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Blockchain and lean construction: an exploration of bidirectional synergies and interactions

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ABSTRACT

Blockchain is a form of digital distributed ledger, referring to databases decentralized across numerous users, facilitating peer-to-peer transactions by eliminating or reducing the need for intermediaries to conduct, validate, or authenticate them. It is characterized by transparency, data immutability and traceability, and consensus processes validating cryptographic signatures. The architecture, engineering, construction, and operations (AECO) industry is increasingly interested in blockchain. Lean construction (LC), a value-focused production management concept, has long been challenging conventional project management practices in AECO. Lack of conversation, however, surrounds whether and how blockchain can (or should) impact LC developments – and vice versa. And if that impact exists – is it significant enough to create value for the related stakeholders? This article offers a conceptual synergistic framework of interactions between blockchain and LC, which can facilitate an understanding on whether there is value in their combined use. A systematic literature review and analysis serve as the foundation of this research. The findings show that LC can be facilitated by blockchain through trust building for relational procurement, data recording for some key activities (e.g. offsite construction, Last Planner System), and streamlining some non-value activities (e.g. payments). In return, blockchain can gain relevance for project management practices when it is defined and implemented in a LC framework. Also, LC can help improve blockchain-related workflows and decision making.

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Lean construction; distributed ledger technology; blockchain; framework; synergy

Introduction

The interest in using the specific distributed ledger technology called blockchain in the Architecture, Engineering, Construction, and Operations (AECO) industry has been rising. Nevertheless, that interest is still nascent, with discussions on blockchain implementation for AECO being accelerated only after 2015 (e.g. see Cardeira, 2022). Several AECO fields that are currently being actively discussed in connection to blockchain – such as management of stakeholders, contracts, information, project lifecycle, and procurement and supply chain, as well as smart cities, sustainability, decentralized organizations, and integration with other technologies like Building Information Modelling (BIM) and the Internet of Things (IoT) (Xu, Chong, & Chi, 2022). Proponents of blockchain claim that the technology's potential in increasing trust, transparency, provenance, and security in multi-party transactions can help AECO overcome some of its persisting challenges (e.g. productivity, smooth stakeholder collaboration), as well as eventually enable new income streams and business configurations

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(Li, Greenwood, & Kassem, 2019). Moreover, it can potentially facilitate the much-hyped further digitalization of the industry – however, while relevant use cases and blockchain ecosystems are fast expanding, those potential benefit claims are yet to be robustly verified in real-life conditions (Tezel, Febrero, Papadonikolaki, & Yitmen, 2021).

A much more mature concept and research field focusing on overcoming such persistent AECO challenges is lean construction (LC). LC was initially conceived as the adaptation of the lean management principles and techniques initially developed in Japanese car manufacturing, into AECO (Koskela, Howell, Ballard, & Tommelein, 2002) – but has since evolved into a research and practice area of many context-aware processes and methodologies (Tzortzopoulos, Kagioglou, & Koskela, 2020). LC can offer an alternative to more conventional project management practices, is supported by specific tools like the Last Planner System (LPS) and visual management, as well as management and procurement practices (such as relational contracts), and digital technologies like BIM, and is guided by fundamental ideas (e.g. waste reduction and variability continuous flow) (Sacks, Koskela, Dave, & Owen, 2010; Tezel, Koskela, & Aziz, 2018).

Compared to blockchain in AECO, LC is more established with a track record of academic and practitioner works demonstrating benefits for AECO in different contexts. Nonetheless, LC is not exempt from criticisms, already starting in the 1990s (e.g. see in Green, 1999). Evidently, several such criticisms still persist, such as LC lacking clear definitions, the positive bias in its narratives, and its occasional closed community feeling (e.g. see in Kifokeris, 2021). Moreover, to tackle several current challenges, LC needs to view them through a requirements-driven lens (Kifokeris, 2021) – which could include the contextually sensible application of a nascent technology like blockchain. Common themes in LC discussions that seem to be relevant to potential blockchain applications in the AECO fields mentioned earlier, can include improving stakeholder trust, enabling process transparency (Sacks, Treckmann, & Rozenfeld, 2009), automating non-value-adding activities (Akinci, Fischer, & Zabelle, 1998), fostering continuous improvement through efficient record keeping (Li, Wu, Zhou, & Liu, 2017), integrating BIM and LC (Sacks et al., 2010), and adopting prefabricated systems (Lu et al., 2021).

Such considerations thus raise the question: What are the synergies and interactions between blockchain and LC (and vice versa) – and is there any significant value in integratively implementing both? This paper aims to initiate the addressing of this question by exploring the two-way interaction between blockchain in AECO and LC. To the best of the authors' knowledge, such potential interactions have scarcely been explored in the literature to date. This exploration is deemed necessary as both concepts can contribute to each other, leading to new research and implementation routes. The paper's aim is realized by proposing a conceptual blockchain and LC synergistic interaction framework. The elements of the framework are explained in detail, along with their impact potentials in practice. Similar conceptualizations exploring the synergies between LC and other technologies have previously been useful for determining future research and application directions (e.g. see Sacks et al. (2010) for BIM, or Rosin, Forget, Lamouri, and Pellerin (2020) for Industry 4.0).

The rest of the paper is organized as follows. The ensuing section presents the theoretical background of the work through a literature review on blockchain for AECO, LC, and the few early studies featuring some discussion regarding their interaction. In the third and fourth section, the methodology and the interaction framework are presented respectively. The paper concludes with a discussion of the framework elements (incl. theoretical contributions and practical implications), as well as some final remarks.

Literature review

Blockchain fundamentals

With the use of distributed digital ledger technologies (DLTs), transactions such as data exchange between peers can be processed, validated, or authenticated without the need – or a reduced need – of involving a central authority (Li et al., 2019). Blockchain, first defined as the underlying technological infrastructure for Nakamoto's (2008) cryptocurrency Bitcoin, is a common type of DLT. With blockchain, transactions are recorded as a chain of interconnected data blocks, with the cryptocurrency being merely the system's functioning token and not the technology itself (Nakamoto, 2008). Essential characteristics of the Bitcoin blockchain are: (i) decentralization across a peer-to-peer (P2P) computer node network; (ii) data immutability once the blocks are chained; (iii) dependability because every node has the same (algorithmically verified) data copy; and (iv) transaction authentication through a proof-of-work method using a cryptocurrency (Bitcoin) (Nakamoto, 2008).

Beyond Bitcoin, blockchain transactions refer to distributed copies kept synchronously by computer nodes with transparent P2P transactional access, where such access is facilitated by cryptographic signatures authenticated by a consensus process (Li et al., 2019). Aside proof-of-work, other algorithmic consensus protocols have been developed to address authentication – such as proof-of-stake, proof-of-authority, ripple protocol consensus, delegated proof-of-stake, stellar consensus protocol, and the proof-of-importance (Wadhwa, 2020). Different consensus protocols are practically translated to different characteristics of blockchain decentralization topologies (from public, fully decentralized permissionless blockchains, to private, partially decentralized permissioned blockchains) (Wadhwa, 2020). Regardless, where high levels of trust, data security, immutability, transparency, and a multi-user consensus are desired, blockchain applications supporting decentralization (even partially) can be favored over fully centralized databases; for AECO, these desired attributes are relevant to, e.g. data provenance issues of collaborative BIM models (Liu, Han, & Zhu, 2023), or construction contract management (Zhang, Liu, Rahman, & Zhou, 2023). These applications typically take the form of smart contracts (i.e. computer protocols that can facilitate, automate, verify, or enforce terms and clauses (Cuccuru, 2017)), or digital tokens that signify value or ownership (Scott, Broyd, & Ma, 2021).

