construction	London, UK	Face-to-face	43
10	Director	Law Consultancy	Construction	London, UK	Face-to-face	43
11	Senior Consultant	Design and consulting firm	Engineering and Construction	London, UK	Online meeting	38
12	Director	Blockchain Development	Construction	Paris, France	Online meeting	42
13	Vice President	Blockchain Foundation	Construction	Washington DC, USA	Online meeting	36
14	CEO	Blockchain technology company	Construction	London, UK	Online meeting	37
15	Senior Researcher	Research institute	ICT	Gothenburg, Sweden	Online meeting	67
16	Head of VDC Infrastructure	Infrastructure	Construction	Jönköping, Sweden	Face-to-face	30
17	Sustainable development responsible	Project development and construction	Construction	Gothenburg, Sweden	Online meeting	22

profiles, their background, and the setting of the interviews. Ten recent industry and policy reports by Arup, the Centre for Digital Built Britain, Deloitte, PricewaterhouseCoopers, and the World Economic Forum regarding the introduction of the blockchain technology to the AEC industry were reviewed via desk research to collect further secondary data.

4 Empirical data presentation and SWOT analysis

The primary data were recorded, transcribed, analyzed through thematic content analysis, and grouped in the SWOT analysis format alongside the secondary data. The SWOT analysis is a business management tool that can be used to evaluate new technologies or directions for an organization or industry (Andersen, 2007; Gould, 2012). Table 2 illustrates the cumulative SWOT analysis for the use of blockchain in the AEC industry based on the empirical data set. The data in Table 2 are expressed in vivo (verbatim) and descriptive codes (Saldaña, 2009) of the primary and secondary data sources after coding them in categories related to strengths, weaknesses, opportunities and threats.

5 Data analysis and discussion

5.1 Strengths

The interviewees highlighted the strengths of the blockchain technology. They iterated that blockchain is a distributed ledger that stores data blocks mathematically

Table 2 SWOT analysis based on empirical data about blockchain technology in construction

Strengths	Weaknesses
Technical -Increased security in data storage and retrieval -Increased data traceability -Increased data transparency -Smooth handover of data -Data interoperability **Ecosystem** -Demonstrable outcomes in other sectors, such as FinTech and LawTech -Clear and time-stamped accountability chain -Immutability and tamper-less ledger of transactions -Able to skip the intermediaries (middlemen) -Authenticity of product, certificate and information -Tokenized ecosystem (utility or security token) consisting of solution engineers is a potential use case -Streamlined procurement and payment processes -True democratization of data and open-book procurement	**Structures** -Private blockchains are more prone to be modified/hacked -Robust data validation (proof-of-stake) systems are necessary -Private blockchains cannot communicate with each other -Scalability of blockchains -Trade-offs in public versus private blockchains (transaction speed, cost, level of trust/security, and data storage capacity) **Skills** -Lack of awareness at senior management level -Lack of skilled human resources **Industry adoption** -Lack of blockchain-based commercial or procurement frameworks -Lack of substantial exemplary use cases -Lack of understanding of requirements for different application opportunities -Lack of legal foundations/regulations -Lack of industry standards for blockchain -Insufficient evidence on the business case -Perceived high-risks and hesitation -Lack of incentives for small players -Volatile cryptocurrency values for public/semi-public blockchains -Need for expanding/integrating legacy digital systems in the industry with blockchain

Opportunities	Threats
New applications -The IoT will be of the prime beneficiaries of blockchains -Facilitate creating decentralized common data environments -Facilitate the creation of true DAOs -Facilitate alliancing/partnering-based procurement arrangements by enabling true open-book accounting -New forms of crowdfunding of assets are possible with blockchain **Industry adoption** -Large and public clients will be the primary beneficiaries of the technology -The trust layer just above the Internet for digital transactions -Accelerate the digitalization in the industry by overcoming concerns relating to security, ownership, and IP rights -Facilitate various applications in commercial, supply chain, and operations management in construction -Reduced commercial transaction costs -Information resilience (opportunity): Blockchains' immutable nature will render information resilience a key subject in the industry -Facilitate easier and correct taxation and insurance calculations **Competition** -Small- and medium-sized enterprises (SMEs) can form trust-based commercial/procurement frameworks on blockchains -SMEs can receive credibility and visibility from participating in blockchains -Direct payments to supply chain tiers by overcoming gatekeepers for interrupted value flow **Business environment** -Stronger government involvement to legitimize the implementation and usefulness -Faster financing and allocation of payments in projects -Protected IP rights -Increased capital movement and investments -New business model enablement -True sharing economy	**Publicaction** -Energy management and use -Powerful organizations and governments trying to dominate and control the blockchain environment **Technology maturity** -Limited view to the technology over cryptocurrencies -The current "noise" and hype—a too optimistic picture of the technology -Not knowing when to use the technology for what purpose **Acceptability** -Information resilience (threat): Blockchains' immutable nature increases system sensitivity to low-quality information. The need for trust will not disappear and information input will be focused on -Lack of governance in P2P transactions -Lack of involvement from professional institutions in policy-making -Traditional culture and lack of innovativeness -Legal, operational, and contractual fragmentation in the industry -Readiness of supply chains for true information transparency and streamlined/automated value transactions **Competition** -The existing digital difference between large organizations and SMEs may worsen -As a disruptive technology, increasing data transparency and P2P transaction possibilities may annoy some third-party intermediary organizations and service providers in the industry that may prompt them to undermine or control the technology

