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POTENTIAL FOR SYNERGETIC INTEGRATION OF BUILDING INFORMATION MODELLING, BLOCKCHAIN AND SUPPLY CHAIN MANAGEMENT IN CONSTRUCTION INDUSTRY

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SUMMARY: *Construction industry nowadays is facing several key issues as the likes of cost and time overruns and unstable business environment which lead to suppressed profitability, quality, and stakeholder satisfaction. Studies have suggested, an improved Supply Chain Management (SCM) towards Sustainable Supply Chain (SSCM) could help in this regard, however there are barriers observed to its implementation in the construction industry. Building Information Modelling (BIM) too is considered a positive disrupter in the construction industry due to the potential in its applications, and one of such potential is improving the SCM. However, similar to SCM, adoption of BIM faces several barriers. Preliminary review suggests that some of its barriers could be resolved by integrating with Blockchain, another disruptor stemming from Industry 4.0. Hence, this paper attempts to assess how the synergy of BIM and blockchain would improve the SCM of the construction industry. For that purpose, through a systematic literature review, the paper structures the barriers of SCM, and barriers and benefits of BIM and blockchain in construction industry across the dimensions of Socio-technical, Industrial, Organizational, Financial, Legal and Institutional, and Sustainability, and conceptually maps the barriers and benefits to identify their collective impact on SCM. From this study it was found that with the help of Blockchain integration, there are a number of potential synergies that may solve critical inherent issues in both BIM and SCM, such as reluctance of information sharing and trust, sustainability concerns and safety, leading to positive cumulative impact on SCM. However, it was also recognized that there can be negative as well as neutral cumulative impacts on areas such as cost, and lack of personnel, knowledge and institutional support that can lead to an opposite impact.*

KEYWORDS: *Blockchain, Distributed Ledger Technology (DLT), Building Information Modelling (BIM), Supply Chain Management, Construction 4.0.*

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1. INTRODUCTION

Construction industry is characterized by several pressing issues such as cost and time overruns, and fluctuating business environments and market conditions (Hirusheekesan and Satanarachchi, 2021a), suppressing the profit margins of construction projects coupled with poor quality and stakeholder satisfaction. In addition, the construction industry is traditionally associated with unsustainable practices and relatively short-term thinking on resource consumption (Hirusheekesan and Satanarachchi, 2021a). In recent past, Sustainable Supply Chain Management (SCSM) is seen as reducing material waste, material and labour idle time, hence reducing cost and resource consumption (Behera et al., 2015, Papadopoulos et al., 2016). Yet in the complex and evolving operational landscape of the construction industry, it is in need of technological innovations to bring out its best use in the construction industry.

One of the key technology focused players in the construction industry is Building Information Modelling or Building Information Management (BIM). BIM practices are seen as increasing the project delivery speed, promoting collaboration among stakeholders, and reducing design errors and changes, and having notable other advantages (Mehran, 2016, Zhang et al., 2016, Abanda et al., 2017, Deng et al., 2020). In addition to these advantages, similar to SCM, BIM too poses operational challenges such as having to materialise in a relatively formalised and less collaborative stakeholder landscape. Despite these, BIM has served to effectively allow the construction industry to ride the wave of the information age rather than to oppose it.

In the information age, industry 4.0 technologies such as Blockchain, Machine Learning, and Artificial Intelligence are making their appearance in many automated industries. Already their potential integration to operations in the industry, particularly in the direction of BIM are being well explored (Nawari and Ravindran, 2019, Khudair et al., 2021, Chung et al., 2022). Among the industry 4.0 technologies however, the Blockchain, which is the most recent among them, appears to have not yet been well addressed with a focused attention to the construction industry. Preliminary review on blockchain reveals that it has several compatible characteristics and advantages, such as the higher transparency and security, promoting trust and less non-compliance of contract (Golosova and Romanovs, 2018, Wang et al., 2018, Clohessy & Acton, 2019). Some of these unique features of blockchain such as high security, incentives on information sharing and trust, and ability to formulate smart contracts to induce compliance could compensate for the operational drawbacks of BIM as well as SCM. However, to determine such a mutual effect, it is important to juxtapose the benefits and drawbacks of both Blockchain and BIM with the challenges of SCM in a systematic manner. Such an exercise may enable us to identify the potential synergies or antagonisms.

Therefore, through a systematic literature review, this paper aims to first explore the key challenges of successful implementation of SCM in the construction industry, and similarly explore the key challenges and benefits of BIM and blockchain in the context of the construction industry. Then by applying a stepwise mapping process, the potential for synergetic integration of the three concepts of SCM, BIM and blockchain, are carefully examined and discussed.

Accordingly, the key objectives of this study are to; a) Identify the barriers for an effective SCM in construction industry, b) Identify the benefits and barriers of BIM adoption in construction industry, c) Identify the benefits and barriers of adopting blockchain in construction industry, d) Explore the potential of integrating blockchain with BIM for an effective SCM in construction industry through mapping their barriers and benefits.

The proceeding sections are dedicated to examining the potential for synergetic integration of the three concepts of SCM, BIM and blockchain, by carefully examining the literature available in these domains.

2. OVERVIEW OF THE CONCEPTS

2.1 Supply Chain Management in Construction Industry

SCM originated and flourished in the manufacturing industry, to reduce inventory investment while increasing customer service and building a competitive advantage (Cooper and Ellram, 1993, Akintoye et al., 2000). It became an explicit area of research in the mid-1980s, originated from the topics, distribution and production (London and Kenley, 2001). Supply chain is a collection of facilities that procure raw materials, transform them into intermediate goods and end products, and finally deliver the products to customers through a distributing system (Lee and Billington, 1995). Alternatively, it is the management of a network of organisations that are involved in carrying out the business process (Briscoe et al., 2001). It is also referred to as autonomous or semi-autonomous business entities, collectively responsible for procurement, manufacturing and distribution activities of one or more families of related products (Swaminathan et al., 1996). Generally, it is the network of organizations from the 'supplier of the supplier' to the 'client of the client', linked upstream and downstream, and focused on different processes and activities that produce value in the form of products and services for the clients (Akintoye, 2000, Papadopoulus et al., 2016). SCM views the entire supply chain as one unit and its basic idea is to recognize the interdependencies and improve its configuration and control (Cooper and Ellram, 1993, Vrijhoef and Koskela, 2000). It aims to produce quality and value in the services and products for the end consumers through integrated processes and activities.

The supply chain in the construction sector can often be extremely complex (Briscoe et al., 2001). They are usually Make-to-Order supply chains, converging all materials to the site where the building is assembled from incoming materials (Dallasega et al., 2018). Construction researchers have applied the SCM philosophy to materials flow, to establish the relationship between site productivity and improved materials management (London & Kenley, 2001). However, SCM in the construction industry differs from that of the manufacturing industry (Vrijhoef and Koskela, 2000) in a significant way. Papadopoulus et al. (2016) listed critical differences between the supply chains of manufacturing and construction sectors as 'the construction product is for a single client most of the times', 'the product changes for each project', 'the place, equipment and methods of production change for each project', 'construction personnel have a high rotation index during the construction time and between projects' and 'not all the parts and material can be stored at site'. In the construction sector, the customer wields great influence on the final product's physical aspects and the value of logistics parameters, while depending on the contract type going onto select contractors and the suppliers, making vulnerable supplier-contractor relationships (Akintoye et al., 2000). Construction supply chain consists of all construction processes, from the client demands, through design and construction, to maintenance, replacement and eventual demolition, with numerous associated organizations, resulting in extreme fragmentation and complexity (Xue et al., 2005). FIG.1 depicts the supply chain of a typical traditional construction project.

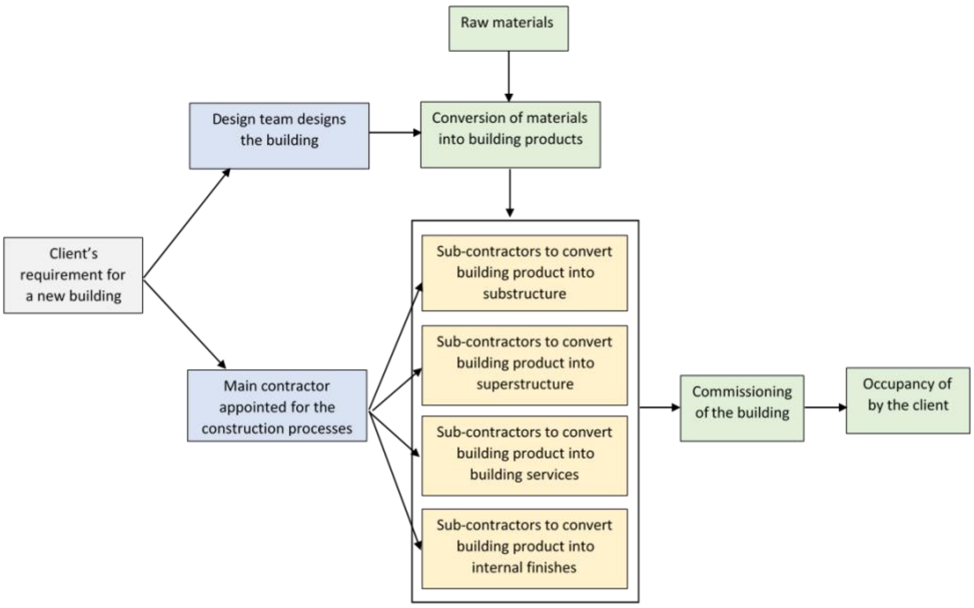

FIG. 1: Typical Supply Chain of a Construction Project.

2.2 Building Information Modelling

Building Information Modelling, occasionally referred to as Building Information Management, is often hailed as a solution to overcome certain prevalent challenges in the construction industry (Abanda et al., 2017). Unlike SCM, BIM has direct focus in the construction industry. In its evolution, BIM goes back to the early days of CAD, and is identified as the new Computer Aided Design (CAD) paradigm (Bryde et al., 2013; Migilinskas et al., 2013). In practice, its journey started with the 1990s Level 0 BIM that used paper drawing, followed by Level 1, Level 2 and Level 3 BIM, gradually increasing collaboration, which has been depicted in FIG.2.

