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EXPLORING STATE-OF-THE-ART RESEARCH ON BLOCKCHAIN ADOPTION IN THE CONSTRUCTION INDUSTRY: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Blockchain is often considered a potential disrupter in how industries operate, due to its decentralised nature and several other salient features like enhanced security, transparency, traceability, immutability etc. The Construction Industry, though regarded as a late adopter of technologies, is striving to harness blockchain to improve its processes. The subsequent research initiatives, however, are scattered around several application areas, with different levels of maturity. This would prove troublesome for a potential researcher to identify a suitable research gap and carry out impactful research. Addressing this, the study attempts to identify the evolution of blockchain research in the construction industry and its current and future trends through a systematic literature review. The review identified that blockchain research is gaining popularity in construction sector exponentially and is expected to continue that pace. The developed countries are dominating these application oriented researches while developing economies are lacking behind. Research on adopting blockchain in procurement and design and construction processes has been done substantially while newer topics are evolving since the beginning of this decade, focusing on the sustainability initiatives of the sector and fusing other digital technologies with blockchain. It is believed that while procurement and design related researches iterate their findings, these new topics would define the blockchain researches in the years to come. Also, attention should be paid on holistically evaluating the blockchain solutions considering not only the technological aspect but also the sustainability, resilience and the productivity of the industry, which is yet to be observed in the studies.

Keywords: *Blockchain; Built Environment; Construction Industry; Distributed Ledger; Technologies.*

1. INTRODUCTION

Construction industry is often considered as a key driver of economic development and activities, contributing an equivalent to 6% of global gross domestic product (Kang et al., 2022). Nevertheless, it has been widely accepted that it is described as a "complex product systems industry" and its projects are characterised by their complexity in design as well as delivery (Erri Pradeep et al., 2021). This has resulted in construction projects facing

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challenges due to poor alignment between stakeholders, compliance issues, inefficiencies in finance and payments and project delays, among others (Ameyaw et al., 2023; Lu et al., 2021a; Nanayakkara et al., 2021). However it has been argued that the advent of Industry 4.0 technologies such as Artificial Intelligence, Internet of Things and Blockchain have the potential to eliminate several of these barriers (Ameyaw et al., 2023; Kiu et al., 2022). Among them, blockchain has garnered specific interest of researchers worldwide, owing to several of its key characteristics such as decentralisation, transparency, immutability and improved security (Msawil et al., 2022; Rodrigo et al., 2020).

Blockchain could simply be referred as a disruptive technology, with a decentralised database that chronologically and securely records transactions (Sheng et al., 2020). It has been reported that blockchains could reform financial markets, supply chains, consumer and business-to-business services, and publicly-held registers (Akinradewo et al., 2022). Further, previous studies confirm that it has the potential to be applied in several industries such as finance, identity protection, transportation, healthcare and logistics management (Perera et al., 2020). In addition, Scott et al. (2021) in their exploratory review, established that blockchain could be used throughout a construction project, in multiple phases ranging from procurement and supply, to energy and carbon footprint, throughout design and construction as well. Regardless of this, blockchain adoption has not received significant interest yet, as a potential disrupter in the construction industry. This could be attributed to the negative shade around cryptocurrency owing to its market instability and alleged role in money laundering (De Filippi et al., 2022). However, it is worth noting that blockchain is not merely a cryptocurrency or its financial applications (Akinradewo et al., 2022), instead it is the underlying technology behind cryptocurrencies, and blockchain as a technology, has immense potential of applications in construction and other industries.

Partly due to this perception, the studies conducted on the domain of blockchain applications in construction industry are majorly ad-hoc and spread over multiple areas with asymmetric levels of research in which some have matured to the development of prototypes while some are still in conceptual or exploratory levels. This could be detrimental to a potential researcher to identify the possible gaps in the completed studies so far and to get an idea of the current level of blockchain adoption in the construction industry. While some of the previous studies have attempted to do this, the global research on blockchain has evolved since they were published. Accordingly, this study intends to analyse the available literature that explicitly discuss the application of blockchain in the construction industry and present the evolution, current trends and the state of their research to assist organisations and personnel to understand the applicability of blockchain in the construction industry.