encoded and chained over multiple nodes for increased data security, traceability, and transparency. The technology provides a transparent and time-stamped chain of accountability, enabling the authentication of a product, service, transaction, document (certificate), and information. Moreover, blockchain allows smooth data transfer, and for public blockchains, data interoperability among different applications can be achieved for the AEC industry. Promising blockchain outcomes were also reported, such as FinTech and LawTech, for evidence of the technology's potential in other industries. The majority of the interviewees pointed out the potential capacity of blockchain technology to create a true sharing and P2P economy that will eliminate the need for third-party middlemen and intermediaries to nest on the value generated between the service provider and the purchaser. Hence, the interviewees believe that blockchain can help streamline the procurement and payment processes, and create true open-book accounting-based procurement arrangements, which are necessary for partnering and alliancing in the industry.

5.2 Weaknesses

Some interviewees pointed out that the full potential of blockchains can only be realized over public blockchains, because private blockchains do not differ greatly in terms of data security from distributed databases, making them prone to unsolicited changes in data and manipulations. In addition, private blockchains currently cannot communicate with each other. Nevertheless, for the sake of enhanced or centralized control of their blockchain applications over faster transaction rates, senior management in the AEC industry may opt for private blockchains. This condition is related to the existing lack of awareness at senior management level. The benefits and challenges of public and private blockchains should be properly communicated to senior management in the AEC industry. The current trade-offs between public and private blockchains in terms of transaction speed, costs, initial investment, level of data security, and data storage capacity require careful consideration and an informed analysis of business needs against the available blockchain types. Additionally, the diffusion of the blockchain technology will require the implementation of vigorous data validation systems and procedures in the industry as data authentication will become increasingly important.

The current state of the art in blockchain predicates that the number of transactions that public blockchains can handle per second is limited due to the limited size of allowable blocks for safety concerns. This technological limitation gives rise to the question on blockchains' scalability, considering that their use is aimed to be increased substantially in the near future alongside smart cities and digital twins. Lack of skilled human resources with a solid understanding of the AEC industry and blockchain development and their interfaces with law, engineering, and construction management is another major concern. The analysis of the primary and secondary data reveals that the absence of blockchain-based commercial or procurement frameworks and governance mechanisms for the AEC industry limit the operationalization of the technology.

No substantial exemplary use cases have been reported in blockchain-based asset tokenization, SCM, and procurement in the AEC industry. Gaps in legal regulations supporting blockchain-based supply chain and procurement mechanisms are hindering factors, limiting the evidence on business gains for the industry. Alongside the nonexistent industry standards for blockchain, the perceived high-risks and hesitation associated with the immaturity of the technology prompt AEC managers to adopt a "wait-and-see" mentality toward blockchain. For small companies, the lack of incentives for blockchain adoption is a serious barrier. Similarly, the volatile price of cryptocurrencies used to operate public and semi-public blockchains may put organizations off some applications of the technology. The amount of work and investment needed for expanding/integrating the existing legacy digital systems in the industry with blockchain is another concern.

5.3 Opportunities

The first set of opportunities from the blockchain technology adoption in the AEC industry is concerned with improvements in data systems and information flows. Blockchains are envisioned to constitute the trust layer just above the Internet for all sorts of digital transactions in the AEC industry. IoT-based applications will be the primary beneficiaries of blockchain in this arrangement, particularly in facilities management, smart cities, digital twin creations, procurement, and material and physical/digital component supply management. Additionally, blockchains can facilitate the creation of decentralized common data environments, such as blockchain-based cloud BIM platforms, for organizations, towns, cities, and regions in the future as a trusted intermediary for two-way communication. Consequently, blockchain may accelerate the digitalization agenda in the industry by overcoming significant digitalization barriers associated with trust, transparency, data traceability, intellectual property rights, and record keeping.