Blockchain in AECO

Published blockchain-related research within AECO emerged in 2015 (e.g. early studies such as Cardeira, 2022). Since then, there has been a sharp increase in the relevant research activity. Nevertheless, prior to 2019, such research tended to be highly conceptual and hypothetical (Xu et al., 2022). Relevant studies have become more elaborate since 2019, featuring built frameworks, prototypes, and even a few base-level use cases (Kifokeris & Koch, 2022; Tezel et al., 2021; Xu et al., 2022). Given these requirements and considering the classifications provided by domain-significant and current publications, prominent AECO fields where applying blockchain can potentially create value based on its attributes (Scott et al., 2021), are:

- Contract management (Liu et al., 2023; Xu et al., 2022; Zhang et al., 2023), including using smart contracts (Ameyaw et al., 2023).
- Information management across project management teams (Xu et al., 2022).
- Project lifecycle management (Xu et al., 2022), with the added consideration on the circularity of construction materials, components, processes, and even business models (Elghaish, Hosseini, Kocaturk, Arashpour, & Ledari, 2017).
- Production processes, including industrialized construction (Lee, Wen, Choi, & Lee, 2023; Xu et al., 2023a).
- Stakeholder management (Xu et al., 2022).
- Intelligent systems (Xu et al., 2022).
- Integrating blockchain with other technologies (Xu et al., 2022), such as digital twins (Jiang et al., 2023; Zhao, Chen, & Xue, 2023).
- Procurement, supply chain and logistics management (Elghaish et al., 2017; Kifokeris & Koch, 2020, 2022; Scott et al., 2021; Tezel et al., 2021; Xu et al., 2022; Yoon & Pishdad-Bozorgi, 2022).

- Decentralized autonomous organizations (DAOs) for AECO (Lombardi & Dounas, 2022), focusing on implementing cryptoeconomics (Dounas, Lombardi, & Jabi, 2020) and data governance (Hunhevicz, Dounas, & Hall, 2022).

Additionally, the industry report by Arup (Nguyen et al., 2019) segmented the built environment into five markets (cities, energy, property, transport, and water) and then presented blockchain's potential in five subcategories in each market – e.g. smart cities integrated with the IoT (cities), energy microgrids (energy), sale and asset transactions (property), material passports (transport), and utility contracts and billing (water). According to the same report, most applications are still either in the conceptual or early prototype development stage, and commercialization is typically not expected before 2025 (Nguyen et al., 2019). Since that report, some early base-level use cases have emerged (Kifokeris & Koch, 2022), but the prediction of future commercialization still holds. Some studies also try to expand the analysis of blockchain readiness for AECO by mapping specific national contexts (e.g. China, in Gao, Casasayas, Wang, & Xu, 2022).

These studies share the insight that several blockchain attributes can enhance the value of AECO business models, stakeholder roles, organizations, and initiatives. P2P transactions, process simplification, integration of the material, information, and economic flows through automation, smart contracts, record immutability, security through decentralization, consensus protocols, and a decrease in intermediaries' role are some of these attributes (customized per case of implementation). The agglomeration of such insights to derive thematically cohesive blockchain implementation attributes in AECO, was informed by the literature review method itself; as will also be described in the following section, the studies were systematically reviewed in iterations with the concept-centric method augmented with units of analysis (Webster & Watson, 2002). Using this iterative process, on of the main concepts of the literature review, namely blockchain in AECO, eventually branched out into five units of analysis that pointed at topics and themes found across sizeable subsets of the total number of reviewed studies – which in turn translated into five main branches of implementation attributes where the potential benefits of blockchain adoption in AECO lie. Also depicted in Figure 1, those attributes are featured below, along with some indicative references:

- **Features (F)**, or the technology's essential characteristics. These include non-fungible tokens (NFTs) (Dounas et al., 2020), smart contracts (Ameyaw et al., 2023), interoperability, application programming interfaces (APIs), digital distributed ledgers (Li et al., 2019), crypto assets (including cryptocurrencies), throughput (processing rate), data storage and sequencing, and others (Hall, Hunhevicz, & Bonanomi, 2022).
- The consensus procedures' **algorithmic layout (A)**. The proof-of-work, proof-of-stake, delegated proof-of-stake, proof-of-authority, proof-of-importance, ripple protocol consensus, and stellar consensus algorithms are included, denoting different levels of decentralization and permission (Kifokeris & Koch, 2022; Wadhwa, 2020). Not all algorithms are explicitly suitable for all blockchain topologies (Kifokeris & Koch, 2022). For example, while proof-of-work can technically be used in private blockchains, that level of permission, where all nodes are supposed to know each other, would make this algorithm wasteful – proof-of-authority could be a better alternative (Xu et al., 2023b).
- **The permission or authorization levels (PL)** indicate the blockchain privacy settings. These include the public, consortium, hybrid, and private blockchains, arranged from the most open to the most controlled systems (Xu et al., 2023b). Those privacy settings can guide the choice for the consensus algorithm, as described above (Kifokeris & Koch, 2022).
- **Integration with other technologies (TI)** potentially implemented in AECO, such as BIM, IoT, intelligent systems, digital twins, digital building logbooks (DBL), and cloud storage (e.g. see in Elghaish et al., 2017; Li et al., 2021).
- **Application fields (AF)** in AECO, particularly in managing contracts (Zhang et al., 2023), information, design (Xu et al., 2022), production (Lee et al., 2023), project lifecycle (Elghaish et al.,

Figure 1. Potential attributes of blockchain implementation in AECO.

2017), stakeholders (Xu et al., 2022), energy, water, property (Nguyen et al., 2019), procurement and supply chains (Tezel et al., 2021), and production processes (Xu et al., 2023), as well as smart cities (Samuel, Javaid, Alghamdi, & Kumar, 2022), sustainability and circularity (Elghaish et al., 2017), and decentralized organizations (Lombardi & Dounas, 2022).

As mentioned earlier, there is feasibility for commercialized blockchain systems for AECO by 2025, with new implementation pilots reported at an increasing pace by practitioners and researchers (e.g. see in Nguyen et al., 2019). While concerns about the technology have been raised (e.g. its interoperability with other digital and cloud technologies, the available return-on-investment margins, long-term technology implications and needs, and a lack of legal and business frameworks) (Li et al., 2019), it showcases potential advantages that can render investments in relevant systems desirable.

Nonetheless, a return on investment would require blockchain systems to not only fit the specific business model of the AECO company that would like to use it (Kifokeris & Koch, 2022), but also have a bidirectional synergy with AECO-specific frameworks and domains to meet long-standing industry needs. This 'double fit' could be essential for a blockchain implementation that has a practical positive impact on AECO, as the technology itself can be considered as general-purpose (Filippova, 2019) – meaning that it is an 'empty vessel' until properly contextualized, with such a context potentially being offered by both the application case at hand, but also other AECO-specific frameworks. Notably, some studies (e.g. Elghaish et al., 2017; Kifokeris & Koch, 2022; Li et al., 2019) have highlighted the significance of contextualizing blockchain for addressing key contemporary issues faced by AECO, such as sustainability, affordable housing, trust, and transparency, as well as potentially integrating it with other AECO-related frameworks and domains.