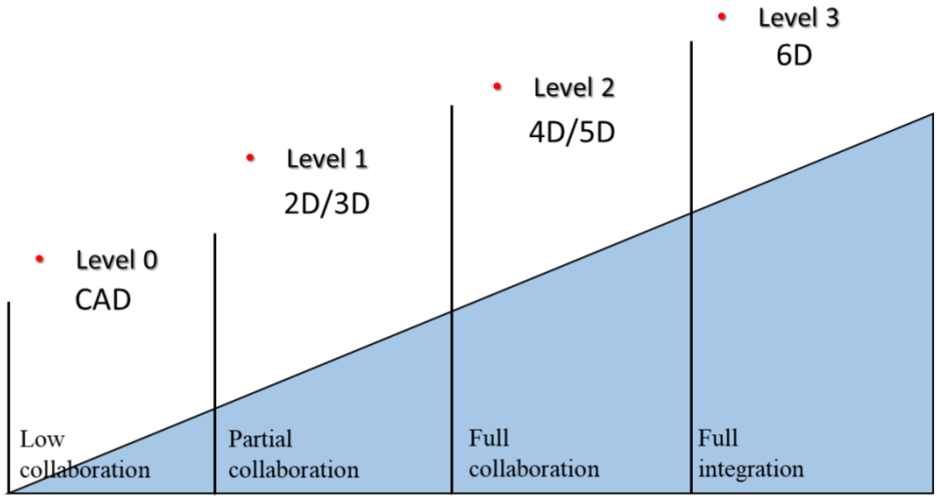

FIG. 2: Evolution of BIM.

In the beginning, BIM application occurred mostly in the design phase (Zhang et al., 2016). However, it has blended with a variety of modern software and technologies with time, to be used throughout the lifecycle of a project, like Life Cycle Assessment, Energy Modelling, Supply Chain and Facilities Management (Edirisinghe et al., 2017, Gerrish et al., 2017, Rathnasinghe et al., 2020, Verdaguer et al., 2022). Urging BIM in construction is backed by its benefits such as promoting collaboration between stakeholders, enhancing the accuracy and quality of the final product, and improved rate of delivery and less errors (Succar 2009, Azhar, 2011, Bryde et al., 2013). BIM has several technological benefits such as being a key driver for sustainability-focused initiatives like lean construction, off-site manufacturing, integrated assessments of environment, economic and social impacts, and energy modelling during the design process (Zhang et al., 2016, Olawumi et al., 2018, Xie et al., 2022, Xu et al., 2022). It plays an active role in project management, controlling material cost and on-site safety management as well (Deng et al., 2020).

According to International Standards, BIM is a "shared digital representation of physical and functional characteristics of any built object which forms a reliable basis for decisions" (Volk et al., 2014). BIM can also be seen as a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's lifecycle (Succar, 2009). A building information model characterizes the geometry, spatial relationships, geographic information, quantities and properties of building elements, cost estimates, material inventories and project schedule (Azhar, 2011). For that, BIM includes information technology frameworks and technologies supporting collaboration over project life cycle to insert, extract, update or modify information in the model (Motawa and Carter, 2013). While BIM integrates tools, platforms and environment (Sacks et al., 2018), fragmented definitions are abound as, "a tool which allows realization of parametric object oriented building design", "set of design software for creation and analysis of information models, with aim to realization of construction projects", or "parametric and object oriented modelling of physical and functional characteristics of construction projects" among others (Jung and Joo, 2011, Matějka and Tomek, 2017, Tan et al., 2019). Overall, the most common role of BIM in a construction project is to increase the collaboration between the processes and stakeholders to facilitate decision making through smooth information flow throughout the lifecycle of a project (Gu and London, 2010). In the most recent dialogue on BIM, the possibility of fusing technologies such as Artificial Intelligence, Blockchain, Machine Learning, Internet of Things and Laser Scanning for an effective and efficient use of BIM, is being actively explored (Ma & Ren, 2017, Khudair et al., 2021, Chung et al., 2022).

2.3 Blockchain

Blockchain or Distributed Ledger Technology is a decentralised, transparent and distributed directory (Turk and Klinc, 2017, Li et al., 2019) that facilitates traceability, record management, and automation of supply chain, payment applications and other business transactions (Yang et al., 2020, Javaid et al., 2021). It allows network members to digitally record and access transactions (Nakamoto, 2008), and is considered as an open-source data set, distributed across millions of computers, utilising avant-garde cryptography (Tapscott and Tapscott, 2016). Blockchain spreads the computational workload across multiple nodes in a network that can make independent decisions as opposed to a centralized network that concentrates on a single central point (Nawari and Ravindran, 2019a). Blockchain is regarded as a database technology that provides smart and coded schemes to verify and store transactions throughout chains of communications (Shojaei et al., 2020).

More descriptively, blockchain is a sequence of blocks (Turk and Klinc, 2017), where a block consists of the header and body (Sheng et al., 2020). Header stores the hash value of the previous block, a timestamp, the hash value of the block and a nonce, which is a random number to verify the hash considering the network rules (Perera et al., 2020). These hash values are unique, and upon any change to a block, the respective hash value would change immediately (Nofer et al., 2017), creating an inconsistency between a new parent block hash and the old parent block hash of the next block, ensuring the integrity of the chain (Rodrigo et al., 2020, Ali et al., 2021). Whenever transactions are sent to the network, they are placed in a pool of unverified transactions, where they are periodically collected and validated by miners before being placed into a block (Nawari and Ravindran, 2019b). Miners apply a consensus mechanism to check each other’s results before including new blocks, ensuring a single version of the ledger in existence, at any moment of time (Scott et al., 2021). The structure of the blockchain has been portrayed in FIG. 3.

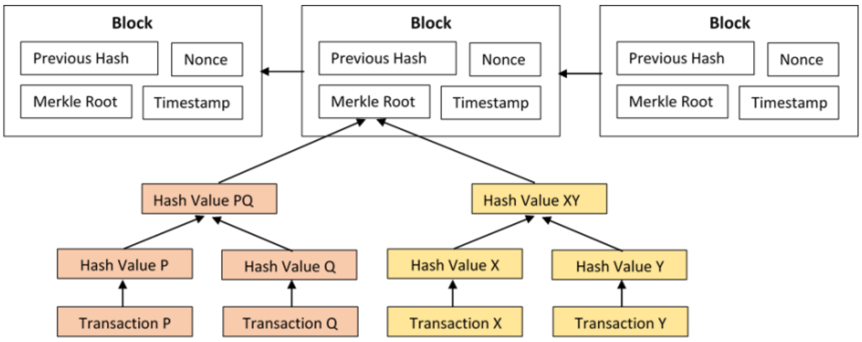

FIG. 3: Structure of a blockchain.

As somewhat visible from the definitions and literature, blockchain is distinguished by its special features like decentralization, persistence, anonymity, transparency, distributed trust, auditability etc. (Wang et al., 2018, Clohessy and Acton, 2019, Rodrigo et al., 2020, Gad et al., 2022). Such a combination is rare to find in traditional transaction recording methods. Therefore, blockchain is perceived as having an immense application potential in fields such as finance, notary public, IoT, smart contracts and healthcare among others (Casino et al., 2019, Perera et al., 2020, Sheng et al., 2020, Javaid et al., 2021).

Blockchain systems can be roughly categorized into public blockchain, private blockchain and consortium blockchain (Wang et al., 2018, Yang et al., 2020). A public or permissionless blockchain, like bitcoin, includes many nodes, allows anyone to participate as a miner and to view the underlying ledger, however being costly and time consuming (Han et al., 2023). In private or permissioned blockchain, only authorized participants can join the network depending on the level and area of access to each user, the transactions in the ledger will be visible and allowed to add transactions (Nanayakkara et al., 2021). As for consortium blockchain, validation of transactions could only be performed by some essential members who have that authority (Ali et al., 2021). The key feature of a consortium blockchain is its possibility to operate under the governance of a group, compromising decentralization to an extent (Perera et al., 2020).

Studies have suggested that blockchain could be used in the construction industry as well (Nawari and Ravindran, 2019b, Perera et al., 2020, Scott, et al., 2021, Chung et al., 2022). It has the potential to be used in almost every phase of a construction project from design and procurement to operation, maintenance and demolition (Scott et al., 2021). It is also proposed that blockchain could be used in property management, document management, construction supply management, asset management, energy management among others (Perera et al., 2020, Yang et al., 2020). Studies have explored blockchain usage in embodied carbon estimation (Rodrigo et al., 2020), property transactions (Nanayakkara et al., 2021), Artificial Intelligence applications (Adel et al., 2022) and BIM (Hijazi et al., 2022). Additionally, smart contracts are computerized transaction protocols that execute the terms of a contract (Li et al., 2019), executed through blockchain, and become handy in construction-related applications (Shojaei et al., 2020). Although not many, some studies can be found in this area related to SCM and payment management (Scott et al., 2021, Chung et al., 2022).

3. METHODOLOGY

This study undertakes an analysis on the benefits and limitations of the aforementioned concepts in the context of the construction industry to investigate the impact of mutual performance of BIM and blockchain in the construction industry for effective SCM. Considering the stage of development as technologies/practices and their level of absorption to construction industry, a two-fold process of superimposing the benefits and barriers in the novel and less absorbed technology (blockchain) on a relatively older and better absorbed technology (BIM) to examine the cumulative impact on a third practice (SCM) was applied. First, how the blockchain's identified benefits and barriers would impact the identified benefits and barriers of BIM was examined through first stage mapping. Then how the cumulative result in turn would impact to resolve or aggravate the barriers of SCM application was examined via the next stage mapping, to identify the aggregated impact. Accordingly, the research methods employed in the two steps in this study; a) to find the benefits and barriers of SCM, BIM and blockchain, b) to assess the cumulative impact of integration of blockchain, and BIM to SCM, too are two-fold. The first primarily uses literature review and thematic analysis as the technique, whereas the second uses an approach of author-perception based mapping, while literature are utilised to inform and structure the perceptions.