Although the interviewees confirmed the potential of the blockchain technology in facilitating smart contracts, e-procurement, creating secure electronic identities and records for construction organizations (proof of work), electronic or physical asset tracking for circular economy, collaborative procurement arrangements, crowdfunding (e.g., communities directly funding construction projects), and secure P2P data transactions for commercial or operational purposes (e.g., enabling BIM processes by reducing commercial disputes), the technological opportunities may not be easily translated into business opportunities. The traceability and transparency functions of blockchain are particularly relevant to large and public client organizations in the industry. Small organizations can form trust-based commercial/procurement frameworks and cooperatives on blockchains among each other to compete with large organizations. They can also receive credibility and visibility from participating in blockchains by rating and assessing collaborators in projects. Accordingly, new business models and existing relational contracts, and partnering/alliancing arrangements will be supported by blockchain, and the use of transparent commercial backbone as blockchain may enable true open-book accounting. Project financing and transaction costs will be reduced substantially, which will help with the inclusion of small organizations in project delivery.

Similarly, new asset funding opportunities will emerge with blockchain (e.g., crowdfunding of assets through tokenization). On the commercial front, enhanced financing and allocation of payments in projects can be realized through blockchain, which will help organizations record more manageable cash flows. Transactions completed on blockchain will facilitate accurate taxation and insurance calculations. Nevertheless, the interviewees explained that a strong government involvement to legitimize the implementation of blockchain is expected in the near future with increasing attention to the technology. Cross-border/regional capital movement and investments in the AEC industry may gain momentum due to the transparency induced by blockchain.

5.4 Threats

The anticipated high diffusion of blockchain applications and number of nodes involved in data transactions will also increase the energy requirements to maintain the nodes exponentially. The interviewees stressed that this condition will further deteriorate the already poor sustainability records of the AEC industry.

The lack of governance in P2P blockchain transactions may lead to commercial disputes or exploitations. The current lack of involvement and laissez-faire approach to blockchain by policy makers of the industry may further contribute to the poor governance of the technology. The existing digital divide between large and small organizations may worsen. Smaller organizations may have to be excluded from blockchain-based supply chain arrangements if they are not sufficiently prepared. If powerful organizations try to dominate and control the blockchain environment, a blockchain elite may emerge. Moreover, as a disruptive technology, increasing data transparency and P2P transaction possibilities may annoy some third-party intermediary organizations and service providers that capitalize on the status quo in the AEC industry, prompting them to undermine or control the technology.

The current “noise” and hype on blockchain draw a very optimistic picture of the technology with many overarching promises that may lead to disappointments in practitioners when they face with the realities. The technology is still maturing with operational issues. Limited view to the technology mostly around the popular cryptocurrencies or commercial arrangements will hamper blockchain’s potential. The interviewees agree that currently, the industry is excited about the technology but does not fully comprehend when to use it and its purpose for business value creation. The hype and generalizations introduced by some consultants do not help with clearing the minds in that sense. In line with this, the research on blockchain should be relevant and supportive of the operationalization of the technology and value creation through it for the AEC industry. Similarly, some interviewees questioned the readiness of the industry and its business culture for the transparency induced by blockchain and streamlined/automated value transfers. The information resilience requirement can be a threat and an opportunity in the future, because blockchain’s immutable nature will increase organizations’ and supply chains’ sensitivity to low-quality data. The need for trust will not disappear but will shift its focus to data input and resilience. The notorious traditional culture and slow take-up of innovations are threats against the blockchain technology, similar to many other technologies and emerging concepts in the AEC industry.