However, specific integration conceptualizations are generally few and dispersed, with only a handful marginally exploring the potential synergy of blockchain and LC. LC could indeed provide a contextual frame and integration focus for blockchain in AECO, as it can serve as a project management backbone in enhancing the efficiency, quality, and value delivery to clients and end-users in AECO (Tzortzopoulos et al., 2020). Accordingly, Alonso et al. (2019) offered a digital twin platform where smart contracts might be used to cut down on production time, based on lean management ideas. According to Dakhli, Lafhaj, and Mossman (2019), LC principles can help in accurately specifying the production activities required for properly developing smart contracts. Using blockchain for an LC-induced reduction of process fragmentation when executing contracts was investigated by Di Giuda, Pattini, Seghezzi, Schievano, and Paleari (2020) and McNamara and Sepasgozar (2021). Hall et al. (2022) discussed how blockchain can lead to the formation of an Industry 4.0 compliant Integrated Project Delivery (IPD) governance structure, a collaborative procurement approach adopted within LC. Bolpagni, Gavina, Ribeiro, and Arnal (2022) further noted that blockchain capabilities can be combined with LC concepts to support IPD and nonlinear project management. Gholinezhad-Dazmiri, Aliasgari, and Hamzeh (2022) illustrated the practitioners' view that blockchain, despite its nascency, can render construction supply chains leaner and more transparent, secure, and traceable. Araújo, Costa, Corrêa, and Ferreira (2022) outlined the role of blockchain's data recording in facilitating LC through digital twins. Similarly, Jiang et al. (2023) demonstrated blockchain's role in establishing secure collaboration mechanisms between digital twins for leaner modular construction processes. Li et al. (2021), Jiang et al. (2021) and Loo and Wong (2023) created blockchain-based frameworks for smart product-service systems focused on off-site manufacturing and prefabricated construction. To this end, future directions for blockchain utilization in industrialized construction are smart contract management, addressing security issues, and achieving a faster approval process (Wang, Wang, Sepasgozar, & Zlatanova, 2022). Finally, Sbiti, Beddiar, Beladjine, Perrault, and Mazari (2021) envisioned a blockchain-streamlined information exchange within a framework merging BIM and LPS.

Lean construction in AECO

The schema in Figure 2, inspired by Thomsen, Darrington, Dunne, and Lichtig (2009), maps the four aspects of the LC domain. In Figure 2, those four aspects take the form of LC principles (P) in the centre, which then managerial (M), support tools and procedures (T), and procurement (Pr) practices leading to the practical realization of the LC principles (Tzortzopoulos et al., 2020). The management (M), tools (T) and procurement (Pr) aspects should be aligned with one another and guided by the LC principles. The explanation of the aspects in Figure 2, is based on the agglomerating the insights of the relevant reviewed studies featured in the bullets below:

- LC principles (P), or the basic ideas and characteristics of LC – including push/pull-based control, enhanced transparency and flexibility, continuous improvement, and standardized work (Sacks et al., 2010). Others focus on the value brought to the customer and how to reduce waste, variability, batch size, cycle time, and inventory (Li, Fang, & Wu, 2020; Tribelsky & Sacks, 2011).

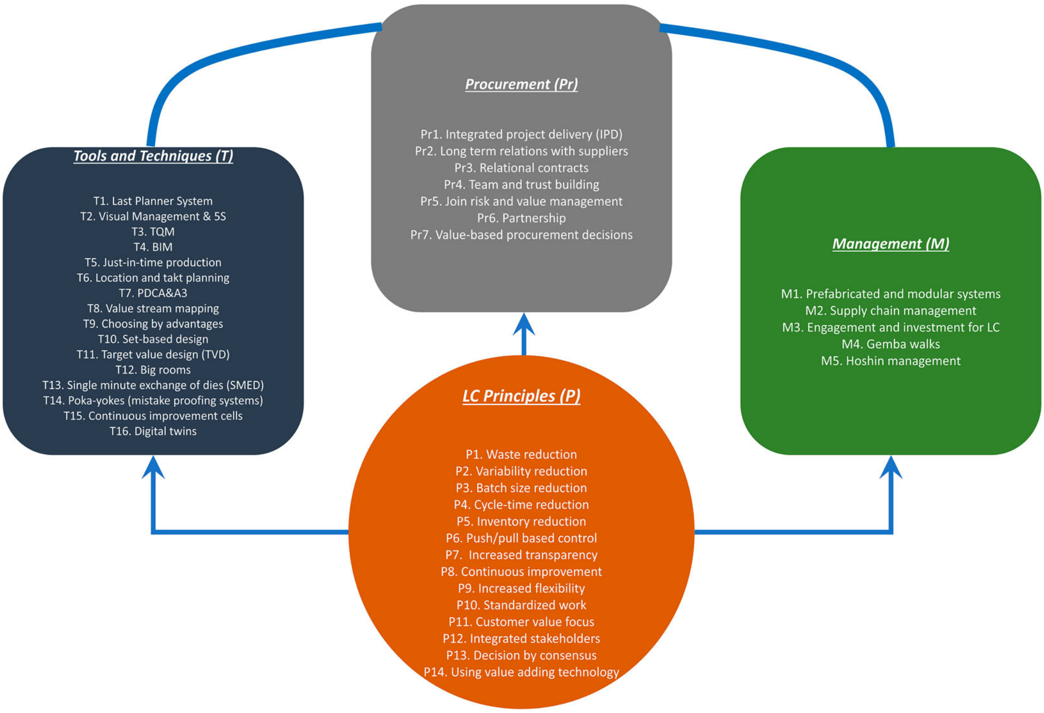

Figure 2. Conceptualization of LC over principles, tools and techniques, procurement, and management for AECO.

- Using prefabricated and modular systems, supply chain management techniques, engagement and investment in LC, Gemba walks, and Hoshin management, represent the LC implications for construction management (M) (Hairstans & Smith, 2018; Lu et al., 2021).
- LC tools and techniques (T), including 5S, TQM, BIM, digital twins, just-in-time manufacturing, location- and Takt-based planning, PCDA and A3, value stream mapping, choosing by advantages, set-based design, and others (Hamzeh, González, Alarcon, & Khalife, 2021; Kpamma, Adjei-Kumi, Ayarkwa, & Adinyira, 2018; Sacks, Brilakis, Pikas, Xie, & Girolami, 2020; Salem, Solomon, Genaidy, & Minkarah, 2006; Tezel et al., 2018).
- The implications of LC for procurement (Pr), including IPD, long-term relationships, relational contracts, team- and trust-building, among other things (De Melo, Do, Tillmann, Ballard, & Granja, 2016; Owen et al., 2010).

It should be added that, as mentioned in the Introduction, LC lacks clear definitions, and the four LC aspects in Figure 2 may subject to change by different LC conceptualizations. The depicted aspects are based on the authors' understanding of the reviewed literature.

The study on blockchain for AECO is still in its infancy, as demonstrated above – though it is increasing quickly, especially after 2019 (Scott et al., 2021). As such many related opinions and aspects have not yet been thoroughly examined in relation to LC. The focus of the studies under examination appears to be on technology issues that could barely affect AECO. This may imply that a sociotechnical and even sociomaterial turn in blockchain research for AECO (e.g. see in Qian & Papadonikolaki, 2021) should be more prominent.

On the other hand, there is mature and extensive research on LC. This could mean that LC has developed into a broad issue that encompasses practically all managerial facets in AECO. While this was not the original intent of LC, it is frequently the way it is defined in practice. Such a framing can present researchers with an analytical issue because even in this article, several of the things that are listed as being connected to LC (such BIM, supply chain management, modular systems, etc.) may be more general rather than LC-specific. Nevertheless, a constant focus on strong contextual framings, such as those found in pilot projects or use cases, may be a solution to this analytical difficulty – as well as providing a testbed for examining synergistic implementations of LC and blockchain. However, until such a pilot project and/or use case emerges, exploratory studies featuring conceptual synergies can be used as a theoretical and methodological foundation.