Systematic literature review employs a structured protocol to identify, interpret, appraise and summarize key research findings from literature that are most relevant to the chosen topic (Maditati et al., 2018). A systematic literature review allows to effectively sort out the data needed using proper selection criteria and screening of literature, which are otherwise available redundantly, and consists of four key steps; (i) Identification of articles, (ii) Screening of articles, (iii) Checking eligibility of articles, and (iv) Inclusion of selected articles and synthesis (Chen et al., 2022). Hence for this study, Scopus and Web of Science along with Google Scholar were searched with relevant keywords. The keywords include mainly but not limited to "Barriers in the implementation of Supply Chain Management in the construction and related industries", "Barriers of Supply Chain Management", "Barriers OR Benefits of Building Information Modelling", "Barriers OR Benefits of Blockchain", "Barriers OR Benefits of Blockchain applied in Construction Industry". For screening, the two factors used to determine paper selection were the year of publication and if the barriers/benefits are addressed in the construction business context or a comparable industry. The rationale behind the first was, some of the barriers/benefits identified a long time ago would have been neutralized with time as the concept evolves. This along with anticipating data saturation, only the literature published on or after 2010 were considered. The rationale for the latter was that the factors must have relevance for the construction industry, yet due to the lack of such focused literature in blockchain, the barriers stated as general discussions also need to be considered anticipating their relevance in the construction industry. Only English peer-reviewed academic literature such as journal articles, conference proceedings, and book chapters were considered and non-peer reviewed literature such as reports, web articles were omitted as enough data were available from academic literature alone. Subsequently, the complete text of the screened papers were reviewed to determine their suitability for inclusion. The articles were chosen based on their explicit discussion of SCM barriers and the barriers and benefits of BIM and blockchain. Those with general discussions outside the construction or related industries (other than with regard to blockchain), or that discuss potential innovations, were excluded as they cannot be effectively framed as existing barriers/benefits. Following these, as graphically depicted in FIG. 4, 21 papers on SCM, 33 on BIM and 20 on blockchain were shortlisted for the study which explicitly discuss the benefits and barriers of employing these techniques in the construction industry.

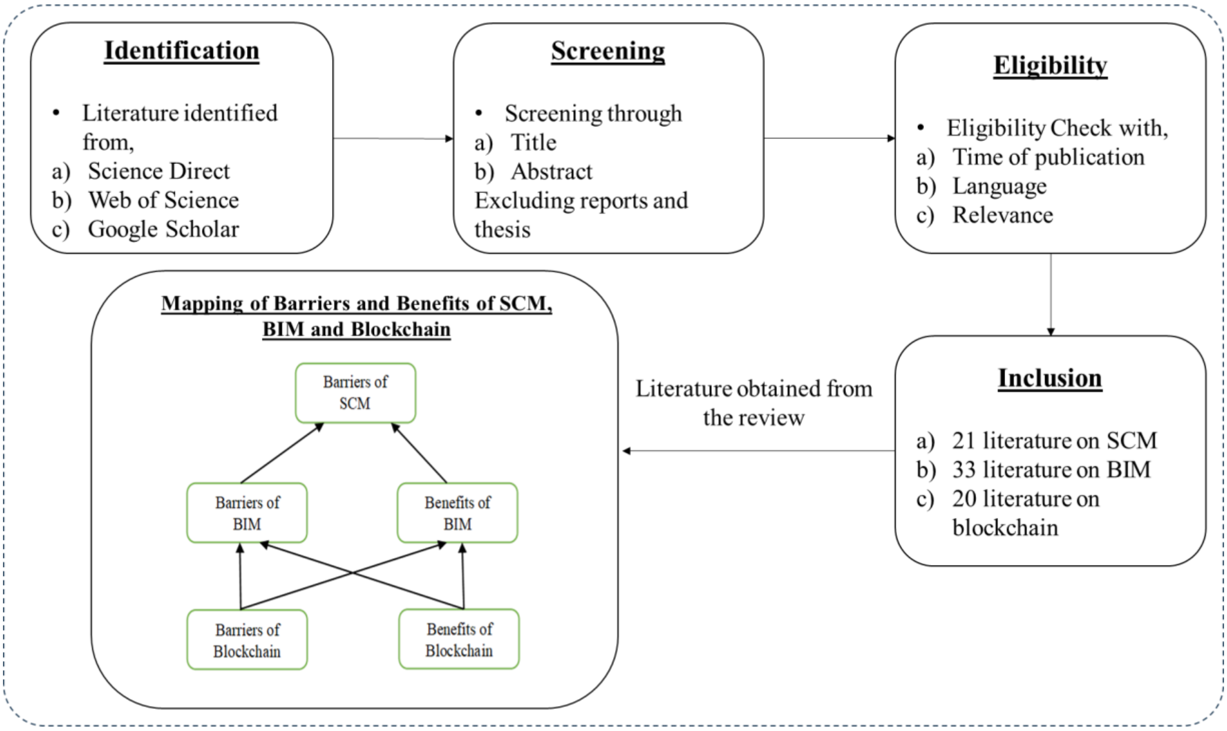

FIG. 4: Methodology of the research.

4. BARRIERS OF SCM MAPPED WITH BENEFITS AND BARRIERS OF BIM AND BLOCKCHAIN

Several benefits and barriers were collected for each SCM, blockchain and BIM from the literature. As they are mostly redundant, making them tedious to assess, they were categorized to key thematic areas. Previous studies about the barriers and benefits have also categorized their results. Deng et al. (2020), Charef et al. (2020), Tan et al. (2019) and Enshassi et al. (2019) have categorized their barriers as technical, management, environmental, financial and legal. Additionally, Costin et al. (2018) introduced process-related, mindset-related and ROI challenges, whereas Bayhan et al., (2019) included workforce and communication categories additionally. A closer look at the underlying meaning of these diverse categories showed that they converge to implications on social and technical perception of the concept under discussion, nature of the construction industry, organizational readiness, financial implications of adopting such concepts, legal implications and sustainability related concerns. Therefore, the benefits and barriers are divided into six categories, namely (i) Socio-Technical barriers, (ii) Industrial barriers, (iii) Organizational barriers, (iv) Financial barriers, (v) Legal and Institutional barriers, and (vi) Sustainability focused barriers. The goal of such a broad categorization is to include all the domains that these factors could affect and to provide a comprehensive analysis of how blockchain integration with BIM will affect SCM.

4.1 Barriers in Supply Chain Management in Construction Management

Table 1 summarizes the identified barriers of SCM implementation in the construction industry. In SCM, among the six categories, industrial barriers received the most attention from literature, implying that the nature of the construction industry impedes SCM optimization. Most of them are concentrated on the industry's inherent nature of uncertainty, fragmentation, one-off approach, short-term relationships etc. (Kim and Nguyen, 2020, Morel et al., 2020). The fragmented nature of industry and the ensuing short-term relationships were cited as the prime barriers (Behara et al., 2015, Salami et al., 2013, Luthra et al., 2022). Collectively, they usually lead to lack of productivity and innovation in comparison to other sectors (Hirusheekesan and Satanarachchi, 2021a). Further, industry's cost-based competitive tendering methods were also scrutinized, blaming too much focus on price and competition, resulting in the negligence of value, trust and cooperation (Costa et al., 2019). This advocates for holistic tendering processes moving beyond the traditional cost and competition model. Appropriate countermeasures would be required to mitigate these for SCM to be effective.

As for the organizational and socio-technical barriers, the usual bureaucratic barriers for any construction-based innovation were highlighted. Notably, the main barriers are lack of communication and information sharing among stakeholders (Luthra et al., 2022, Zhang et al., 2022). Since SCM works on mutual trust and information sharing, these could be crucial. In the case of financial barriers, lack of financial resources and investments and ambiguous financial returns seem the most significant (Lahane and Kant, 2021, Mojumder and Singh, 2021). However, as SCM is still in its infancy in the construction industry, these may disappear over time as the industry improves the processes of accounting for SCM, making financial benefits more evident. Further, the economies of scale as the industry iterates its SCM could eradicate the other financial barrier, i.e., high cost. Nonetheless, the lack of institutional support which is often cited (Mathiyazhagan et al., 2013, Tumpa et al., 2019) may not solve itself over time unless policies incentivizing SCM, and tax rebate schemes are introduced.

TABLE 1: Barriers of Supply Chain Management in Construction Industry.

Categories	Barriers	Description	Citations
Socio-Technical	Rigid procurement processes (SC_1)	Traditional procurement processes often focus on tender price than trust, value and cooperation.	Costa et al., 2019, Kim and Nguyen, 2020, Lahane and Kant, 2021
		Working with the same supplier for long period without using tendering method.	Salami et al., 2013, Papadopoulus et al., 2016, Luthra et al., 2022
	Lack of usage of IT systems (SC_2)	Though application of I.T. is promoted, construction practitioners resist or hesitate.	Kim and Nguyen, 2020, Lamba and Thareja, 2020, Morel et al., 2020
		I.T. of suppliers is inadequate.	Jayant and Azhar, 2014, Salami et al., 2013, Tumpa et al., 2019
Industrial	Complex (SC_3)	Supply Chain includes multiple trading members, making it complex.	Tumpa et al., 2019, Kim and Nguyen, 2020
	One-off approach of projects (SC_4)	Often every construction project is different and delivered to different client requirements.	Behera et al., 2015, Costa et al., 2019, Kim and Nguyen, 2020
		Each project is performed in different places, with different actors.	Behara et al., 2015, Papadopoulus et al., 2016, Costa et al., 2019
	Adversarial short-term relationships (SC_5)	Due to the competitive bidding process, little information sharing and motivation for continuous learning.	Behera et al., 2015, Papadopoulus et al., 2016, Kim and Nguyen, 2020
		Short-term objectives and price-oriented approaches.	Salami et al., 2013 Lamba and Thareja, 2020, Morel et al., 2020
		Actors work in opposition, achieving individual objectives, then working on a common objective.	Costa et al., 2019, Morel et al., 2020
	Fragmentation (SC_6)	Information generated by various sources contributes to fragmentation, resulting in lack of communication.	Behera et al., 2015, Tumpa et al., 2019, Luthra et al., 2022
		Fragmentation and misaligned relations hinder relationships among supply chain stakeholders.	Salami et al., 2013, Luthra et al., 2022, Zhang et al., 2022,
		SCM involves several companies, reducing opportunities for integration. Late involvement of some stakeholders too increases fragmentation.	Papadopoulus et al., 2016, Costa et al., 2019, Tumpa et al., 2019