6 Discussion

6.1 Conceptual model for the preparation of construction supply chains for blockchain

Based on the findings from the SWOT analysis, the preparation of construction supply chains for blockchain requires a robust conceptualization and development of aligned operational processes with the roles and responsibilities of the stakeholders, over potential use cases that could disrupt the AEC industry through integrated digital business models, i.e., construction supply chains and logistics utilizing the technology, contractual and procurement procedures in project lifecycle, and skilled human resources for blockchain. SCM-focused working models for PBA, auction-based tendering, asset tokenization, BIM integration of DLT (blockchain), and material/component tracking are presently under development by researchers and practitioners, and may result in improvements that will reflect across all stages of the project and asset lifecycles. The use case PBA application considers the use of smart contracts to automate payments for a construction project financed by public funds. In the form of smart contracts, PBA could benefit from the blockchain technology. However, the use of blockchain does not fully remove the possibility of payment disputes on construction projects, but it could considerably reduce them by streamlining the payment process and lessening involvements over payment, thus increasing collaboration between project participants (Li et al., 2019a). The use case auction-based tendering (auction smart-contract) includes generating various types of decentralized auctions and receiving bids from pre-selected participants. Auction smart-contract bidding and tendering procedures will increase the efficiency, transparency, and auditability by any participating party, helping overcome unethical issues such as bid-shopping. The use case asset tokenization (crowd-sale smart-contract) comprises initiating decentralized fund-raising events, where tokens are delivered and can signify any virtual asset, such as shares, bonds, or any kind of entitlements for investment or donation. By using the crowd-sale smart-contract, raising funds for public projects for investment or donation purposes can be more efficient, transparent, and auditable for investors, donators, developers and governing bodies (Li et al., 2019b).

Through such developments and potential use cases outlined above, blockchain will force organizations to innovate and change their business models and will transform their organizational structures as feasible options to conventional approaches and traditional processes become available through blockchain. At an organizational level, DAOs will turn into business as usual via smart contracts and seamless, automated, and transparent business transactions. DAOs are organizations represented by rules encoded as a computer program and operate similar to conventional organizations but are not owned by anyone; they are automated and function in a decentralized manner on a P2P network. They integrate machine learning technology, and any profit originated from a DAO is built on a stake mechanism (Zhang and Wen, 2017). At the beginning of the organizational transformation process, the probable influence of the blockchain technology on the AEC business models can be uniformly spread over to the means projects are funded. Financial insurance for potential damages is usually needed regardless of the source of funding used for clients and contractors (e.g., working capital bank loans, lender and shareholder equity in the partnerships) (Li et al., 2019b). If blockchain can minimize such risks, it will reduce or even eliminate the requirement for such instruments (Underwood, 2016). Gambardella and McGahan (2010) pointed out that currently, technological solutions pursue commercial opportunities to initiate. As a source of finance for construction, crowdfunding/crowdsourcing is a commercial opportunity. Zamani and Giaglis (2018) highlighted that blockchain permits the exclusion of intermediaries. The technology will change the roles of individuals and internal business structures. Hierarchies will become much flatter with autonomous decision-making based on experience and skills, which minimize senior management engagement (Kypriotaki et al., 2015). Current roles will be concealed, whereas new roles will be generated such as that of a smart contract mediator (Tapscott and Tapscott, 2017).

Scholars suggest the utilization of smart contracts to support procurement and supply chain activities ensuing in automated payments, provenance tracking, contract administration, disintermediation, ownership and control of data, and redefining trust (Mathews et al., 2017; Barima, 2017; Zheng et al., 2017). The value that the blockchain technology can provide is deployed at the beginning of the procurement process and can facilitate the collaboration among various stakeholders. All transactions done by the participants will be stored and recorded on a blockchain during procurement and delivery, thus providing an oversight of the deliveries and enhancing the regulatory system (Li et al., 2019b). Integrating blockchain applications to the company's supply chain processes can revolutionize the procurement with embedded trust and transparency, streamlined payments, removed intermediaries, and improved security and productivity. Procurement functions leveraging blockchain can ensure that transactions will not expire, and data accrue timelessly for easy reference. Blockchains provide end-to-end transparency for any transaction, and considering that documents are indestructible and not vulnerable to data manipulation, all illegitimate considerations are blocked. Accordingly, tokenization of business processes and value may lead to new business models for managing projects, such as offering token-based incentives when project supply partners provide maintenance data in a correct and timely manner.

Beyond the hype and mainstream discourse, the general public is required to be educated about the benefits and functionality of the blockchain technology. People should be informed about the limitations and potential security and privacy issues of blockchain to make it an effective user-operated data-driven platform. Furthermore, to reduce resourcing as a possible obstacle to its adoption, vigorous progressive planning is required to prepare sufficiently skilled people to run the process (Li et al., 2019b). Robust regulation is needed to protect users from unskilled providers, deceit, and accountability (Sun et al., 2016). Legal and regulatory foundations should be established for the technology, such as blockchain-based procurement frameworks for public or large clients or the introduction of a common cryptocurrency for asset tokenization that may lead to the establishment of an asset-token exchange market. Lack of standards and sufficiently skilled IT staff are the key barriers to overcome within the industry (Kshetri, 2017). Active and new talent is required in the industry for successful implementation. A nationwide blockchain skills initiative can be launched to lead in capacity development about blockchain.