As such, the current study can take up this role. In this vein, the synergistic framework of integration between the blockchain and LC aspects shown in, correspondingly, Figures 1 and 2, is conceptualized in the section after the Research method.

Research method

To create a new conceptual framework for the LC-blockchain interaction, a systematic literature review augmented with units of analysis (Webster & Watson, 2002) was performed to evaluate the research output on LC and blockchain in AECO. The literature review was thus focused on qualitatively capturing the gap of interaction between the domains of LC and blockchain and was gauged to be completed when no new relevant concepts could be found (Webster & Watson, 2002). 'Lean construction', 'digital ledger technology', and 'blockchain' were the main concepts and keywords guiding the review. Then, along the course of the literature research, units of analysis (in the form of more keywords) such as 'information management', 'smart contracts', and 'value-based procurement decisions' emerged, which helped in underpinning more explicit points of integration and synergy – in a process described as an abductive loop (Bell, Bryman, & Harley, 2019).

The literature review was carried out in iterations, and its timeframe emerged along the concept-centric reasoning described above – which translated to commencing at 2015 (first mentions of blockchain implementation in AECO) and concluding in 2023. Nonetheless, some background references were published prior to 2015 (especially regarding LC), while most relevant blockchain references were published later than 2015, and predominantly from 2019. Based on that evolution, the review of the literature was mainly placed in 2019–2023 (save for a number of older references strengthening the study's background) and centred primarily (but not exclusively) on journal publications. The search strings corresponding to the searched concepts and units of analysis were used to assess 37 search engines with technical and/or managerial content. After omitting 29 engines featuring irrelevant results, the ones returning most relevant sources were Taylor & Francis Online, Google Scholar, BASE, Semantic Scholar, Mendeley, WorldWideScience, Scopus, and the International Group for Lean Construction (IGLC) database. The searched terms were looked for using filters and Boolean operators in each publication (including their titles, abstracts, keywords, body texts, author affiliations, and references).

This process resulted in, initially, 615 results. Then, by applying inclusion and exclusion criteria (Dundar & Fleeman, 2017), those results were progressively filtered into the sources included in this study. Particularly, in the first inclusion-exclusion phase, most conference papers were excluded, and journal articles were kept – resulting in an intermediate sum of 304 publications. This criterion was implemented to exclude papers featuring early content that was later improved into journal articles, as well as focus on journal articles displaying higher quality than most conference contributions. As an exception, some high-relevant conference papers that were unique (i.e. not reworked into journal articles) were still included. In the second inclusion-exclusion phase, specific combinations of concepts and units of analysis (e.g. 'relational contracts' and 'smart contracts') deemed to better facilitate this study's research goal were sought in the publications of the intermediate sum. This led to excluding eventually irrelevant or marginally relevant studies, and finally to the 86 (out of a total of 90) references featured in this study – with the remaining four being the methodological references of the current section. The flowchart on Figure 3 illustrates the above-described literature review process.

Following the literature review and the insights derived thereof, the LC-blockchain synergistic framework was conceptualized according to the abductive reasoning of qualitative research –

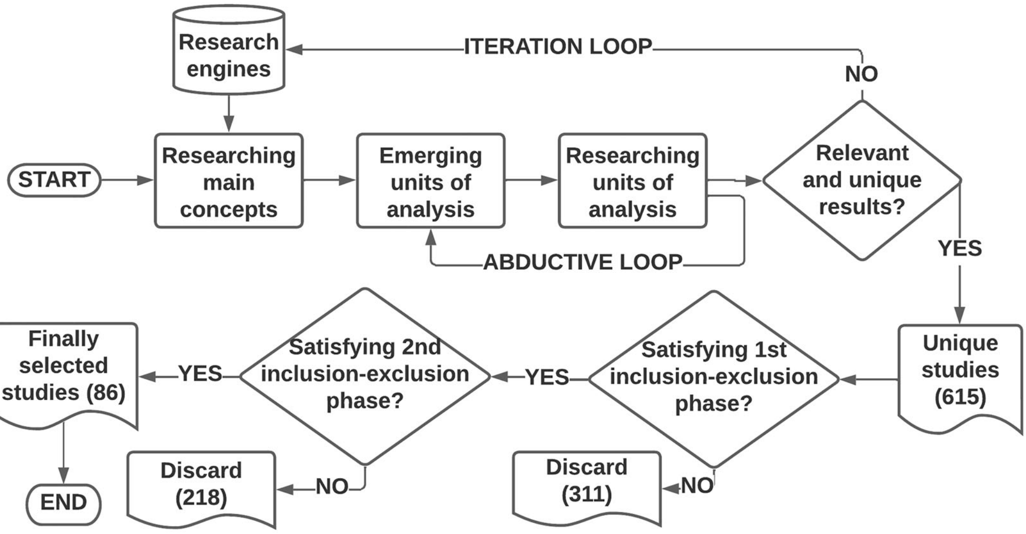

Figure 3. Research method for the literature review.

with which conceptualizations are developed iteratively between theory and data (Bell et al., 2019) – in the current case, data as research content. Through abduction, critical reflections and insights were formed (Bell et al., 2019), and the authors assessed the conceptual framework components considering the anticipated advantages and return impact of interaction points that may guide future LC-blockchain implementations. In support of the abductive method and for furtherly underpinning the framework's components as derived from the literature review, the authors reflected upon those through five 1-hour sessions inspired by the 'author-reader' evaluation method (Kassem, Iqbal, Kelly, Lockley, & Dawood, 2014).

Synergy and interaction between LC and blockchain: a conceptual framework

To create a schema of LC-blockchain synergy, the conceptual framework of interactions between LC and blockchain will incorporate the potential attributes of blockchain implementation in AECO (Figure 1), and the LC domains (Figure 2). The dimensions of the two-way synergy structure (from LC to blockchain and vice versa) are shown in Figure 4.

Based on the alphanumeric coding used in Figures 1 and 2, as well as the synergy analysis illustrated in Figure 4, the interaction networks between blockchain and LC, and the contributions of one to the implementation of the other in AECO, are schematically presented in Figure 5 (from blockchain to LC) and 6 (from LC to blockchain). In particular, the alphanumerical elements related to blockchain in Figure 1 and to LC in Figure 2, functioned as the nodes of the interaction networks. Then, as described in the Method section, the abductive reasoning (Bell et al., 2019) and the 'author-reader' evaluation method (Kassem et al., 2014) were implemented to understand and conceptualize the potential connections of those nodes, thus forming the edges of the interaction networks. Finally, the networks' layout reflects a Fruchterman-Reingold force directed graph, as it was deemed to be the most visually clear and informative graph type for the present number and distribution of nodes and edges (Fruchterman & Reingold, 1991). These networks are then explained through, respectively, Tables 1 and 2, where the LC-blockchain synergistic framework is demonstrated using the coding of Figures 1 and 2. The potential interactions are explained in detail, with some exemplary relevant references underpinning the explanations (Figure 6). Notably, some elements correspond to specific components (e.g. AF1), while others to families of components (e.g. AF). The anticipated impact potential in practice is displayed using color coding akin to that