2. BLOCKCHAIN

Blockchain is a decentralised transaction ledger that acts as part of a large computing architecture, including many other functions related to storage, communication, file serving and archives (Rodrigo et al., 2020). It can secure the information while inducing trust in the system through several of its key characteristics like immutability, integrity, transparency and auditability among others (Msawil et al., 2022; Yang et al., 2022). In blockchain, merkle trees, consensus algorithms and other technologies pave way for multiple nodes to maintain a shareable and immutable ledger and induce collaboration

within a decentralised system (Sheng et al., 2020). Data can be bundled into blocks and each block is a package data structure containing an encrypted hash of the previous block, a timestamp and exchange information (Shu et al., 2022). The header in the block contains metadata such as previous block hash, nonce, timestamp and merkle root (Li et al., 2021).

Hash value is a unique identifier of the block generated by a hash function, characterizing the contents of the block and usually 64 characters long while nonce are random values which make the first digits of corresponding hash values equals to zero (Kim et al., 2020). The data structure of a blockchian is show in Figure 1.

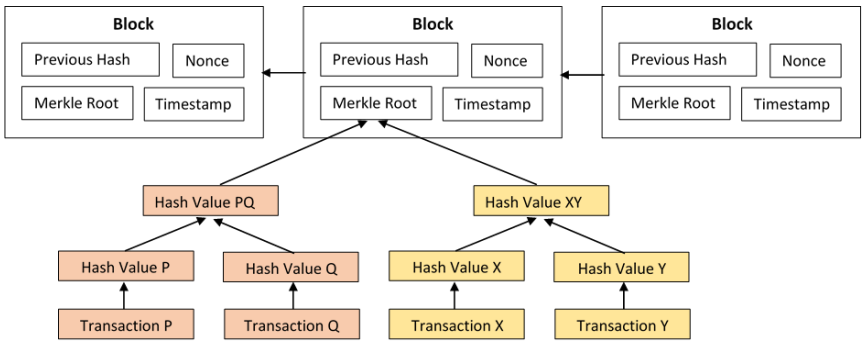

Figure 1: Data structure of a Blockchain

3. METHODOLOGY

The key intentions of literature review papers can be binary: summarising available literature in a topic by identifying key themes and issues while suggesting grounds for future research, and enfolding any scientific literature against existing knowledge and theories (Maditati et al., 2018). Among the several literature review techniques available, systematic literature review (SLR) employs a structured protocol to identify, interpret, appraise and summarise key research findings from literature that are most relevant to the chosen topic (Chen et al., 2022). Typically, SLR consists of four key steps: 1) Identification of articles; 2) Screening of articles; 3) Checking the eligibility of articles and 4) Inclusion of selected articles and synthesis (Chen et al., 2022), which have been demonstrated over the course of this section.

3.1 REVIEW PROTOCOL

Initially, the selection of the databases to be used for the study was done to ensure a sound and holistic literature could be retrieved. Accordingly, SCOPUS and Web of Science databases were selected for the purpose of this study as they contain relatively more published articles and they have deemed to possess a better comprehensive coverage of most of the prominent publishers related to this study such as Elsevier, Taylor and Francis, Emerald etc.

Consequently, taking account of the original objective of this paper, i.e. identifying the current state and focus of blockchain related research in construction industry, the research question was developed as "What are the application and focus areas of construction industry related blockchain research globally?" Emphasising it, taking account of the keywords and titles of the articles gathered during the preliminary literature review, the key search string was formulated as **((“Blockchain” OR “Distributed Ledger Technology”) AND (“Construction Industry” OR “Construction Sector”**

OR "Built Environment" OR "Built Sector" OR "Building Sector" OR "Building Industry")). Also, the search was limited to journal articles omitting grey literature including conference proceedings to ensure authenticity and credibility while also considering the probability of more application oriented, impactful articles being sent to journals than conferences. Also, the language was limited to English. Time of publication however, was not limited as the first publication related to the topic appeared in 2017, from which the articles published up to the period of search were included. Following the search in the article title or abstract or keywords fields, 102 and 94 records were yielded from the SCOPUS Index and Web of Science, respectively. After removing the duplicates, a total of 127 articles were screened for review.