		Separation between design and construction, lack of communication and collaboration.	Kim and Nguyen, 2020, Morel et al., 2020, Mojumder and Singh, 2021,
	Lack of training (SC_7)	Parties, especially small firms, often have little training on skills of SCM.	Salami et al., 2013, Kim and Nguyen, 2020, Lamba and Thareja, 2020, Mojumder and Singh, 2021
	Lack of understanding of SCM. (SC_8)	Parties do not understand the role of themselves and others and the benefits of SCM	Salami et al., 2013, Kim and Nguyen, 2020, Lamba and Thareja, 2020
	Discouraging innovation (SC_9)	Parties resist implementing innovative ideas, preferring to follow method statements and duties in the contract.	Behera et al., 2015, Costa et al., 2019, Kim and Nguyen, 2020
Organizational	Lack of communication, information sharing (SC_{10})	Ineffective communication & inefficient information sharing.	Behera et al., 2015, Kim and Nguyen, 2020, Samper et al., 2022
		Lack of company information systems that enable information sharing.	Salami et al., 2013, Costa et al., 2019, Zhang et al., 2022
	Dissatisfied customers (SC_{11})	Parties do not pay much attention to the customers' requirements.	Mathiyazhagan et al.,2013, Kim and Nguyen, 2020, Zhang et al., 2022
		Lack of coordination resulting in delays and dissatisfied customers.	Behera et al., 2015, Mojumder and Singh, 2021
	Non-supportive organizational structure (SC_{12})	Inappropriate to support SCM. Multi-tiers subcontracting system often sacrifice the efficiency.	Jayant and Azhar, 2014, Kim and Nguyen, 2020, Morel et al., 2020, Samper et al., 2022
		Not being supportive for cooperation with the suppliers.	Salami et al., 2013, Tumpa et al., 2019, Lamba and Thareja, 2020
	Lack of support from top management (SC_{13})	Management not knowing the idea of SCM, not being open to the idea of any change in their styles.	Salami et al., 2013, Costa et al., 2019, Tumpa et al., 2019, Lamba and Thareja, 2020
	Lack of motivation for continuous learning (SC_{14})	Construction firms by nature show little motivation for continuous learning.	Behera et al., 2015, Lamba and Thareja, 2020
		Construction culture features conservatism, closed mind set not opened to questioning and inflexible.	Mathiyazhagan et al., 2013, Costa et al., 2019, Tumpa et al., 2019, Luthra et al., 2022
	Less sharing of risk and benefits (SC_{15})	Self-interest along the chain. Parties resist treating others fairly and tend to manipulate the parts regarding their environment.	Salami et al., 2013, Costa et al., 2019, Kim and Nguyen, 2020, Morel et al., 2020
	Contractual non-commitments and lack of trust (SC_{16})	Even strategically and legally allied, not all parties would share managing supply chain.	Salami et al., 2015, Morel et al., 2020, Luthra et al., 2022
		Stakeholder relationships are characterized by exclusion, conflict and mistrust.	Behara et al., 2015, Salami et al., 2015, Costa et al., 2019
		Lack of long-term relationships and partnering.	Kim and Nguyen, 2020, Morel et al., 2020

Financial	Lack of financial resources, capabilities and benefits (SC_{17})	Lack of financial resources and capabilities.	Tumpa et al., 2019, Lahane and Kant, 2021, Mojumder and Singh, 2021
		Lack of financial benefits in the long run.	Lahane and Kant, 2021, Samper et al., 2022, Zhang et al., 2022
		Ambiguous financial returns.	Mathiyazhagan et al., 2013, Kim and Nguyen, 2020
	Lack of investment (SC_{18})	Capital requirement for the supply chain management.	Lamba and Thareja, 2020, Morel et al., 2020, Zhang et al., 2022
		Lack of upfront investment in supply chain implementation.	Tumpa et al., 2019, Lahane and Kant, 2021, Samper et al., 2022
	High cost (SC_{19})	High cost on research and investment.	Mathiyazhagan et al., 2013, Tumpa et al., 2019; Samper et al., 2022
Sustainability	Recycling (SC_{20})	Lack of recycling or reuse efforts in the industry.	Jayant and Azhar, 2014, Tumpa et al., 2019
	Green supply chain initiative (SC_{21})	Discouraged due to several reasons like lack of awareness, support from senior management, financial capabilities etc.	Mathiyazhagan et al., 2013, Jayant and Azhar, 2014, Lamba and Thareja, 2020
	Integrating circularity and lifecycle thinking (SC_{22})	Often neglected due to substantial upfront capital, lack of research and specialized personnel.	Lahane and Kant, 2021, Luthra et al., 2022, Zhang et al., 2022
Legal and Institutional	Lack of institutional support (SC_{23})	Lack of institutional support towards tax rebate policies, incentives, grant etc.	Mathiyazhagan et al., 2013, Tumpa et al., 2019, Morel et al., 2020, Lahane and Kant, 2021
		Lack of government policies incentivizing SCM.	Jayant and Azhar, 2014, Lamba and Thareja, 2020, Luthra et al., 2022
		Unwanted institutional intervention.	Samper et al., 2022

4.2 Benefits and Barriers of Building Information Modelling

4.2.1 Benefits of Building Information Modelling

Table 2 summarizes the benefits of BIM. Most of the technological benefits of BIM are based on eliminating the key issues in the construction industry like increasing productivity, efficiency and project delivery speed (Mehran, 2016, Zhang et al., 2016, Sriyolja et al., 2021). These are owing to the BIM model's ability to digitally design, commission, and detect errors and clashes. This reduces the time spent on reworks and decluttering, increasing the accuracy and the speed of the project (Matarneh and Hamed, 2017, Deng et al., 2020). Furthermore, it has been empirically demonstrated that BIM may be used throughout the lifecycle of a construction project, reducing fragmentation (Liu et al., 2015, Gerrish et al., 2017, Khudair et al., 2021).

A crucial industrial benefit is noticed, positing that BIM will promote accountability due to the inclusion of all stakeholders, instilling a sense of belonging and ownership (Tan et al., 2019). On the organizational level, BIM is perceived as removing an inherent disadvantage, namely the lack of collaboration among stakeholders (Abanda et al., 2017, Matarneh and Hamed, 2017, Tan et al., 2019). The capacity of BIM to include ICT frameworks for design and decision making encourages stakeholder engagement (Motawa and Carter, 2013). The ability to utilize digital platforms also, is recognized as improving resource management and decision making (Abanda et al., 2017). In addition, BIM is discussed as a driver of sustainable construction as it reduces wastage while facilitating energy efficiency and lifecycle assessment (Deng et al., 2020, Sriyolja et al., 2021), therefore, as the construction industry transitions to sustainable processes, BIM could play an important role in it.

TABLE 2: Benefits of Building Information Modelling.

Categories	Benefits	Description	Citations
Socio-Technical	Increased project delivery speed (BIM_{1+})	Using BIM in the construction leads to better time management.	Mehran, 2016, Zhang *et al*., 2016, Sriyolja *et al*., 2021
		Less time spent on site; commissioning increases the speed of delivery of the project.	Motawa and Carter, 2013, Abanda *et al*., 2017, Babatunde et al., 2021
		Compared to previous working modes, BIM decreases the total project duration by 7%.	Deng *et al*., 2020
	High accuracy (BIM_{2+})	BIM can eliminate unbudgeted change by 40% and decrease construction errors and conflicts.	Liu *et al*., 2015
		Exclusion of construction plus installation coordination issues prior to the procurement.	Motawa and Carter, 2013, Mehran, 2016
		Reduces rework during construction and detects clashes.	Matarneh and Hamed, 2017, Deng *et al*., 2020, Sriyolja *et al*., 2021
		Helps with synchronizing the design and construction plans and detecting design errors.	Bortoluzzi et al., 2019, Khudair *et al*., 2021, Xie et al., 2022
	Increased productivity and efficiency (BIM_{3+})	Buildings can be constructed quickly and precisely through automated assembly and enhanced processes, decreasing errors and conflicts, increasing efficiency.	Liu *et al*., 2015, Tivendale and Liu, 2015
		BIM has increased the profitability and productivity of construction projects.	Mehran, 2016, Zhang *et al*., 2016, Gerrish *et al*., 2017
		Less site disruption increases the productivity of the construction projects.	Abanda *et al*., 2017, Herr and Fischer, 2019
		BIM adoption maximizes productivity.	Matarneh and Hamed, 2017, Deng *et al*., 2020, Sriyolja *et al*., 2021
Industrial	Present in all stages of the project, reducing fragmentation. (BIM_{4+})	BIM was initially applied to the construction stage, later encompassing the operation and maintenance stages and infrastructural management.	Liu *et al*., 2015, Gerrish *et al*., 2017, Herr and Fischer, 2019
		Beneficial for all stages of construction projects.	Mehran, 2016, Edirisinghe et al., 2017
		Can be utilized on design, procurement, construction, operation and maintenance of a construction project.	Deng *et al*., 2020, Khudair *et al*., 2021, Edirisinghe et al., 2017
	Accountability (BIM_{5+})	Due to the inclusion of all stakeholders, there will be accountability.	Matarneh and Hamed, 2017, Abanda *et al*., 2017, Khudair *et al*., 2021
		Sense of belonging and ownership due to the inclusion.	Abanda *et al*., 2017, Tan *et al*., 2019

	High safety (BIM_{6+})	Projects that use BIM have recorded a significant decrease in accidents in the site.	Abanda *et al*., 2017, Koutamanis, 2020, Olawumi et al., 2018
Financial	Reduced cost (BIM_{7+})	Assists all stakeholders with reduction of costs and increase in profitability.	Mehran, 2016, Zhang *et al*., 2016, Khudair *et al*., 2021
		Lower preliminary costs, lower overheads and less waste leads to reduction of cost.	Abanda *et al*., 2017, Bortoluzzi et al., 2019
		The reduction of errors reduces the cost of the project significantly.	Deng *et al*., 2020, Khudair *et al*., 2021, Sriyolja *et al*., 2021
Organizational	Efficient decision making (BIM_{8+})	Collaborative viewing of models leads to improved communications and trust and enables rapid decision making.	Gu and London, 2010, Mehran, 2016, Abanda *et al*., 2017
	Increased collaboration among stakeholders (BIM_{9+})	BIM includes ICT frameworks and technologies that support stakeholder collaboration over project life cycle.	Motawa & Carter, 2013, Koutamanis, 2020
		BIM integrates design, construction, maintenance, and demolition data about building into a rich model.	Liu *et al*., 2015, Edirisinghe et al., 2017, Gerrish *et al*., 2017
		BIM promotes integrated collaboration communication and controlled project delivery.	Mehran, 2016, Zhang *et al*., 2016, Abanda *et al*., 2017
		BIM can be used as a collaborative design platform for information sharing to solve the interoperability.	Deng *et al*., 2020, Khudair *et al*., 2021
	Better resource management (BIM_{10+})	BIM platform improves efficiency of resource management and decrease human errors.	Edirisinghe et al., 2017, Tan *et al*., 2019, Koutamanis,2020
Sustainability	Facilitation of energy efficiency (BIM_{11+})	Performance assessment and simulation could be done leading to effective energy management and analysis from design to operation.	Gerrish *et al*., 2017, Walasek & Barszcz, 2017, Olawumi *et al*., 2018
	Facilitating lifecycle assessment (BIM_{12+})	Manages and predicts the process from planning to demolition and can control irregularities.	Edirisinghe *et al*., 2017, Deng *et al*., 2020
	Minimizing waste (BIM_{13+})	BIM assist stakeholders in reduction of waste and carbon emissions.	Liu *et al*., 2015, Olawumi et al., 2018, Koutamanis, 2020
		BIM reduces the overall cost of the project by reducing the waste.	Abanda *et al*., 2017, Costin et al., 2018, Sriyolja *et al*., 2021
		BIM reduces unwarranted changes of design and improves collaboration among stakeholders.	Motawa and Carter, 2013, Abanda *et al*., 2017; Costin et al., 2018