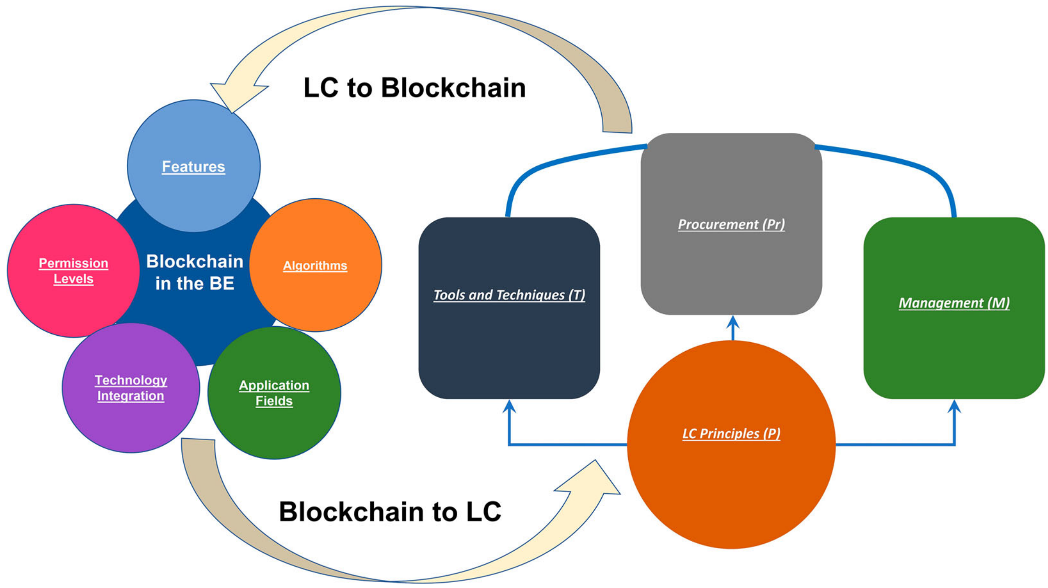

Figure 4. LC and blockchain synergy analysis framework.

of the networks and expresses the authors' forecast of the extent to which synergistic relationships can impact and affect elements from blockchain to LC and vice versa.

In Table 1, the synergetic relationships are analyzed by matching and evaluating the synergy impact potential of the blockchain in AECO attributes from Figure 1 with the requirements outlined in the literature for the LC elements from Figure 2. Accordingly, the way certain LC elements from Figure 2 can affect the blockchain in AECO elements from Figure 1, is shown in Table 2.

Discussion

The discussion of this study revolves around the literature review insights related to the two components of the synergistic framework (i.e. blockchain and LC), as well as the framework itself and the state of interaction it conceptualizes.

Regarding the literature review, the research on LC is mature and broad. One the one hand, this translates to an abundance of sources that can be studied. On the other hand, LC ends up being a wide topic covering almost all managerial aspects of construction – and even though this has not been the origin of LC, it is indeed the way it is often framed in practice. Such a framing can pose an analytical challenge for researchers, as even in this article, certain aspects denoted as LC-related (like BIM, supply chain management, modular systems, etc.) could be considered to be more generic rather than specific to LC. Nonetheless, a solution for this analytical challenge could be a strong contextual framing; while the current study is explorative, further studies on the synergy between LC and blockchain could be placed in specific contexts (e.g. pilot projects), so that the relation of elements like, e.g. BIM, to LC are more specific.

In contrast, the research on blockchain for AECO is still nascent (though rapidly growing, especially after 2019) (Scott et al., 2019) – and numerous associated viewpoints and features have not been deeply explored in relation to LC. Thus, even though our mapping of blockchain attributes aims to connect the depicted elements across the pertinent studies, a lot revolve around technological factors that may only have a slight impact on AECO. This suggests that the current technology-focused blockchain research for AECO should take a more pronounced sociotechnical (Qian & Papadonikolaki, 2021), and even sociomaterial turn (Kifokeris & Koch, 2022).

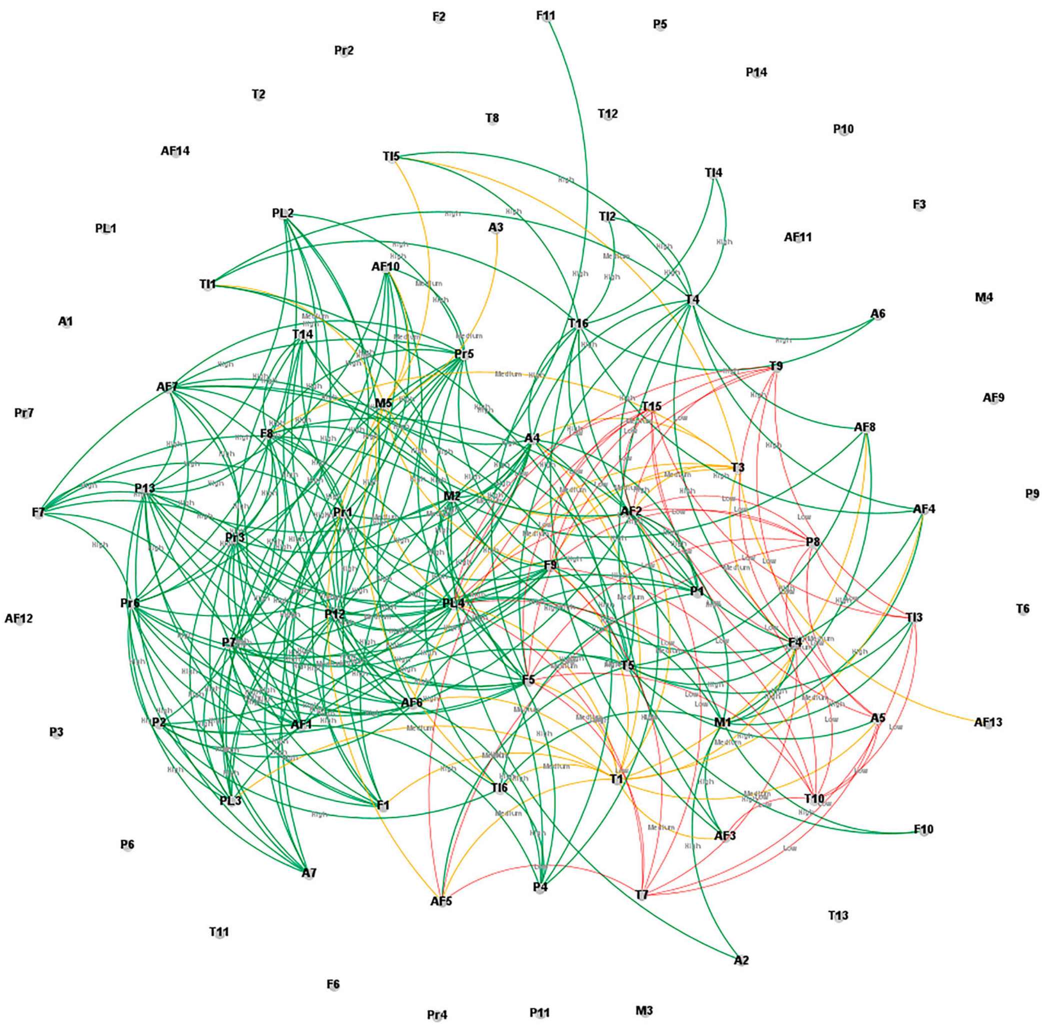

Figure 5. Network of synergies and interactions between blockchain and lean construction – blockchain contributions to LC.