The identified strengths of the technology for the AEC industry match well with the general rhetoric about the potential benefits of blockchain for SCM in general. However, for the AEC industry, improved trust and transparency induced by digital ledgers can help mitigate three critical issues in construction supply chains: The low level of digitalization compared with other industries through increased trust and guaranteed intellectual property rights, high fragmentation in project procurement, and adversarial culture prevalent among supply chain actors. In the future, soft cooperatives among different sized organizations executing their transactions on blockchain can be formed in construction supply chains to jointly provide project solutions, products, components, services, or procure construction projects.

Beyond general discussions around the potential of or requirements for blockchain in SCM in construction, which seem to have been the main focus in the current AEC literature, more in-depth analyses are now required to elicit specific requirements and implementation conditions for specific applications. For instance, an asset tokenization application for crowdfunding for development projects by private investors will have different requirements from those of IoT-based off-site component supply tracking application on blockchain or smart contract application by a public client. This will encourage and facilitate early adopters of the technology. Alongside different organizational characteristics (e.g., public/private clients, investors, Tier 1 contractors, and SMEs), these investigations should consider different supply chain characteristics of different AEC sectors (e.g., building, civil, energy, and infrastructure). In this sense, it is important to objectively evaluate the strengths and limitations of the technology considering different blockchain options, and if there is actually a need for a DLT based solution in SCM arrangements. The apparent rise in blockchain pilots in SCM applications in other industries such as energy, retail and logistics will present important learning opportunities to study for the AEC industry.

Based on the SWOT analysis results and considering the potential implementations of the blockchain technology in the AEC industry, the afore-described conceptual framework developed is shown in Fig. 6, featuring suggestions for developing use cases, innovating business models, transforming procurement, and upskilling construction.

6.2 Potential research areas for blockchain in the AEC industry

Based on Fig. 6, the potential research areas for further development of blockchain in the AEC industry are summarized in Table 3.

First, with regards to developing use cases and experimenting with novel applications, cross-comparison with other industries and sectors is needed to understand the boundaries of the technology and determine the blockchain implementations that could be translated into the AEC industry. These steps could provide a basis from which cross industry benchmarking and the identification of best practices can be captured and used by practitioners. Ownership can be recorded for many types of assets such as buildings and can be made explicit for shared BIM models, leading to enhanced trust between parties. Linking the models with digital passports (ID) on blockchain involves elements within a built asset's BIM model linked to entries in the product passport blockchain, making it easy and transparent to retrieve information about the materials contained in various components and products (assets) when they reach end of life. It also applies to components and off-site/modular elements in the asset. Similarly, the identification of key project or asset information/document types to be blockchained over project life-cycle encompasses that blockchains can be used to trace key project or asset information, maintaining a record of ownership for key project life-cycle information/documents. Creating a framework for IoT and blockchain integration for the AEC industry comprehends an integrated IoT platform by using the blockchain technology to increase the effectiveness of IoT use in AEC supply chains. Creating a framework for BIM and

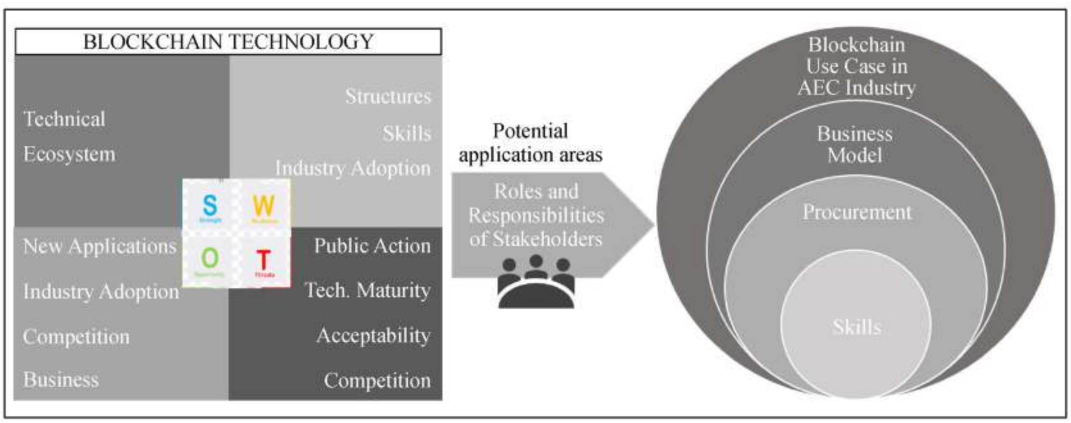

Fig. 6 Conceptual framework for the preparation of construction supply chains for blockchain in the AEC industry.