4.2.2 Barriers of Building Information Modelling

Table 3 summarizes the barriers in adoption of BIM in the construction industry. BIM adoption, like SCM, faces several significant socio-technological and industrial barriers. The absence of BIM software compatibility is such a notable widespread barrier (Bui et al., 2016, Herr and Fischer, 2019). This is due to the lack of interoperability or that BIM software in general does not adhere to domestic standards or requirements. This needs to be addressed as numerous regions including Europe, Australasia and China have their own standards to which the software should adhere; as a result, players in the technology diffusion process are bound to encounter incompatibilities in the technical landscape. Another important barrier is, though BIM enhances the project pace and cost, literature suggests that it increases the workload (Charef et al., 2019, Deng et al., 2020), offsetting the total effect. Workload increases are mostly because of relatively heavy initial work in model development, since stakeholders must expend additional time and effort to ensure the degree of development and compatibility (Bui et al., 2016, Walasek and Barszcz, 2017). Similarly, while BIM increases information sharing (Olawumi et al., 2018, Xie et al., 2022), research has also found information aversion and stakeholder mistrust as barriers to BIM adoption. Though such reluctance and mistrust depend on the contract type, such counterproductive barriers need to be dealt with rigour as they could reverse the initial intentions of applying BIM. Another key barrier is the lack of focus on dispute resolution mechanisms for BIM-based projects (Liu et al., 2015, Ma et al., 2020). Although BIM in Levels 2 and 3 promotes collaborative design and management paradigm, stakeholders could be disinclined to assume responsibilities for a mistake of another party. This could inhibit the adoption as well as adaptation to a novel BIM environment. Hence, sound dispute resolution and risk sharing mechanisms on different contract types are necessary for a successful BIM adoption.

High implementation and maintenance cost of software is considered a main financial barrier (Tan et al., 2019, Utomo and Rohman, 2019), complemented by the ambiguous economic benefits due to the lack of empirical evidence from previous BIM-based projects (Migilinskas et al., 2013, Charef et al., 2019). Nonetheless, as adoption grows, costs may be reduced through economies of scale, generating sound data on the economic benefits of BIM adoption. The absence of standard contract form (Koutamanis, 2020, Sriyolja et al., 2021) and lack of standards and execution guidelines from the governments/institutions (Babatunde et al., 2021, Xu et al., 2022) were also cited as a significant barrier of BIM. As with SCM, proper consideration must be given to this because, despite BIM's relatively bottom-up progress, it will confront difficulties in the absence of adequate institutional and regulatory backing. Therefore, adequate awareness initiatives and empirical evidence must be offered to key industries to motivate BIM learning and adoption.

TABLE 3: Barriers for the implementations of Building Information Modelling.

Categories	Barriers	Description	Citations
Socio-Technical	Lack of compatibility of BIM software (BIM_{1-})	International BIM software may not always conform to domestic standards and codes.	Gu and London, 2010, Bui et al., 2016, Tan et al., 2019
		Less interoperability.	Bui et al., 2016, Walasek and Barszcz, 2017, Charef et al., 2019
		Domestic BIM software does not meet the actual work requirements.	Deng et al., 2020, Ma et al., 2020
		Insufficient maturity of software function and platform.	Liu et al., 2017, Charef et al., 2019, Xu et al., 2022
	Increase in workload (BIM_{2-})	BIM increases the workload compared to the previous methods.	Gu and London, 2010, Herr and Fischer, 2019, Matarneh and Hamed, 2017
		Stakeholders spend extra time and effort ensuring the model have the required development.	Bui et al., 2016, Oraee et al., 2019, Tan et al., 2019
		BIM increases the design workload.	Deng et al., 2020, Xu et al., 2022
Industrial	Lack of security (BIM_{3-})	Professionals are worried about the safety of the information database.	Gu and London, 2010, Mehran, 2016, Herr and Fischer, 2019
		Many researchers worry about the intellectual property rights over BIM implementation.	Olawumi et al., 2018, Charef et al., 2019, Tan et al., 2019, Celik et al., 2023
	Lack of BIM specialists and knowledge (BIM_{4-})	Lack of skilled personnel, leading to lack of BIM expertise and suitable conceptions to use BIM features.	Liu et al., 2015, Liu et al., 2017, Mehran, 2016, Zhang et al., 2016

		Lack of expertise in both the organization and the project team.	Gu and London, 2010, Walasek and Barszcz, 2017, Costin et al., 2018
		Contractors claimed that lack of skilled personnel in BIM is more critical than consultants, suggesting that BIM talents tend to gather in consultancy.	Bui et al., 2016, Ma et al., 2020, Koutamanis, 2020
	Resistant to change (BIM_{5-})	BIM changes project delivery and an organization's structure, to which the stakeholders are resistant.	Liu et al., 2016, Charef et al., 2019, Oraee et al., 2019
		Unwillingness to learn and adapt to BIM.	Mehran, 2016, Olawumi et al., 2018, Koutamanis, 2020
		Resistance to change.	Gu and London, 2010, Bui et al., 2016, Matarneh & Hamed, 2017
		Lack of time, motivation and energy to learn BIM.	Charef et al., 2019, Herr and Fischer, 2019, Deng et al., 2020
	Inadequate market demand (BIM_{6-})	No demand from client and other relevant stakeholders.	Matarneh and Hamed, 2017, Charef et al., 2019, Oraee et al., 2019
		Lack of client's requirement or pressure from competitors.	Walasek and Barszcz, 2017, Olawumi et al., 2018, Ma et al., 2020
Financial	High cost (BIM_{7-})	High initial and implementation cost of the software.	Olawumi et al., 2018, Charef et al., 2019, Deng et al., 2020
		Lack of comprehensive ways of cost savings in BIM.	Mehran, 2016, Deng et al., 2020
		Concerns on squandering time on labour training, under or overestimating the resources to be allocated.	Tan et al., 2019, Utomo and Rohman, 2019, Xu et al., 2022
		Extra investment on BIM use.	Bortoluzzi et al., 2019, Ma et al., 2020, Xie et al., 2022
		Implementation of BIM involves huge capital outlays.	Herr and Fischer, 2019, Abanda et al., 2017, Babatunde et al., 2021
	Ambiguous economic benefits (BIM_{8-})	Lack of comprehensive cost savings by BIM adoption.	Migilinskas et al., 2013, Mehran, 2016, Xu et al., 2022
		Economic benefits brought by BIM are often ambiguous.	Olawumi et al., 2018, Tan et al., 2019, Deng et al., 2020
		Doubtful return on investment.	Migilinskas et al., 2013, Charef et al., 2019, Utomo and Rohman, 2019
Organizational	Learning curve (BIM_{9-})	Initial inaccuracies due to learning curve.	Liu et al., 2015, Olawumi et al., 2018, Gerrish et al., 2017

		Lack of empirical evidence from the previous successful projects.	Migilinskas et al., 2013, Liu et al., 2017, Utomo and Rohman, 2019
		Companies that successfully use BIM are reluctant to share experiences.	Herr and Fischer, 2019, Deng et al., 2020
	Inconsistent managerial processes (BIM_{10-})	Lack of support from senior management	Migilinskas et al., 2013, Liu et al., 2017, Mehran, 2016
		Leaders at the corporate level lack long-term vision and confidence in BIM.	Deng et al., 2020, Xie et al., 2022, Xu et al., 2022
		Leaders and professionals in developing nations are afraid of BIM as it requires a transition from the conventional processes.	Babatunde et al., 2021
	Lack of information sharing and trust (BIM_{-11-})	Stakeholders have shown negative attitudes towards working collaboratively.	Liu et al., 2017, Olawumi et al., 2018, Tan et al., 2019
		Lack of effective collaborative work processes between project participants.	Oraee et al., 2019, Utomo and Rohman, 2019, Deng et al., 2020
Legal and Institutional	Absence of standard form of contract for BIM application (BIM_{12-})	There are potentially serious contractual issues that must be addressed.	Gu and London, 2010, Mehran, 2016, Matarneh and Hamed, 2017
		A new form of contract is needed to avoid potential arguments centred on BIM responsibilities and liabilities.	Liu et al., 2017, Tan et al., 2019, Deng et al., 2020, Xu et al., 2022
		Inadequate institutional support for regulation resulting in each BIM user adopting their own principle.	Charef et al., 2019, Herr and Fischer, 2019, Babatunde et al., 2021
	Lack of BIM standards and guidelines (BIM_{13-})	Absence of detailed guidance or standards on how BIM could be best utilized.	Zhang et al., 2016, Gerrish et al., 2017, Costin et al., 2018
		No relevant document to formalize and standardize BIM-based workflow.	Tan et al., 2019, Xu et al., 2022
		Insufficient institutional guidance and laws.	Charef et al., 2019, Oraee et al., 2019, Deng et al., 2020, Babatunde et al., 2021
	Lack of dispute resolution mechanism (BIM_{14-})	Responsibilities for inaccuracies and immature dispute mechanisms.	Liu et al., 2015, Liu et al., 2017, Oraee et al., 2019
		BIM implementation blurs the responsibility amongst stakeholders, preventing assigning of individual liability when mistakes are done.	Tan et al., 2019, Celik et al., 2023
		Lack of clear definition of organizational responsibilities if disputes arise.	Ma et al., 2020

4.3 Benefits and Barriers of Blockchain

4.3.1 Benefits of Blockchain

Although blockchain has not yet won much attention in the construction industry, it offers several socio-technological benefits to rationalize its adoption in the construction industry. Table 4 summarizes such potential benefits, derived with the help of literature which discusses blockchain in various industrial applications. Few of its notable benefits are high security (Golosova and Romanovs, 2018, Justinia, 2019), veracity of the data (Wang et al., 2018, Abu-elezz et al., 2020) and the anonymity of the users (Niranjanamurthy et al., 2019). These characteristics are due to the proof of validity and authorization to enforce constraints that blockchain employs (Clohessy and Acton, 2019), limiting the possibility to create bogus entries, reinforcing the security of the network. Anonymity is further enhanced by the ability to generate several addresses, avoiding identity exposure (Ali et al., 2021). Yet, many of these operate as double-edged swords, exploitation of which would be detrimental and might create impediments to blockchain adoption in general for any industry.