The title and abstract of the yielded articles were screened to assess the relevance to the research question, followed by which 60 articles were excluded while 67 were shortlisted for further scrutiny. The shortlisted articles were further assessed for eligibility. Among which, only the articles that discuss about the specific application of blockchain in construction industry were included while articles that provide an overview, barriers and influencing factors of blockchain adoption in construction industry, and those discuss about more broader topics such as sustainability and resilience of the industry were omitted. Finally, 51 articles were shortlisted for the study. Figure 2 presents the framework of the SLR methodology used in the study.

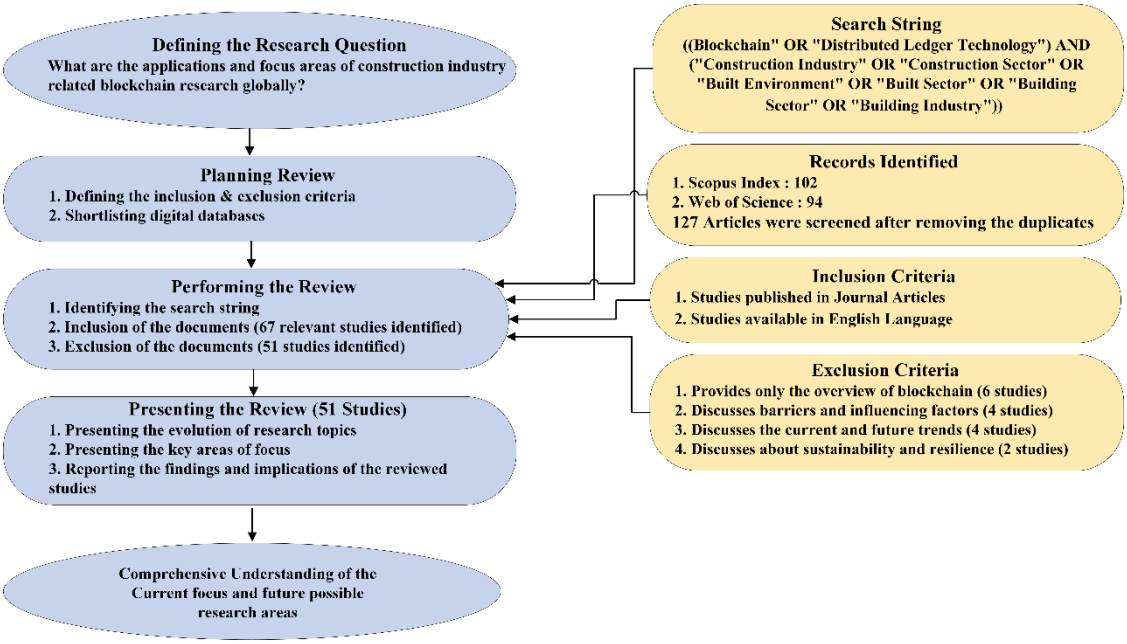

Figure 2: Systematic literature review framework

4. RESULTS

The shortlisted articles were reviewed to gather their metadata and the areas of key focus from which the following figures and sub-sections were derived. Figure 3 and figure 4 depict the number of publications in each year, till the time of writing this paper and the key methodologies used in them respectively. Figure 5 illustrates the heat map of the countries from which these papers were emerged, moving from low intensity greener colours to a higher intensity yellow colours as the number of papers from the countries increases.