Table 3 Potential research areas for blockchain in AEC industry

Theme	Research area	Implementation for blockchain in AEC industry
Use cases	Cross-comparison with other industries and sectors	Blockchain implementations and translating them into the AEC industry
	Linking the models with digital passports (ID) on blockchain	Elements within a building's BIM model linked to entries in the product passport blockchain, making it easy to retrieve information about the materials contained in various components and products (assets) when they reach end of life
	Identification of key asset information/document types to be blockchained over lifecycle	Blockchains can be used to trace key asset information, maintaining a record of ownership for each asset over lifecycle
	Creating a framework for BIM and blockchain integration for the AEC industry	Development of a blockchain-aided BIM for sustainable building design and construction coordination and collaboration in multiple building life cycle stages
Business models	Demonstrating the business case for blockchain	Business roles and strategies (including business models) to fully exploit the technology
	Devising blockchain-based models for project management and governance	Business management process governance builds on appropriate and transparent accountability in terms of roles, responsibilities, and decision processes for different programs, projects, and operations; the blockchain might change governance toward a more externally oriented model of self-governance based on smart contracts
	Devising models for creating co-operatives on blockchain-based governance and commercial management systems	Blockchain technology supports novel data ownership and governance models with built-in control and consent mechanisms for commercial management systems
	Investigating the potential for DAOs in the AEC industry	DAO in the form of smart contracts include challenges involving security issues, unclear legal status, and technical limitations, as well as future trends regarding parallel blockchain
Procurement	Dynamics of trust in AEC supply chains	Collaboration and information sharing through changing the trust relationship by using blockchain
	Models for incentivizing the industry for good practice through blockchain	Providing and recording rewards over blockchain for every correct and on-time delivery
	Devising models for payment, tendering and procurement supported with blockchain	Smart contracts enabling a fair, transparent, and independently verifiable (auditable) tendering scheme
	Creating a framework for IoT and blockchain integration for the AEC industry	An integrated IoT platform by using blockchain technology to increase the effectiveness of supply chain in AEC
	Devising new procurement and tendering models on blockchain	Blockchain can revolutionize how the supply chain is valued and compensated, increasing the transparency and traceability of payments
Skills/Structures	Understanding types of critical project data that should be blockchained Data/information resilience for immutable blockchain	Protection of critical project data for managing data
	Understanding the provenance and ownership matters that can be blockchained	Blockchain-enabled devices allows for supply chain tracking of materials and services in real-time. Ownership can be recorded for many types of assets such as buildings and can be made explicit for shared BIM models, thus increasing trust among parties
	Identification of macro- and micro-level requirements for the penetration of blockchain in the AEC industry	From macro- and micro-level perspectives, the competitive forces and rivals existing in the AEC market

blockchain integration incorporates the development of a blockchain-aided BIM for sustainable building design and construction coordination and collaboration in multiple building life cycle stages, including data on BIM model ownership, approval, and update/modification history.

Second, demonstrating the business case for blockchain comprises the transformation of business roles and business strategies (including business models) to fully exploit the blockchain technology. Cases of business models that are successful in creating shared value through blockchain should be analyzed and spread. Devising blockchain based models for project management and governance involves business management process governance building on appropriate and transparent accountability in terms of roles, responsibilities, and decision processes for different programs, projects, and operations. Blockchain might change the project governance toward a more externally oriented model of self-governance based on smart contracts. After solving accountability, models should be devised for creating co-operatives on blockchain-based governance and commercial management systems. Hence, the blockchain technology supports novel data ownership and governance models with built-in control and consent mechanisms for commercial management systems. Ultimately, investigating the potential for DAO in the AEC industry embraces that DAO in the form of smart contracts include challenges involving security issues, unclear legal status, and technical limitations, as well as future trends regarding parallel blockchain.