Blockchain also offers benefits like addressing trust concerns among the users (Perera et al., 2020, Ali et al., 2021) and increasing decentralization (Golosova and Romanovs, 2018, Tijan et al., 2019). Nevertheless, these are still under debate. Each action in blockchain is recorded and accessible to all participants, and it cannot be easily altered or erased, increasing transparency. Furthermore, decisions taken over the chain such as validating transactions or adding/removing users, could only be made with the consensus of all users, improving user trust. Although still debated if it is an advantage or disadvantage, one of the main features of blockchain is its decentralized cooperation, where integrity guarantees are not provided by a centralized party, rather, by the consensus of the entire network, reducing bureaucracy and delays. Furthermore, the ability for any user to view the information at any time boosts transparency in the organization, resulting in effective record keeping (Golosova and Romanovs, 2018, Niranjanamurthy et al., 2019, Perera et al., 2020).

It should be highlighted however, that most of the potential benefits of blockchain are in the socio-technical domain while only some could be found in the organizational domain. This could be as blockchain adoption is still in its infancy and has not been fully implemented as a dependable tool in any industry. The debate on its safety, security and feasibility is still at forefront, hence not many financial benefits are mentioned in the literature as well. More benefits may be discovered as adoption grows, especially in the financial and organizational domains. Additionally, some of the benefits like decentralized cooperation and disintermediation may later be perceived even as barriers.

TABLE 4: Benefits of Blockchain.

Categories	Benefits	Description	Citations
Socio-Technical	Anonymity (BC_{1+})	Improve trust between node to node, therefore data transfer can be anonymous	Nofer et al., 2017, Niranjanamurthy *et al*., 2019, Clohessy and Acton, 2019
		Each user interacts with the network using a generated address. A user could generate many addresses avoiding identity exposure.	Tijan *et al*., 2019, Ali *et al*., 2021, Li et al., 2019
		In blockchain transactions, as public and private keys are used, people can choose to remain anonymous, enabling third parties to verify their identity.	Perera *et al*., 2020, Rodrigo et al., 2020, Gad et al., 2022
	High security (BC_{2+})	Security is increased by the use of its own proof of validity and authorization to enforce the constraints.	Golosova and Romanovs, 2018, Niranjanamurthy *et al*., 2019, Abu-elezz *et al.*, 2020
		Private blockchain restricts access to pre-defined users reinforcing the system's security.	Clohessy and Acton, 2019, Perera et al., 2020, Yang et al., 2020
		Using off-chain data storage and heavy processing improving the security of data.	Tijan *et al*., 2019, Ali *et al*., 2021, Chung et al., 2022
		Uses encryption mechanisms involving asymmetric public-key cryptography to secure the validity of the stored information and to prevent fraud.	Li et al., 2019, Islam *et al*., 2020, Perera *et al*., 2020
	Auditability (BC_{3+})	Can show any transactional issue and correct them if it is necessary, making it traceable and auditable.	Tijan *et al*., 2019, Ali *et al*., 2021, Chung et al., 2022

		Transactional chains store history of ownership providing auditability.	Niranjanamurthy *et al*., 2019, Yang *et al*., 2020, Gad et al., 2022
		Transactions cannot be altered/deleted once added to the blockchain.	Clohessy and Acton, 2019, Li et al., 2019, Rodrigo et al., 2020
		Since transaction is validated and recorded with a timestamp, users can easily verify and trace previous records through accessing any node.	Wang *et al*., 2018, Islam *et al*., 2020, Perera *et al*., 2020, Casino *et al.*, 2019
	Veracity (BC_{4+})	Inability to create bogus entries as each user is provided with the unique identity and could be traced back.	Golosova and Romanovs, 2018, Perera et al., 2020, Gad et al., 2022
		Fool proof data.	Niranjanamurthy *et al*., 2019
		Since each transactions spreads across, and the network needs to confirm and record in blocks distributed in the whole network, it is nearly impossible to tamper.	Wang *et al*., 2018, Abu-elezz *et al*., 2020, Doguchaeva *et al*., 2022
		Mathematical operations used in blockchain are indispensable to the system, forcing the verifying nodes to expend processing power which would be wasted if they include any fraudulent or invalid transactions.	Turk and Klinc, 2017, Tijan *et al*., 2019, Perera et al., 2020
		Same copy of the historical records of the ledger is replicated and stored in the network.	Perera *et al*., 2020, Ali *et al*., 2021, Celik *et al.*, 2023
	Increased quality (BC_{5+})	Blockchain data is complete, timely, accurate and widely available.	Niranjanamurthy *et al*., 2019, Tijan *et al*., 2019, Ali *et al*., 2021
	Decentralized cooperation (BC_{6+})	Blockchain is a decentralized system, and it is the main benefit of this technology.	Golosova and Romanovs, 2018, Celik *et al.*, 2023, Han *et al*., 2023
		A transaction can be conducted between any two peers without the authentication of the central agency.	Wang *et al*., 2018, Justinia, 2019, Yang *et al*., 2020
		The elimination of a central authority/broker with innovative consensus protocols.	Wang et al., 2018, Clohessy and Acton, 2019, Nanayakkara et al., 2021
		Integrity guarantees are not provided by any centralized party, but rather the consensus of the entire network.	Wang et al., 2018, Nawari and Ravindran, 2019b, Tijan *et al*., 2019,
		Blockchain consists of a decentralized peer-to-peer network.	Li et al., 2019, Nawari and Ravindran, 2019b, Perera *et al*., 2020
Industrial	Execution of smart contracts (BC_{7+})	Programmable blockchains like Ethereum use scripting languages to write digital contracts that could be used in construction contracts.	Clohessy and Acton, 2019, Justinia, 2019, Ali *et al*., 2021, Doguchaeva *et al*., 2022,
	Improved trust (BC_{8+})	Each action is recorded to the blockchain, and the data of records are available to every participant and cannot be changed.	Golosova and Romanovs, 2018, Justinia, 2019, Abu-elezz *et al.*, 2020
		Does not necessitate high confidence levels in single authorities, distributing the trust.	Clohessy and Acton, 2019, Li et al., 2019, Chung et al., 2022

		When adding data, majority of the participants need to accept it to become part of the blockchain, increasing the trust among the users.	Nawari and Ravindran, 2019b, Perera *et al*., 2020, Ali *et al*., 2021
	Improved customer experience (BC_{9+})	Traditionally, transactions take a lot of time during the banking processing. Using blockchain reduces the processing time.	Golosova and Romanovs, 2018, Niranjanamurthy *et al*., 2019, Tijan *et al*., 2019, Ali *et al*., 2021
Organizational	Transparency (BC_{10+})	Registration of each transaction allows viewing the information of the transaction at any time and it is public for all users.	Golosova and Romanovs, 2018, Niranjanamurthy *et al*., 2019, Perera *et al*., 2020
		Creates an efficient and accurate record keeping.	Clohessy and Acton, 2019, Casino *et al.*, 2019, Yang *et al*., 2020
		Every member has access to the same data, providing a single point of truth.	Tijan *et al*., 2019, Islam *et al*., 2020, Ali *et al*., 2021, Han *et al*., 2023
		Each transaction could be traced back to the previous transaction iteratively.	Wang *et al*., 2018, Chung et al., 2022, Doguchaeva *et al*., 2022
	Disintermediation (BC_{11+})	The system works without third-party organization and all the participants make the decisions.	Golosova and Romanovs, 2018, Justinia, 2019, Islam *et al*., 2020
		Blockchain enables a database to be directly shared without a central administrator.	Turk and Klinc, 2017, Niranjanamurthy *et al*., 2019, Gad et al., 2022
		Integrity guarantees are not provided by any centralized party, but rather the consensus of the entire network.	Tijan *et al*., 2019, Chung et al., 2019, Doguchaeva *et al*., 2022
		Blockchain negates the involvement of third parties, avoiding the need to trust the intermediaries.	Li et al., 2019, Perera *et al*., 2020, Han *et al*., 2023

4.3.2 Barriers of Blockchain

Blockchain too has crucial socio-technological barriers as shown in Table 5. Notables are the scalability (Abu-elezz et al., 2020), interoperability (Gad et al., 2022) and data storage issues (Wang et al., 2018, Perera et al., 2020), which could have significant implications for its application in the construction industry. It is perceived that public blockchains have limits on transaction processing rate and data transmission latency. This restricts the rate of processing transactions executed per second, curtailing the speed and storage capacity of blockchain solutions (Niranjanamurthy et al., 2019, Shojaei et al., 2020). Also, the rapid growth in the blockchain applications have created heterogeneous solutions (Gad et al., 2022), creating an interoperability issue. However, as IT is a highly transformative industry with rigorous innovation, rapid improvements can be expected. Literature has extensively focused on security concerns as well, especially since the blockchain based smart contracts being merely computer programs that could easily contain security loopholes making the networks susceptible to theft and loss causing cyber-attacks (Islam et al., 2020, Doguchaeva et al., 2022). Also, the ability to access all the data by the entire user base naturally risks the privacy of data. However, the emergence of "Permissioned Blockchain" privileges certain users reducing the risk, yet at the same time, compromising the decentralization to an extent (Perera et al., 2020).

Further, decentralization and disengagement of a trusted third party make it challenging for the institutions and legal authorities, impeding the social acceptance of blockchain (Abu-elezz et al., 2020, Ali et al., 2021). General blockchain technology is viewed with caution in many contexts, because of their application to reinforce criminal and unethical activities such as money laundering and terrorism funding (Perera et al., 2020). In addition, there is a key technological and social barrier in blockchain called selfish mining (Gad et al., 2022), where the mined blocks are kept without broadcasting. The blockchain is susceptible to attacks of colluding selfish miners.