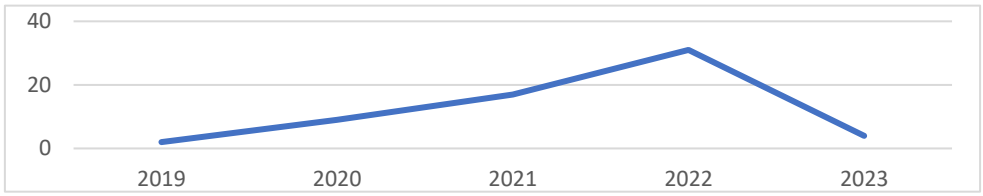

Figure 3: Number of publications in each year

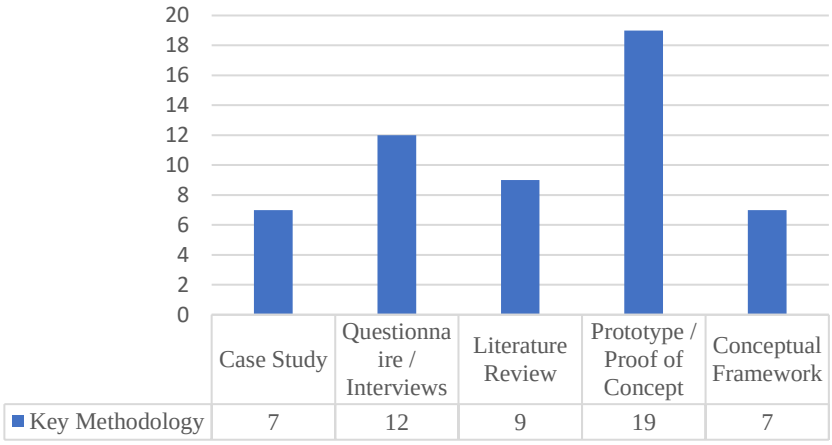

Figure 4: Key methodology used in the studies

Figure 5: Density of studies published by countries

Table1 categorises and tabulates the key areas of focus in each of the studies and the number of studies that discussed them while figure 6 depicts a tree map derived from table1.

The analysis and findings from these figures and tables have been elaborated in the ensuing discussion section while the subsections to follow, discuss the state of research in each of the categories from Table1.

Table 1: The key areas of focus and the number of studies that discuss them

Procurement	Design & Construction	Operations & Maintenance	Construction Intelligent Systems	Sustainability
Payment & Cash flow (6)	Building Information Modelling (4)	Property Transactions (1)	Artificial Intelligence (1)	Circular Economy (1)
Smart Contracts (8)	Digital Twins (3)	Asset tracking (1)	Chatbots (1)	Environmental Monitoring(1)
Supply Chain (8)	Off-site construction (3)	Facilities Management (1)		Carbon Trading (1)
Contract Administration (5)	Quality Compliance (2)	Waste Management (1)		Carbon Estimation (1)
	Stakeholder Management (2)	Safety & Health (2)		
	Integrated Project Management (6)			

4.1 PROCUREMENT (DISCUSSED IN 27 PAPERS)

Out of the 6 papers that discussed payment & cash flow in the procurement category, Ahmadisheykhsarmast and Sonmez (2020) developed a novel smart contract payment security system named SMTSEC, to reduce payment issues. Similar attempts were made