Third, the dynamics of trust in AEC supply chains involve collaboration and information sharing through changing the trust relationship by using blockchain. Trust, as a complex construct of dynamic nature, will be an essential asset to support blockchain-based construction supply chain collaboration. Models for incentivizing the industry for good practice through blockchain involves giving and recording rewards over blockchain for every correct and on-time delivery across the supply chain. Devising models for payment, tendering, and procurement supported with blockchain includes smart contracts and enabling a fair, transparent, and independently verifiable (auditable) tendering scheme. The tendering scheme can be made fully open, autonomous, fair, and transparent by using smart contracts. Devising new procurement and tendering models on blockchain comprises that blockchain can revolutionize how the supply chain is evaluated, valued and compensated, increasing the transparency and traceability of payments on streamlined processes.

Fourth, considering the skills in the AEC industry, the work of various actors of the industry and how it can be supported by the blockchain technology should be determined. Hence, understanding types of critical project data or documents that should be blockchained involves the proper protection of critical project data for managing data and digital assets in a blockchain deployment. Accordingly, research on data and information resilience in the AEC industry for preparedness for the immutable blockchain infrastructure should be accelerated. Similarly, the understanding of the provenance and ownership across project life-cycle that can be blockchained includes blockchain enabled systems and applications allowing for supply chain tracking of materials and services in real-time. Finally, the identification of macro- and micro-level requirements for the penetration of blockchain in the AEC industry comprises the competitive forces and rivals existing in the AEC market for blockchain from macro- and micro-level perspectives. Figure 7 displays those potential implementation areas. Figure 8 demonstrates some key SCM applications of blockchains over the project lifecycle.

7 Conclusions

Blockchain has recently gained substantial attention from the AEC industry like many other industries. As a disruptive technology, it has strengths, offers great opportunities, carries some weaknesses, and possesses serious threats. By using primary and secondary data, this research project aimed to understand the current issues associated with creating blockchain-based construction supply chains and a conceptual framework for the preparation of such supply chains for blockchain in the AEC industry. The findings mostly agree with the recent literature investigating the implementation of blockchain in the AEC industry and SCM in general. Additionally, potential research areas for further development of the implementation of blockchain in the AEC industry were communicated. More research is needed to better understand the specific roles and responsibilities of stakeholders (e.g., governments, policy makers, clients, large and small organizations, suppliers, and end users) to overcome the identified threats and weaknesses of the technology. Furthermore, detailed requirement analyses are needed to realize and operationalize the strengths and opportunities of blockchain for the industry. Alongside those more conceptual discussions, blockchain use cases and pilots around those opportunities are needed for a better understanding of the implementation of the technology in the AEC industry. This study has shown that blockchain cannot be fully leveraged in the AEC industry without necessary adaptations and transformations in business models, procurement arrangements, and upskilling the industry. These stepwise changes are necessary for reaching a plateau of productivity in successfully importing blockchain in project life-cycle. To utilize the real value of this emerging technology for the AEC industry, beyond the hype, good-will, skepticism, and excitement currently surrounding it, an in-depth understanding of matters associated with the use cases, business models, procurement arrangements, value creation and industry skills/structures must be achieved.