In terms of the number, substance, and linkages between the synergistic components, the interaction framework's two mirrored aspects (from blockchain to LC and vice versa) are highly diverse. Conversely, in terms of quantity, both framework dimensions contain a sizable number of recurrent components. This is acutely shown in terms of technology integration, where more commercialized (e.g. BIM, IoT) rather than emerging (e.g. DBL) technologies are found in most instances of the framework. These technologies interact with blockchain features of data storage and retrieval, as well as algorithms and permission levels pointing to more private (but still partially decentralized) structures with an established level of control. This, along with irregular elements that only show up on specific instances, demonstrates that the blockchain-LC synergy can have certain components at its heart. However, such a synergy seems to be heterogeneous, as more LC components are often matched to the relevant blockchain elements in the 'Blockchain to LC' dimension rather than the opposite. This may demonstrate the contextual 'flexibility' of blockchain components, as well as their technological 'materiality' in their capacity to support LC (Dainty, Leiringer, Fernie, & Harty, 2017). This is also in-line with blockchain proponents' claim and the common rhetoric in the literature as to the technology being potentially

Table 1. Framework of synergies and interactions between blockchain and lean construction – blockchain contributions to LC.

	Blockchain to lean construction		
No	*Explanation*	*Blockchain element*	*LC element*
1	Multi-attribute and multi-stakeholder contractual agreements supporting LC, such as IPD, relational contracts, and partnerships (Mesa et al., 2019), can be facilitated through a trusted and decentralized blockchain network. This enables technology-induced trust alongside relational trust (Qian & Papadonikolaki, 2021)	F1; F5; F7; F8; F9; A4; A7; PL2; PL3; PL4; AF1; AF6; AF7; AF10	Pr1; Pr3; Pr5; Pr6; P7; P12; P13
2	Blockchain can streamline platform processes in industrialized and modular construction, which features a mode of production supporting LC (Li et al., 2020). Prefab. material logistics, provenance, certification, manufacturing and sourcing related data could be recorded on blockchain (Li et al., 2021).	F4; F10; A2; PL4; AF2; AF3; AF4; AF7; AF8; TI3; TI6	M1
3	A blockchain-powered network of relevant stakeholders can be implemented across the supply chain, helping in its streamlining and waste reduction as a lean supply chain management approach (Eriksson, 2013). In that regard, supplier certification, performance, guarantees, payment, approvals, and contract data could be recorded on blockchain (Tezel et al., 2021).	F1; F4; F5; F7; F8; F9; F11; A2; A4; PL3; PL4; AF7; AF8; TI1; TI6	M2
4	Hoshin kanri is a strategic planning tool in lean management (Nicholas, 2016). Key hoshin targets and performance metrics for departments and teams could be recorded on blockchain. This may be relevant for large, multinational organizations.	F9; A3; PL4; AF2; AF5; AF10; TI3; TI5; TI6	M5
5	Last Planner is a collaborative planning framework, which is one of the key contributions of LC to the AECO industry (AlSehaimi, Tzortzopoulos Fazenda, & Koskela, 2014). Key Last Planner data (e.g. PPC, constraint logs, phase, lookahead and weekly plan) for large, risky and critical projects with multiple parties could be recorded on blockchain.	F1; F4; F5; F9; A4; A5; PL3; PL4; AF2; AF3; AF4; AF5; AF6; AF8; TI6	T1
6	TQM is also considered as a LC enabler (Li et al., 2017; Koskela, Tezel, & Patel, 2019). To this end, quality logs, documentation, certificates, and performance data for large, risky and critical projects with multiple parties could be recorded on blockchain.	F4; F8; F9; A4; PL4; AF2; AF6; AF13; TI5	T3
7	BIM is an important enabler for LC (Sacks et al., 2010). Some BIM management data (e.g. clash records, approval history, handover data, ownership, IoT sensor data and IFC code) could be recorded on blockchain (Nawari & Ravindran, 2008).	F4; F5; A4; A6; AF2; AF3; AF4; AF8; TI1; TI2; TI4; TI5	T4
8	Digital twins can enable and facilitate LC, and blockchain can help in that through its data recording attribute (Araújo et al., 2022; Zhao et al., 2023). Blockchain can establish secure collaboration mechanisms between digital twins for leaner processes (Jiang et al., 2023).	F4; F5; A4; A6; AF2; AF3; AF4; TI1; TI2; TI4; TI5	T16
9	Data for logistic scheduled dates, responsibilities and material/component manufacturers (provenance) could be recorded on blockchain for key materials/components and just-in-time production (Queiroz, Telles, & Bonilla, 2020).	F4; F5; F9; F10; A4; A5; PL3; PL4; AF4; AF5; AF7; AF8; TI1; TI3	T5
10	Continuous improvement data, such as responsibilities and targets for important efforts (Salem et al., 2006), could be immutably recorded on a blockchain.	F4; F5; F9; A5; PL4; AF2; AF5; TI3	T7; T15; P8
11	Critical choosing-by-advantages (Zoya, Kpamma, Ayarkwa, & Adinyira, 2016) options and decisions could be recorded on a blockchain.	F4; F5; F9; A5; PL4; AF2; TI3	T9
12	Set-based-design development progress and decision-making points (Neto, Costa, & Ravazzano, 2019) could be recorded on a blockchain.	F4; F5; F9; A5; PL4; AF2; AF3; TI3	T10

(*Continued*)

Table 1. Continued.

	Blockchain to lean construction		
No	*Explanation*	*Blockchain element*	*LC element*
13	Adopting smart contracts on blockchain will partially automate contract execution, reducing mistakes, waste, and cycle times in those activities (Zhang et al., 2023).	F8; A4; PL4; AF1; AF2; AF6; TI6	P1; P2; P4; T14
Synergy Impact	*Higher*	*Medium*	*Lower*