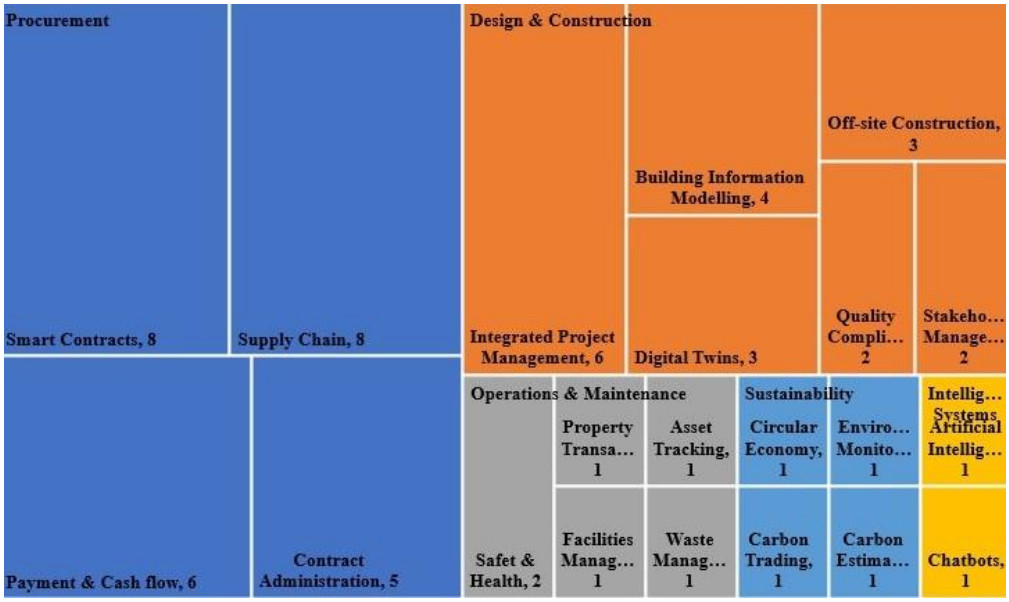

Figure 6: Tree map on the key areas of focus

by Ameyaw et al. (2023) and Nanayakkara et al. (2021), while they were limited to questionnaires/interviews to get expert opinion. Blockchain was also found to be effective

in automating progress payments (Hamledari and Fischer, 2020; Sonmez et al., 2022), though the attempts are restricted to interviews and conceptual frameworks. In most cases, smart contract applications are discussed concurrently with payment & cash flow, though Chung et al. (2022) explored the fusion of smart contract with BIM through literature reviews. It was perceived that, major influencing factors of the adoption of blockchain in payment management is the increased trust and transparency.

Supply chain related research however, seems to be relatively matured as Hijazi et al. (2022; 2023), Wang et al. (2021), Lu et al. (2021b) have done proof of concept and case studies, providing application oriented papers while Singh and Kumar (2022) and Tezel et al. (2021) adopted literature review and interviews, respectively. Wang et al. (2021) specifically, reports a two-year design science research study of enabling blockchain to the supply chain of a consortium in the UK's construction sector. Also, Hijazi et al. (2022; 2023) integrate BIM and blockchain for supply chain data delivery through proof of concept. The outputs of these studies suggest that blockchain has a viable potential to be applied in supply chain of construction projects.

Ibrahim et al. (2022) introduced an ecosystem prototype using a smart contract within a novel cryptocurrency blockchain for construction while Sigalov et al. (2021) describes a framework called BIMcontracts, integrating BIM with blockchain for data exchange and digital contract management workflow. These two articles discuss about the adoption of blockchain in the domain of contract management. Further, Kiu et al. (2022) identifies the possibility of using blockchain in the electronic document management while Msawil et al. (2022) conducted a literature review on the applicability of blockchain in construction contract administration. It is understood that the major influencing factor is the high security and easy dispute resolution on blockchain (Ibrahim et al., 2022; Msawil et al., 2022).

4.2 DESIGN & CONSTRUCTION (DISCUSSED IN 20 PAPERS)

As for the design & construction, the possibility of integrated project management is the most discussed topic. Yang et al. (2022) demonstrate the applicability of blockchain to grant reliability and efficiency of information management, pertaining to scaffolding work, including the several parties involved, through a case study. It was also deemed through proof of concept that blockchain-aided processes address the issues of design liability and improved security (Erri Pradeep et al., 2021). Other than these, Teisserenc and Sepasgozar (2021a; 2022) and Ni et al. (2021) discuss the possibility of integrating BIM and digital twins, respectively with blockchain conceptually. Altogether, these studies prove that blockchain adoption in project management would induce inclusion among the several stakeholders involved.

BIM and Digital Twins are another set of frequently mentioned domains on the application of blockchain in built environment. BIM has been considered a viable option to integrate with blockchain to address the issues in supply chain (Hijazi et al., 2023), contract administration (Sigalov et al., 2021) and project management (Ni et al., 2021). Similar trend could be seen in digital twins as well (Hunhevicz et al., 2022; Teisserenc and Sepasgozar, 2021b).