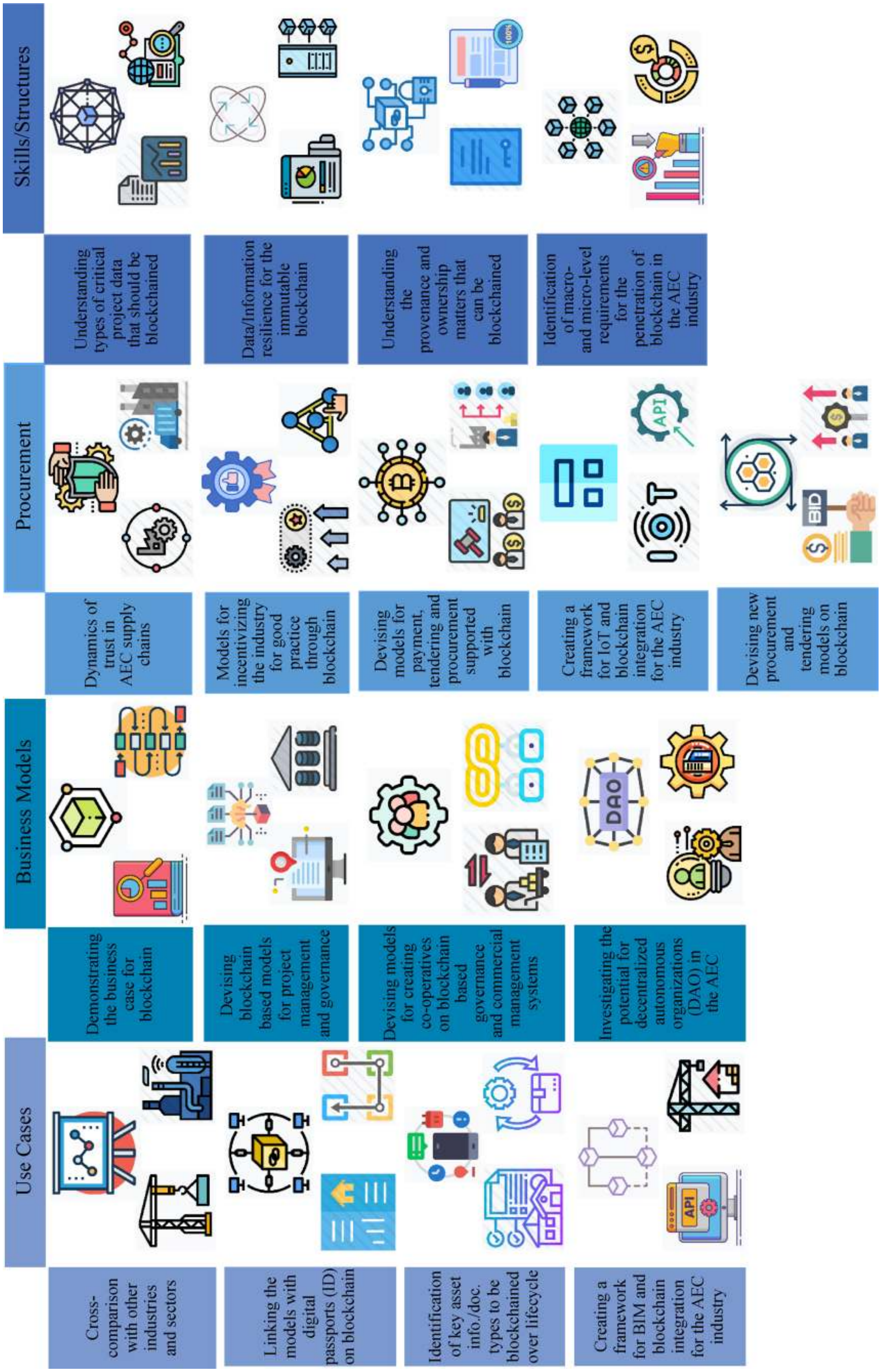

Fig. 7 Potential research areas of blockchain in construction supply chain.

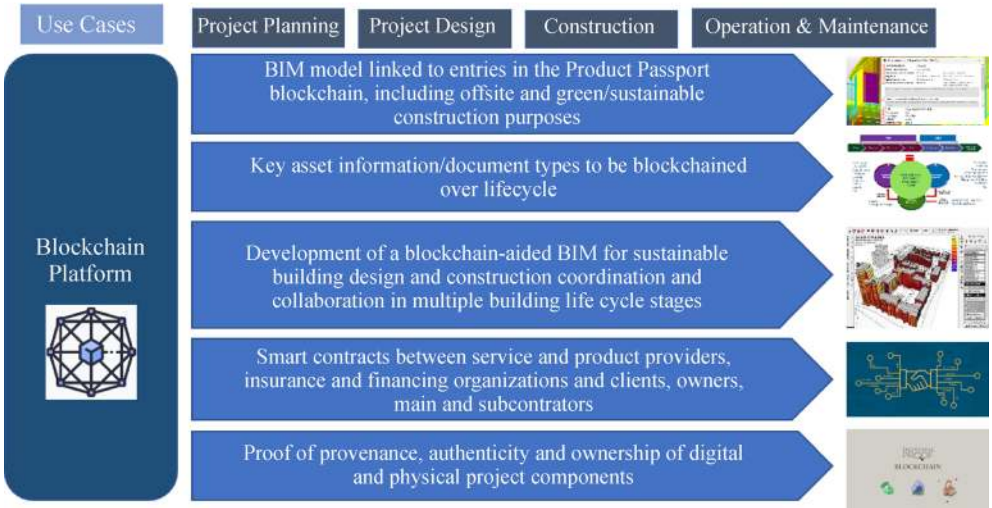

Fig. 8 Potential use cases of blockchain in construction supply chain throughout the lifecycle.

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