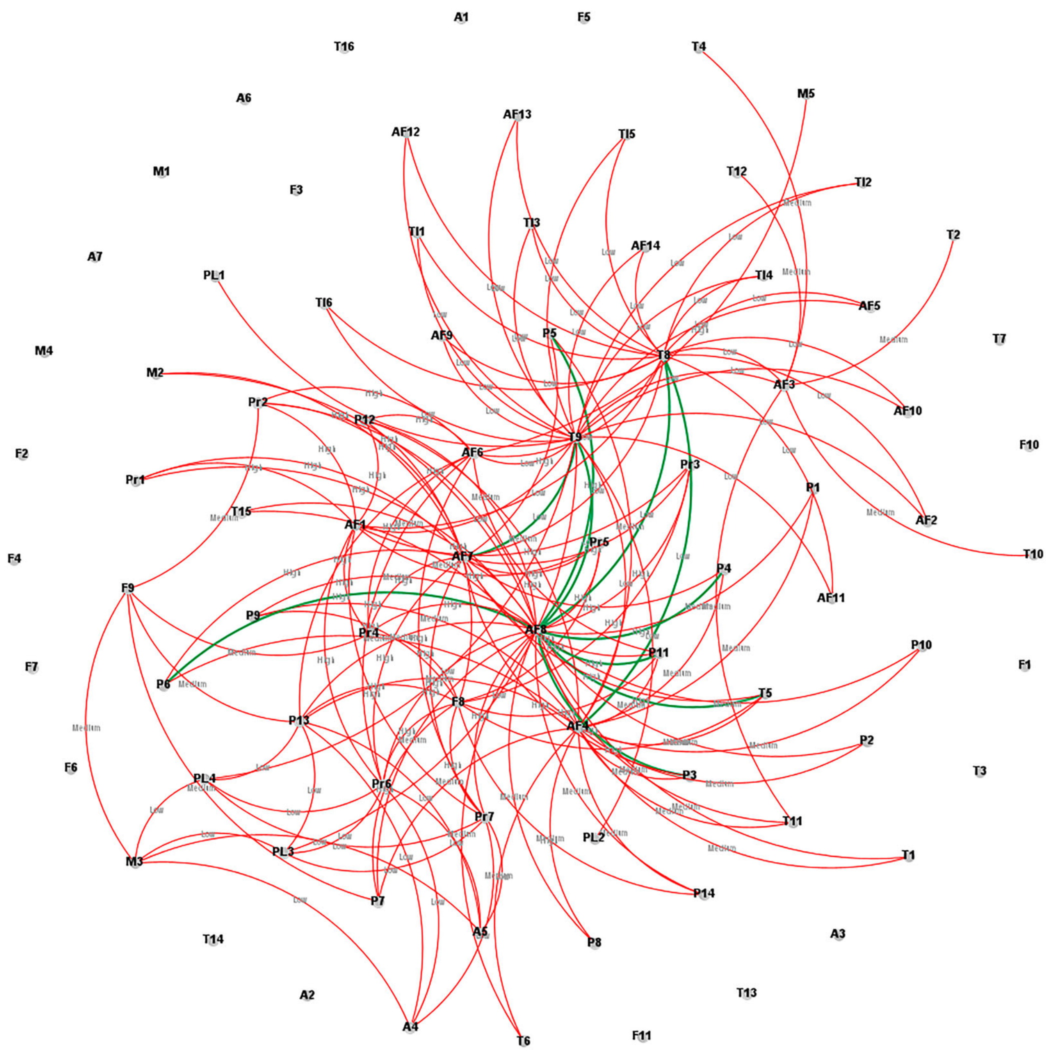

Figure 6. Network of synergies and interactions between blockchain and lean construction – LC contributions to blockchain implementation.

disruptive to many current business arrangements and established systems (Li et al., 2019) – even if such a claim will be supported better when more use cases with positive results are demonstrated. In comparison, the LC elements have a higher specificity.

Moving past quantity, the analysis of the synergies' content reveals that blockchain can support and inform LC in a largely technical manner, i.e. by streamlining, digitizing, and decentralizing tools,

Table 2. Framework of synergies and interactions between blockchain and lean construction – LC contributions to blockchain implementation in AECO.

Lean construction to blockchain			
No	*Explanation*	*LC element*	*Blockchain element*
1	Core LC principles like reducing variability, cycle times, and batch sizes, selecting an appropriate production control approach, designing the production system for flow and value, ensuring comprehensive requirements capture and flow down, focusing on concept selection, and cultivating an extended network of partners (Sacks et al., 2010), as well as procurement-related tenets like early involvement of key participants and mapping the value stream in lean project delivery (Mesa et al., 2019) can inform the development of smart contracts (Scott et al., 2021; Yoon & Pishdad-Bozorgi, 2022), for an optimized value delivery to the contracted stakeholders.	P7; P9; P11; P12; P13; P14; Pr3; Pr4; Pr5; Pr6; Pr7; T5	F8
2	Core LC principles like standardization, instituting continuous improvement, ensuring comprehensive requirements capture and flow down, verifying and validating, deciding by consensus and considering all options, and cultivating an extended network of partners (Sacks et al., 2010), as well as procurement-related tenets like integrated governance and project team, collaborative trust, and predictable and rapid workflow in lean project delivery (Mesa et al., 2019) can set a benchmark for data trust requirements (Perera et al., 2020) when designing the blockchain framework.	P7; P13; M3; Pr2; Pr4	F9
3	Core LC principles like instituting continuous improvement, verifying and validating, deciding by consensus and considering all options, and cultivating an extended network of partners (Sacks et al., 2010), as well as procurement-related tenets like early involvement of key participants, increasing relatedness among all project participants, and defining value from the customer's perspective in lean project delivery (Mesa et al., 2019) can inform the customization of the consensus algorithms (Perera et al., 2020; Yang et al., 2020), which will most probably support (quasi-) permissioned architectures.	P13; M3; Pr6; Pr7	A4; A5; PL3; PL4
4	Core LC principles like instituting continuous improvement, verifying and validating, deciding by consensus and considering all options, selecting an appropriate production control approach, designing the production system for flow and value, and cultivating an extended network of partners (Sacks et al., 2010), as well as procurement-related tenets like integrated governance and project team, and relational contracts in lean project delivery (Mesa et al., 2019) can inform a blockchain-powered contract management (e.g. in the consensus privileges held by the stakeholders in the network) (Li & Kassem, 2021).	P12; Pr1; Pr2; Pr3; Pr4; Pr5; Pr6; Pr7	AF1
5	LC-inspired tools and techniques for design optimization (El Reifi & Emmitt, 2013) can inform a blockchain-powered design management (e.g. on the choice of the design data to be stored in the blockchain) (Mahmudnia et al., 2022).	T2; T4; T10; T11; T12	AF3
6	LC-inspired tools and techniques for production optimization (Sacks et al., 2010; Tezel et al., 2018) can inform a blockchain-powered production management (e.g. on the choice of the production data to be stored in the blockchain) (Mahmudnia et al., 2022).	T1; T5; T6; T8; T11; T15; P1; P2; P3; P4; P5; P6; P7; P8; P9; P10; P11; P12; P13; P14	AF4; AF8
7	Core LC principles like instituting continuous improvement, deciding by consensus and considering all options, and cultivating an extended network of partners (Sacks et al.,	P11; P12; P13; M5; Pr2; Pr4; Pr6; Pr7	AF6

(*Continued*)

Table 2. Continued.

Lean construction to blockchain			
No	*Explanation*	*LC element*	*Blockchain element*
	2010), as well as procurement-related tenets like integrated governance and project team, early involvement of key participants, and increasing relatedness among all project participants in lean project delivery (Mesa et al., 2019) can inform a blockchain-powered stakeholder management (e.g. on the choice of the permission levels and implemented data security protocols in the blockchain architecture).		
8	Core LC principles like reducing variability, cycle times, and batch sizes, selecting an appropriate production control approach, designing the production system for flow and value (Sacks et al., 2010), procurement-related tenets like allowing customer demands to pace push and pull production in lean project delivery (Mesa et al., 2019), and procurement and supply chain-related tools and techniques like cooperative relationships and large-scope procurement deals (Eriksson, 2013) can inform a blockchain-powered procurement and supply chain management (e.g. when writing smart contract clauses) (Queiroz et al., 2020).	T5; T9; P3; P4; P5; P6; P11; M2; Pr1; Pr2; Pr3; Pr4; Pr5; Pr6; Pr7	AF7; AF8
9	Value stream mapping (VSM) (Tezel et al., 2018) could facilitate an effective blockchain technology and application integration with existing processes through process redesign. Integrating blockchain with existing work process and legacy IT systems at organizations is a practical concern (Li et al., 2019).	T8	TI; AF
10	CbA (Zoya et al., 2016) could be adopted to select blockchain technology integration, application, and permission levels for a project, which require informed decisions (Perera et al., 2020). CbA will also introduce decision making over relative advantages with group dynamics to blockchain implementations.	T9	TI; AF; PL
Synergy Impact	*Higher*	*Medium*	*Lower*

techniques, tasks, and procedures specific to, e.g. production, supply chain, contract, and procurement management. As a result, the problem of a pragmatic, rather than systematic, integration may appear when the appropriation of LC components into blockchain designs comes with little theoretical or methodological contribution of blockchain to LC. Nonetheless, the blockchain to LC mode can potentially form a more indirect synergy where blockchain supports the implementation of another concept facilitating LC, such as BIM (Sacks et al., 2010), prefabricated and modular construction (Li et al., 2021), IPD (Mesa, Molenaar, & Alarcón, 2019), and digital twins (Hamzeh et al., 2021; Sacks et al., 2020). As the integration of blockchain with those concepts deepens through research and implementation (Scott et al., 2021), their joint facilitating role for LC could be expected to become more emphasized. On the other hand, LC can provide guidance to blockchain in areas like design and customization, as well as supply fundamental tenets (primarily linked to procurement). This finding aligns with the notion that blockchain is a general-purpose technology (Filippova, 2019) and that it should be contextualized in AECO. In that vein, several LC tools, such as CbA and VSM, could be practically utilized for decision-making and incorporating blockchain components into current processes.