Another key area is off-site construction, which was discussed in 3 papers. Li et al. (2021) developed an innovative Two-Layer Adaptive Blockchain-based Supervision (TABS) for off-site modular housing production. The key benefit in this is the lack of tampering and

privacy leaks. Jiang et al. (2021) too, proposes a blockchain-enabled cyber-physical smart modular integration construction platform to facilitate cross-enterprise information sharing among multiple stakeholders, reinforcing inclusion and privacy. Meanwhile, Bakhtiarizadeh et al. (2022) explored the applicability blockchain in the off-site construction sector of New Zealand through questionnaire surveys.

In addition to these, quality compliance has also garnered the attention of the researchers. Sheng et al. (2020) developed a blockchain based framework for managing quality information, referred as "Product Organisation Process qualityChain", establishing through case study that blockchain can decentralise the management of quality information, achieving consistent and security. Wu et al. (2021) came up with an on-site construction quality inspection exploiting blockchain and smart contracts. Meanwhile, Kang et al., (2022) and Lu et al. (2021b) presented a blockchain-based model to rebuilt trust and uplift construction efficiency, i.e. stakeholder management.

4.3 OPERATIONS & MAINTENANCE (DISCUSSED IN 6 PAPERS)

When considering the operations & maintenance, Perera et al. (2021) did a commendable attempt in developing blockchain-based trusted property transactions in the built environment, eliminating the middlemen involved in property transactions, hence reducing cost. Van Groesen and Pauwels (2022) demonstrated a plug-and-play framework of interacting applications and a workflow to operate it for asset tracking. Further, Xu et al. (2022) developed a blockchain-enabled occupational safety and health deployment framework to create privacy and occupational safety, while Liu et al. (2022) and Gunasekara et al. (2022) explored the possibility of using blockchain in waste management and facilities management, respectively. While the earlier two articles demonstrate prototypes, these studies are limited to conceptual framework and interviews.

4.4 CONSTRUCTION INTELLIGENT SYSTEMS (DISCUSSED IN 2 PAPERS)

As for the construction intelligent systems, both the papers retrieved are authored by Adel et al. in 2022. The first paper introduces a tailorable decentralised AI system which utilises blockchain. The proposed system validates and audits the decision-making processes. The second paper proposes a novel information exchange and management system for construction firms, integrating blockchain and chatbots, to track work progress. Both these studies present a prototype to be assessed for its suitability in the construction industry.

4.5 SUSTAINABILITY (DISCUSSED IN 4 PAPERS)

The application of blockchain in the sustainability domain of the construction industry is largely centered on carbon estimation and trading. Shu et al. (2022) presented an emissions-trading system which could also handle carbon emissions within the materialisation phase of a project while Rodrigo et al. (2020) conducted a literature review followed by a questionnaire survey for the potential application of blockchain for accurate estimation of embodied carbon in construction supply chain. In addition, Zhong et al. (2022) proposed a blockchain-enabled framework for on-site environmental monitoring by proof of concept and Shojaei et al. (2021) investigated blockchain to facilitate circular economy. A blockchain model was presented and tested through a synthetic case study.

5. DISCUSSION

While the first publication on blockchain in the construction industry dates back to 2017, the earliest article used in this study is from 2019, since most of the early publications were either grey literature or those that provide an overview or discuss the challenges of blockchain adoption. More application based studies started to appear on 2019, growing exponentially till 2022 at an annual average of 174%, as it could be seen from figure 3. It was identified during the preliminary review that the number of review papers and the blockchain use-cases in construction industry, they discuss have also gradually increased, suggesting that a similar growth in use-case studies could be observed for 2023 and the years to come. In addition, the outlook appears to be more positive given the fact within the first quarter of 2023 itself, 4 articles have already been published.