Generally, it is convinced that nodes with over 51% computing power could reverse the blockchain and its transactions (Wang et al., 2018), adding doubt to its reliable and trust-based uses in the financial domains.

Another somewhat different, yet crucial barrier observed is the high energy consumption of the computer hardware that runs the blockchains (Gabison, 2017, Abu-elezz et al., 2020). Due to the proof-of-work model of mining, high computational power is needed (Islam et al., 2020, Perera et al., 2020), therefore it is likely to consume higher energy compromising sustainability. Construction industry which already faces the criticism of unsustainable energy consumption, may reinforce such criticisms if heavily relied on blockchain. Nevertheless, attempts are made to address this drawback using other consensus mechanisms such as Ethereum switching to Proof-of-Stake, drastically reducing the energy consumption during mining, suggesting in future it may have better energy performance.

TABLE 5: Barriers for the implementation of Blockchain.

Categories	Barriers	Description	Citations
Socio-Technical	Scalability (BC_{1-})	Related to the limited rate of processing transactions executed per second.	Niranjanamurthy et al., 2019, Abu-elezz et al., 2020, Rodrigo et al., 2020
		The prefixed block size and block creation time are efficient for a fixed number of transactions processing, but a higher number of transactions cause slower processing.	Turk and Klinc, 2017, Boutkhoum et al., 2021, Gad et al., 2022
		Public blockchains have limits on transaction processing rate and data transmission latency handling on average 3-20 transactions per second.	Wang et al., 2018, Casino et al., 2019, Perera et al., 2020, Yang et al., 2020
	Security (BC_{2-})	Blockchain is susceptible to cyber-attacks taking control over the majority of blockchain networks.	Abu-elezz et al., 2020, Yang et al., 2020, Ali et al., 2021
		Given the similarities between smart contracts and programs, errors frequently exist with smart contracts, causing theft and losses.	Clohessy and Acton, 2019, Li et al., 2019, Islam et al., 2020, Boutkhoum et al., 2021, Gad et al., 2022
		The user's private key is the identity and security credential. If it is stolen, it is hard to recover the information.	Casino et al., 2019, Nawari and Ravindran, 2019b, Niranjanamurthy et al., 2019, Perera et al., 2020
	Interoperability (BC_{3-})	Due to the lack of trust and limited open standards, cause difficulties in exchange of information.	Nawari and Ravindran, 2019b, Abu-elezz et al., 2020, Ali et al., 2021
		The fast-paced growth in blockchain created heterogeneous solutions creating interoperability issue.	Casino et al., 2019, Li et al., 2019, Islam et al., 2020, Gad et al., 2022
	Privacy (BC_{4-})	As there are no privileged users in a public blockchain, every node can be accessed without any permission.	Clohessy and Acton, 2019, Niranjanamurthy et al., 2019, Perera et al., 2020, Ali et al., 2021
		Cannot guarantee the transactional privacy as values of transactions and balances for each public key are publicly visible.	Wang et al., 2018, Nawari and Ravindran, 2019b, Perera et al., 2020, Boutkhoum et al., 2021
		Public blockchains jeopardize information privacy due to its immutability.	Gabison, 2017, Clohessy and Acton, 2019, Nawari and Ravindran, 2019
	Slow processing (BC_{5-})	Confirming a transaction might take a long time and high processing time.	Casino et al., 2019, Niranjanamurthy et al., 2019, Shojaei et al., 2020

	Data storage (BC6-)	Not considered suitable for storing Big Data due to the large volumes of data and low velocity of data.	Wang et al., 2018, Casino et al., 2019, Perera et al., 2020
	Social acceptance (BC7-)	Decentralization of data make it difficult for legal authorities, highlighting privacy as a concern.	Gabison, 2017, Abu-elezz et al., 2020, Ali et al., 2021
		Lack of trust with regards to the decentralized system.	Gabison, 2017, Clohessy and Acton, 2019, Gad et al., 2022
		Represents a complete shift to a decentralized network which might not attract users and operators.	Li et al., 2019, Nawari and Ravindran, 2019b, Niranjanamurthy et al., 2019
	Selfish mining (BC8-)	The mined blocks are kept without broadcasting and could view the data, only when satisfying specified requirements.	Gabison, 2017, Wang et al., 2018, Gad et al., 2022
		Generally, it is convinced that nodes with over 51% computing power could reverse the blockchain and the transaction.	Wang et al., 2018, Nawari and Ravindran, 2019b, Prakash et al., 2022
	Criminal Activity (BC9-)	The exchange of cryptocurrencies or tokens occur pseudonymously and can be used for any illegal activities, it is difficult to track users.	Li et al.., 2019, Perera et al., 2020, Prakash et al., 2022
Industrial	Lack of skilled personnel (BC10-)	Lack of qualified specialists.	Casino et al., 2019, Li et al., 2019, Doguchaeva et al., 2022
		Lack of research done.	Clohessy and Acton, 2019, 0Niranjanamurthy et al., 2019
Organizational	Organizational Readiness (BC11-)	The organization might not be ready to transform to the decentralized method of doing operations.	Clohessy and Acton, 2019, Li et al., 2019; Ali et al., 2021
		Lack of organizational policies.	Boutkhoum et al., 2021
Financial	High cost (BC12-)	Implementation cost of the network is high.	Niranjanamurthy et al., 2019, Abu-elezz et al., 2020, Yang et al., 2020
		Maintenance cost of the network is high.	Wang et al., 2018, Yang et al., 2020, Ali et al., 2021
		The average cost of the transaction is between 75 and 160 dollars and most of it is due to energy consumption and high initial cost.	Golosova and Romanovs, 2018, Clohessy and Acton, 2019
Sustainability	High energy consumption (BC13-)	Due to the large number of users joining the networks.	Gabison, 2017, Wang et al., 2018, Abu-elezz et al., 2020
		General sustainability concerns.	Li et al., 2019, Islam et al., 2020, Ali et al., 2021
		High level of energy consumption for data processing and storage.	Casino et al., 2019, Boutkhoum et al., 2021, Doguchaeva et al., 2022
		Power consumption is needed for keeping a real-time ledger. The miners are attempting to solve a lot of solutions per seconds to validate transactions.	Golosova and Romanovs, 2018, Clohessy and Acton, 2019, Islam et al., 2020, Perera et al., 2020
Legal and Institutional	Lack of regulations and laws (BC14-)	Lack of a legal framework regulating blockchain.	Clohessy and Acton, 2019, Abu-elezz et al., 2020, Islam et al., 2020

	It is challenging to manage the governance of the blockchain platform among different participants.	Niranjanamurthy et al., 2019, Ali et al., 2021, Doguchaeva et al., 2022,
Contractual Enforcement (BC_{15-})	If any voluntary contract is sanctioned by the central government and not connected with the law, contractual enforcement issue arises.	Gabison, 2017, Islam et al., 2020, Gad et al., 2022

4.4 Conceptual Map to explore the synergies of Blockchain, BIM and SCM

In FIG.5, FIG.6 and FIG.7 the barriers and benefits of SCM, BIM and blockchain are mapped demonstrating how they can impact each other. Green arrow indicates a unit positive impact (+1) while red arrow represents a unit negative impact (-1). For instance, based on the literature discussions, it could be easily perceived that the accountability among participants by BIM adoption (BIM_{5+}) could be enhanced by auditability, improved trust and transparency while being negatively influenced by criminal activity and lack of regulations related to blockchain adoption. Hence, the net impact created by 3 positive and 2 negative impacts is (+1). Similar analysis was done to the rest of the barriers and benefits of BIM as well. The cumulative impact was carried forward to FIG. 7 in which they were mapped with the barriers of SCM. For example, the adversarial short-term relationships in SCM (SC_5) could be neutralized by the positive impact by the increased collaboration among the stakeholders (BIM_{9+}). Hence, the aggregated impact for SC_5 is.

Impact Carried forward by BIM Benefit + Impact on SC Barrier = +5 + (+1) = +6

The validity and suitability of the above method is reinforced by studies like Sacks et al. (2010) and Tezel and Aziz, (2017) which use somewhat similar conceptual mapping processes to demonstrate the relationship between BIM and lean construction and I.T and visual management in construction industry respectively.

Accordingly, it was identified that the integration of blockchain with BIM neutralizes the original cost saving of BIM (BIM_{7+}) due to blockchain's high cost (BC_{12-}) and high energy consumption (BC_{13-}). They also neutralize the sustainability drive created by BIM (BIM_{11+}). In addition, integration of blockchain may nullify the project speed (BIM_{1+}) and productivity (BIM_{3+}) supplemented by BIM. However, blockchain enhances the collaboration of stakeholders (BIM_{9+}) which may reduce bottlenecks for BIM implementation especially in its higher levels of maturity. Similar impact could be seen with respect to accuracy of BIM models (BIM_{2+}) as well.

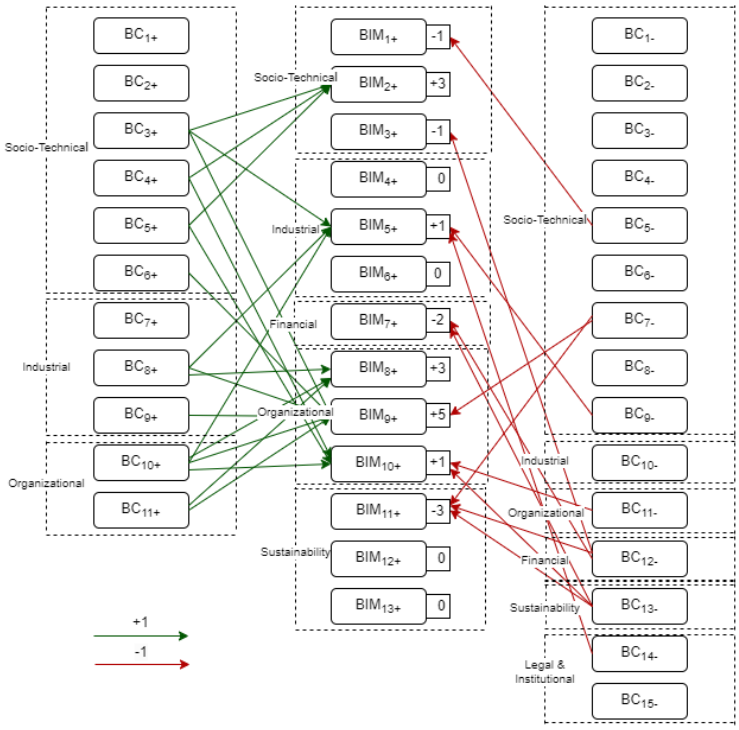

FIG. 5: Mapping the benefits of BIM with barriers and benefits of blockchain.