Regarding the synergistic connections, some links are bidirectional (such the fundamental LC principles, the permissioned blockchain algorithm structures, and the blockchain characteristics mostly related to data provenance, storage, and retrieval), while others are unidirectional. This is aligned with the framework's heterogeneity mentioned above. The elements' connections are necessarily influenced by the content of their synergy, demonstrating that not all areas of LC-blockchain interaction are completely clear-cut.

A more devoted contextual focus should also be explored for more concretely describing the LC-blockchain interaction. Such a focus could be placed on promoting circularity for AECO, i.e. the contextualization of circular economy towards sustainable and green construction, considering the global difficulties pointing to more resource-economic viewpoints (Ogunmakinde, Egbelakin, & Sher, 2022). The UN Sustainable Development Goals and the pertinent problematization of how AECO may become more circular can therefore provide the context for circularity (Ogunmakinde et al., 2022). As a result, while the possibility of interaction between blockchain and LC can be thought of as an improvement factor in long-standing industry goals such as high productivity, quality, and delivery of value to clients and end-users of AECO (Tzortzopoulos et al., 2020), this can also be taken up a notch by considering sustainability and circularity through a resource-economic lens.

Similarly, this blockchain-LC contextual focus can be directed toward the implementation of another relevant concept (e.g. BIM, prefabricated and modular construction, digital twins) (Turk & Klinc, 2017). To this end, the interactions between LC and blockchain can positively (or negatively) affect the adoption of those tertiary concepts for AECO while occupying researchers and practitioners alike in the meantime. It is also expected that the LC community will be investigating more deeply into how blockchain and those tertiary concepts will together enable LC on theoretical and practical levels.

The scope of blockchain applications is expanding from virtual currencies to financial applications, to the entire social realm (Xu, Chen, & Kou, 2019). Based on this, blockchain is delimited to Blockchain 1.0, 2.0, and 3.0 (Swan, 2015). Blockchain 1.0 is related to the use of cryptocurrencies (Mainelli & Smith, 2015). Blockchain 2.0 includes smart contracts, smart property, decentralized applications (DApps), DAOs, and decentralized autonomous corporations (DACs) (Swan, 2015). Blockchain 3.0 envisions more advanced smart contracts for establishing highly autonomous distributed organizational units (Pieroni, Scarpato, Di Nunzio, Fallucchi, & Raso, 2018). The LC-blockchain synergy discussions presented in this paper treat the issue at a project or organizational level. With the advent and diffusion of Blockchain 2.0 and 3.0, industry, sector and economy-level discussions will be more valid, leading to investigations into how blockchain can induce 'leanness' at a more macro level. This also includes the infusion of LC principles into the decentralized autonomy and laws of this new economic arrangement.

The contrast between developing blockchain concepts and applications for AECO and the maturity of LC research and execution cannot be over-emphasized. Concerns, issues, obstacles, and barriers faced by blockchain in AECO should be addressed to achieve a more seamless synergy with LC (Perera, Nanayakkara, Rodrigo, Senaratne, & Weinand, 2020). These issues can include its interoperability with other cloud and digital technologies, return-on-investment margins, and a lack of legal and business frameworks (Elghaish et al., 2017; Mahmudnia, Arashpour, & Yang, 2022). Accordingly, it is proposed that, to prevent pointless implementations, the applicability of the interactions identified in this research should be supported using a decision-making framework, such as the one created by the World Economic Forum (Mulligan, Scott, Warren, & Rangaswami, 2018). Finally, the requirements and limitations of different blockchain permission levels should be well understood for any real-life application (Yang et al., 2020).

Conclusions

Blockchain, which reduces or eliminates the need for trusted third parties to process, validate, or authenticate transactions, is a digital database decentralized across various locations and individuals. Due to the recent identification of numerous application prospects, interest in blockchain for AECO has been rising. Despite this interest, the authors are aware of no explicit discussions of how it might interact with LC. Therefore, the purpose of this article was developing a conceptual synergistic framework between blockchain and LC, by analysing both concepts into their components and then exploring their interaction.

Blockchain holds the potential to support trust and transparency in LC applications in multiparty arrangements (e.g. IPD), which in the current narrative are more relational through contractual and social dynamics, with technology-induced trust as an added benefit. Moreover, it can automate process benefits where necessary non-value activities such as contract control and execution, payment arrangements, validation of transactions and data records by external parties are streamlined. However, this does not imply that it should replace the social and relational components of LC structures. On the other hand, by influencing its features, LC can assist the technology in becoming more pertinent to the needs of project management in AECO, which in return will increase its business value. The proposed interaction framework demonstrates how the quantity, substance, and linkages between the synergistic elements in its two mirrored dimensions are extremely varied. Given that blockchain has been claimed to have a disruptive potential, more of its components are being paired with their corresponding LC elements as facilitators. As for the content, LC can mould blockchain components using its guiding principles, management and procurement dimensions, and tools. Additionally, the links between blockchain and LC in the interaction structure demonstrate that not all synergy points are completely clear, with some being bi- and others unidirectional.

This study contributes to the AECO body of knowledge by conceptually initiating the bridging between the mature field of lean construction and the nascent field of blockchain implementation in AECO in an analytical way showing that there is potential value in a theoretical and practical synergy between the two fields. This can in turn contribute to the relevant industrial and societal practice – blockchain is shown to take up an increasing space in the discourse and emerging implementation practices within AECO, so a synergy with lean construction concepts, tools and techniques already forming a practical reality in the AECO praxis can be conceived as something to be expected in the mid-term.

To operationalize the synergy between the two notions, it should be positioned within a significant current challenge facing AECO. Circularity appears to be a good contender for that, whether it is defined narrowly to focus on environmental sustainability or broadly to include socioeconomic aspects. However, for LC 4.0, in which DLTs can be a significant data recording layer, it may be vital to further define and investigate the two-way synergy between DLTs/blockchain and LC.

The study's limitations are related to its narrowly focused evaluation of the literature and framework conceptualization, which at times is solely dependent on the authors' interpretation and synthesis. As such, recommendations for future study could include reviewing, revising, and expanding the proposed frameworks to modify and expand the synergy dimensions – as the perceptions and conceptualizations for both LC and blockchain can be many in that regard. Furthermore, experienced practitioners could update and expand the interaction framework experimentally, as well as validate it through surveys and case studies. Additionally, creating blockchain designs guided by LC, as well as LC implementation scenarios using blockchain, is advised. Another research area is determining priorities among the interactions in Tables 1 and 2. It may also be beneficial to investigate the LC-blockchain interactions from a Transformation-Flow-Value (Koskela, Rooke, Bertelsen, & Henrich, 2007) perspective. Finally, the synergistic elements could be detailed for each project lifecycle stage (i.e. design, construction, maintenance/operations, refurbishment/retrofitting, demolition).

Disclosure statement

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