As for the key methodology used in the studies, it could be seen that 19 articles used prototype/proof of concept (Erri Pradeep et al., 2021; Hijazi et al., 2023; Wang et al., 2021) which is the highest while the lowest of the pack, case study and conceptual framework each were used in 7 studies (Hamledari and Fischer, 2021; Liu et al., 2022; Sonmez et al., 2022), as shown in figure 4. An interesting trend observed is that majority of the studies strive to provide more demonstrable output through case studies and prototypes as opposed to the findings of earlier similar studies (Scott et al., 2021), in which theoretical and exploratory studies dominated numerically, as discovered in the preliminary review. However, it should be noted that the review protocol of SLR in the study shortlists only the use-case based studies and hence this trend might change when exploratory and grey literature are included as well. Nevertheless, it should be acknowledged that demonstrable output are starting to emerge in the recent years, which is a positive sign for blockchain adoption in the construction industry.

In addition, another notable finding was most of these application based studies are from developed countries such as Australia, Hong Kong, China, USA and UK (Ameyaw et al., 2023; Chung et al., 2022; Rodrigo et al., 2020), as it could be seen from figure 5 in which they are denoted with higher density. This reinforces a popular notion that economic development and rigorously embracing new, disruptive technologies go hand-in-hand, especially when considering the likes of construction industry, which is often characterised by its immense contribution to Gross Domestic Product.

When pondering on key areas of focus, it should be noted that applications of blockchain in procurement related areas are the most present among the articles retrieved for the study (Ibrahim et al., 2022; Nanayakkara et al., 2021; Tezel et al., 2021), taking a larger area of figure 6, suggesting that the potential of blockchain is the most in procurement phase of a construction project when compared to others, while closely followed by design & construction (Ni et al., 2021; Sigalov et al., 2021; Yang et al., 2022). However, when considering the operations & maintenance, though this category has not gained the depth in research like the earlier two based on the number of articles, studies have touched several areas of application such as waste management (Gunasekara et al., 2022), property transactions (Perera et al., 2021), and asset tracking (van Groesen & Pauwels, 2022). Similarly, sustainability related research are also yet to gain popularity, judging from the number of articles. Nevertheless, it is safe to acknowledge that though the sufficient depth has not been attained yet in these two categories, the research has been matured to an extent in the existing topics owing to the several proof of concept studies evolving, moving forward from the exploratory reviews and expert opinions.

Another key observation is that, procurement and design related applications somewhat attribute to the inherent scope of applications of blockchain that could have been diffused from the financial industry as similar payment and logistics related solutions are already being practiced in other industries. However, more advanced topics such as artificial intelligence (Adel et al., 2022) and sustainability related topics like carbon estimation and trading (Rodrigo et al., 2020) have started to appear only from this decade, suggesting that these could be the key areas of focus for the years to come as construction industry itself is gearing towards digitalisation and sustainable processes.

6. CONCLUSIONS

Summing up, it could be seen that the interest and popularity of blockchain based research in the construction industry is gaining momentum exponentially over the years. The transition from exploratory reviews and surveys towards prototypes and proof of concept has been witnessed rapidly within the span of a half a decade. The developed countries as usual, dominate these application oriented studies numerically, urging the developing economies as well, to reflect on the outcome of these studies and strategically orient their research on blockchain adoption in their construction sector.

As for the research trends, the research on using blockchain in the procurement and design and construction processes are reaching maturity, as relatively higher number of studies with diverse methodologies have already appeared. While there is scope for more research and iteration in these areas, a more recent trend is, fusing intelligent systems like artificial intelligence with blockchain and harnessing blockchain for sustainability related initiatives of the built environment. It could be argued that this would define the blockchain research for the latter half of this decade. In addition, while blockchain solutions are being presented by researchers, negligence could be sensed with respect to their impact on the sustainability, productivity and resilience of the construction industry. As these topics are gaining attention, owing to the increased impact on climate change, increase in population and resource constraints, focusing only on the technological aspect would prove the efforts fruitless. Hence, during the years to come, due diligence should be given to the holistic evaluation of these emerging blockchain solutions as well, on the sustainability, productivity and resilience, which would pave way for an effective adoption of blockchain in the construction sector.

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