As for the barriers of BIM, many are complemented by blockchain barriers. Specially the lack of agreed upon guidelines (BIM_{13-}), lack of specialists and expert knowledge (BIM_{4-}), lack of a standard form of contract (BIM_{12-}) and dispute mechanism (BIM_{14-}) become more critical due to the integration with blockchain, may be as both these are fairly new and need more development. The security aspect also would be of concern for the practitioners (BIM_{3-}). The only barrier of BIM that is counterbalanced by blockchain is the trust concerns with relation to information sharing (BIM_{11-}). This is due to the disintermediation (BC_{11+}), transparency (BC_{10+}), and auditability (BC_{3+}) conceptually promised by blockchain.

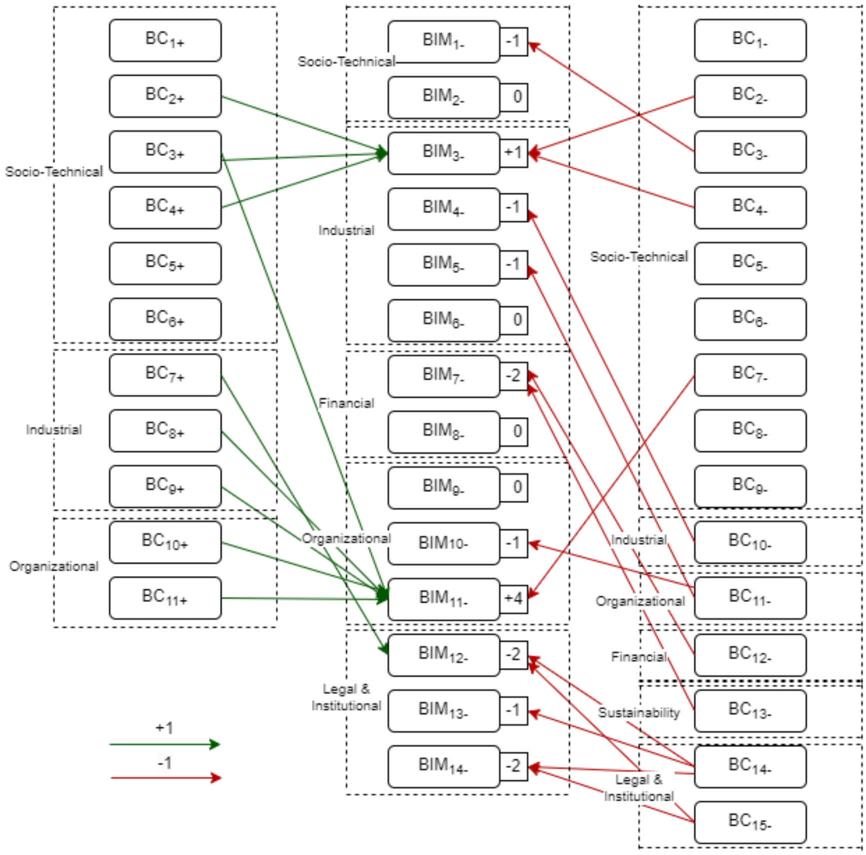

FIG. 6: Mapping the barriers of BIM with the benefits and barriers of blockchain.

Integration of BIM with SCM, complements several barriers of SCM such as lack of institutional (SC_{23}) and management support (SC_{13}), lack of training and knowledge (SC_7), high cost (SC_{19}) etc. However, the important factor to be noted here is that most of these barriers could be eradicated with time over proper awareness and economies of scale, especially those related with the support of stakeholders and collaboration. The key area in which this integration works the most for SCM is in increasing the trust, realationships and satisfaction of the stakeholders (SC_5, SC_{10}, SC_{16}). It is deemed that this synergy would promote sharing of benefits and risk among stakeholders while increasing the trust among them. It would also improve the circularity and lifecycle thinking (SC_{22}) of the industry while promoting the recycling efforts (SC_{20}) to extend the success of SCM to further to SSCM.

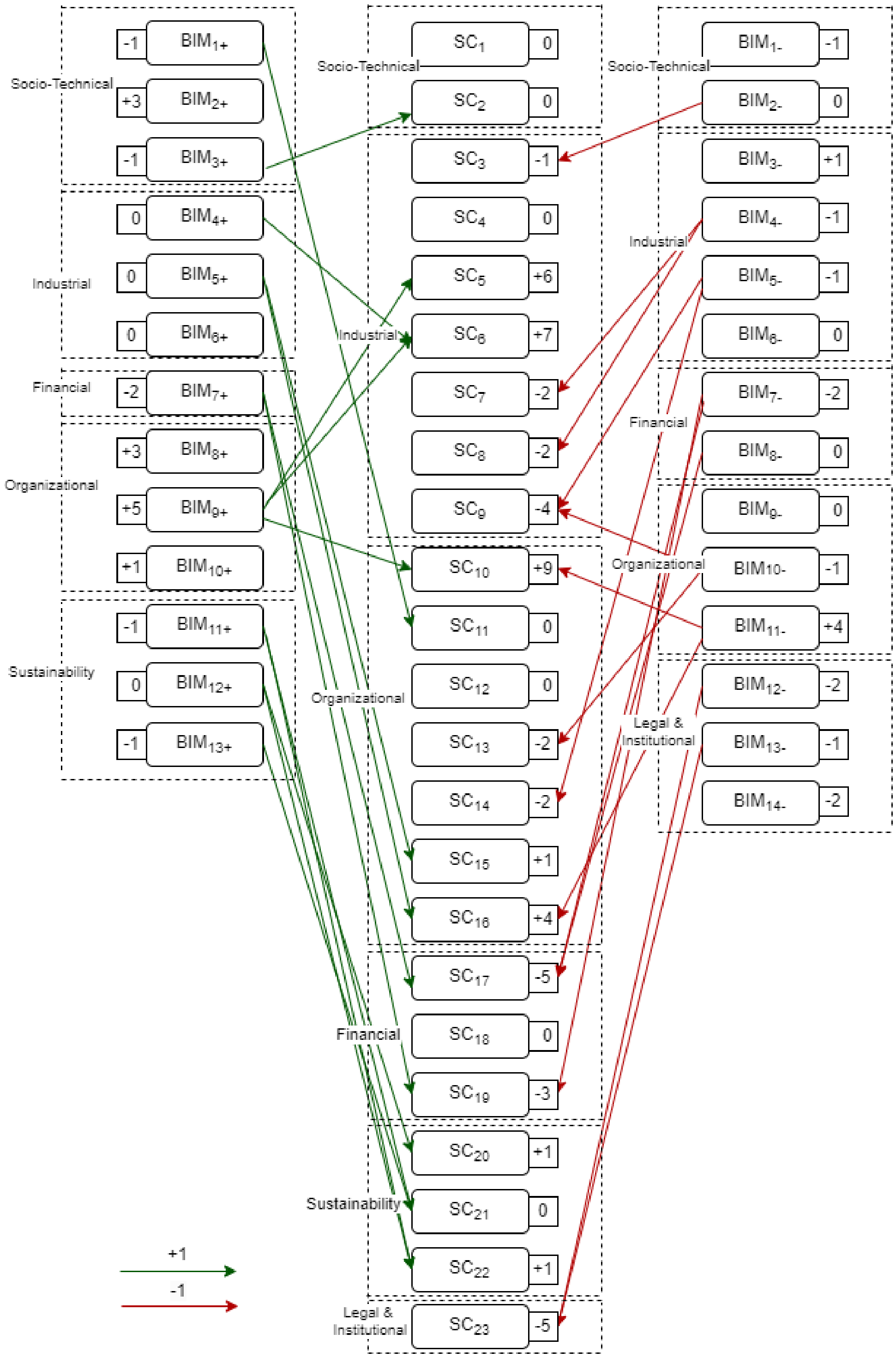

FIG. 7: Mapping the barriers of SCM with the benefits and barriers of BIM.

5. CONCLUSION

The study has revealed several advantages and disadvantages for the applications of SCM, BIM and blockchain as stand-alone yet interactive technologies in the construction sector. They span across various Social, Technological, Industrial, Organizational, Financial, Legal-Institutional and Sustainability focused dimensions. The study focused on identifying the barriers and benefits of BIM and blockchain to explore their likely cumulative impact on resolving the observed general barriers of the SCM. Some of the barriers identified are highly strenuous to overcome as they are linked to the nature of the industry, e.g., fragmentation, one-off approach, high workload etc. However, some are associated with stakeholder interaction such as the lack of trust, risk sharing, information sharing etc. which could effectively be overcome with inclusion and communication, and similarly, there are other barriers such as lack of knowledge and training that can be supported with proper awareness. Such barriers were commonly seen for all three concepts and as have demonstrated, may be relatively easy to resolve with interactive integration of technologies. However, more technology-specific barriers identified may require more time and investment in research and development to synergistically neutralize.

Further, particularly regarding the potential synergies of blockchain with BIM to reach optimum SCM, it should be noted that some barriers are complemented while some of them are neutralized. In other words, the synergy could occur both in positive and negative directions. Positive fusions could be seen as a conceptual space that primarily fosters collaboration and trust among stakeholders, with some potential for a slight uptick in cost, safety, and sustainability concerns. However, the lack of knowledge, expertise, support from government and management and the natural tendency to discourage innovation seemed to easily aggregate as all these concepts are new to the construction industry. Further it was identified that there can be occasions where the integration could undermine the beneficial influence of individual technologies, such as the case where incorporating blockchain could raise safety and privacy concerns for the BIM adoption in SCM. All these aspects need to be carefully examined to increase their overall positive synergetic impact.

Further, when such technology integration operates in a real-world setting, it should be highlighted that the strength of these links and impacts may vary across contexts, being influenced by other external forces such as global, regional and national policy or logistic trends. Therefore, to precisely determine the impacts additional empirically valid contextual studies must be conducted.

6. LIMITATIONS AND FUTURE DIRECTIONS

While this study could arguably be one of the firsts to explore the barriers and benefits of SCM, BIM and blockchain adoption in the construction industry simultaneously, one of the major limitations in this study is the analysis is based on a conceptual mapping alone, and the results would vary across contexts. Quantitative assessments, preferably supported by a questionnaire survey can strengthen the contextual validity of the results.

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