

Research on Blockchain Technology for Enhancing Transparency in Supply Chain Management Practices in Construction Engineering

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Abstract

This study explores how blockchain technology can help improve supply chains in the construction industry through managing transparency by systematically matching industry challenges with technological solutions. This research uses two publicly available datasets: the Dataset for Material Logistics on Construction Sites, which includes 55 construction professionals from Nigeria, and the Blockchain Adoption Challenges in Supply Chain dataset, which includes responses from supply chain practitioners from India and America who have experience with blockchain. For this analytical method, it encompasses integrating descriptive statistical analysis, cross-national comparative analysis, and problem-solution matching analysis to establish links between transparency deficits and blockchain capabilities. The results show that the most critical transparency problems are related to quality information asymmetry (4.87), price transparency insufficiency (4.71), and transportation problems (4.45), while 78% of construction professionals still rely on traditional work progress observations instead of using digital logistics tools. The blockchain adoption analysis shows that the main drivers for its adoption include enhancing supply chain visibility (4.72) and improving traceability of products and materials along the supply chain (4.65); there is also a notable difference across nations in terms of technical infrastructure readiness-4.50 for American respondents versus 4.12 for Indian respondents. The matching analysis indicated that among the blockchain features, data immutability, real-time tracking, smart contract automation, and distributed ledger sharing were found to address the identified construction supply chain transparency challenges. This research offers evidence in the form of a problem-solution matching framework to construction enterprises seeking guidance for informed decision-making on blockchain adoption during digital transformation initiatives.

Keywords

Blockchain Technology; Construction Supply Chain; Transparency Management; Smart Contracts; Supply Chain Traceability.

1. Introduction

The construction industry, being one of the most significant sectors in the global economy, has faced numerous challenges in terms of supply chain management, mainly affecting the success of construction projects. In fact, construction supply chains exhibit complexity because they involve many players, including construction material suppliers, contractors, subcontractors, and clients, who have to coordinate in order to enable success in projects. The complexity and fragmentation in

construction supply chains have resulted in fundamental issues such as cost overrun, delays, disputes related to construction quality, and lack of trust [1]. All these issues stem from the absence of clarity or lack of transparency in construction information.

Recently, there has been growing academic interest in the ability of blockchain technology to overcome these issues of transparency in construction supply chains. Blockchain technology has attributes such as immutability, decentralization, and transparency, which seem to make it suitable for construction [2]. Blockchain technology allows all members of the supply chain to share and verify information in the same, or rather tamper-proof, record, thereby potentially overcoming issues of information silos in construction [3]. It has been shown that the use of blockchain technology can change the nature of supply chains in terms of recordkeeping organization-wide [3].

The adoption of blockchain technology in the management of construction supply chains has been considered from different aspects in current literature. Researchers have identified the applications of blockchain technology in construction, from tracking construction materials to facilitating automated payments [4]. Literature in the management of supply chains has also identified important aspects related to the adoption of blockchain technology, covering both the benefits and challenges that come with the technology shift [5]. Notable here is the adoption of crypto-assets underpinned by blockchain technology in managing construction supply chains, which tackles an important issue concerning delays in payments that are prevalent in construction and can affect the contractor interface in construction projects [6].

Although there are many studies emerging in the literature, there are significant gaps in the knowledge concerning the effective use of blockchain technology in construction supply chains. Although some theoretical analysis has already been developed concerning the assessment of construction supply chains' readiness for use with blockchain technology [7], there is little research concerning the actual issues regarding construction supply chain transparency that can potentially be resolved through the use of blockchain technology. The construction industry today relies strongly on conventional or manual methods in terms of construction material logistics, and it was found in studies that most construction professionals' work progress tracking relies on observation rather than technology [8].

However, emerging works have recently started to investigate innovative ways of closing the gap between construction works and digital representations of construction using the Blockchain technology. The development of smart construction objects acting as oracles in Blockchain technology can therefore be considered an emerging technology in construction, promoting the automated collection and verification of data that can contribute towards increased construction supply chain transparency [9]. Nonetheless, based on comprehensive literature studies, construction technology using Blockchain technology has not moved beyond its embryonic stage since many of the construction applications have not been tested at a macro-level [10]. Most of the current works are focused on the Blockchain technology construction capabilities or construction supply chain issues in separation.

In the context of the above discussion, the current research constitutes a significant attempt to fill the research gap in the analysis of construction supply chain transparency issues and factors related to the adoption of blockchain technology in the construction industry. Using knowledge from construction logistics studies and related blockchain adoption studies, the current research endeavors to discuss the fundamental construction supply chain transparency issues and relate these issues with some characteristics of the adoption of blockchain technology. In terms of practical applications, the current research can offer construction companies scientific evidence concerning digital transformation endeavors, such as how to make proper assessments and applications of blockchain technology from offline to online construction settings. In today's construction landscape where there is an escalating need for construction supply chain transparency, the current research can offer relevant knowledge concerning the adoption of blockchain technology.

2. Data and methods

2.1 Construction Supply Chain Logistics Data

The first dataset utilized in this research is the Dataset for Material Logistics on Construction Sites, accessible through the Data in Brief repository (<https://doi.org/10.1016/j.dib.2018.08.194>). The current dataset consists of questionnaire data collected from 55 construction practitioners in Nigeria, ranging from architects to quantity surveyors who have first-hand experience in managing material logistics in construction projects. The questionnaire tool covers several aspects of material logistics issues in construction practice. The data variables in the current dataset cover issues related to material logistics, accuracy of material delivery, logistics issues, and perceived benefits in logistics. Items in the dataset have been responded to using Likert scales, which make it quantitative in assessing the level of importance of any issue related to transparency. The current dataset offers evidence related to determinations of critical issues in managing supply chains in construction practice, including issues related to material characteristics verification, reliability of suppliers, and managing all construction stakeholders involved in a construction project. Ensuring representation from all construction practitioners means that the dataset presents all aspects related to the construction supply chain.

2.2 Blockchain Supply Chain Adoption Data

The second dataset employed in this analysis is the Blockchain Adoption Challenges in Supply Chain dataset, available through the Mendeley Data repository (<https://data.mendeley.com/datasets/fwn3s4h88v/1>). The current dataset represents survey data gathered from supply chain practitioners in India and the United States who have at least three years of experience with the adoption of blockchain technology in supply chains. The variables in the current dataset represent constructs based on existing technology adoption theory, such as performance expectancy, facilitating conditions, social influence, and adoption intention. Variables related to performance expectancy are designed to measure perceptions related to the benefits of using blockchain technology in terms of increased supply chain visibility and traceability. Facilitating conditions' variables aim to measure factors related to the support infrastructure and industry standards that can support the success of blockchain technology adoption. Variables under social influences measure factors that can affect adoption, such as pressure from partners or industry and government initiatives. The current dataset benefits from its cross-sectional nature since it allows comparisons between countries in terms of factors that can influence adoption of the technology in different market settings, such as the state of technology support infrastructures in those environments.

2.3 Research Methods

The analytical methodology utilized in the current research combines the strengths of three distinct methods in order to fulfill the research tasks. Descriptive statistical analysis comprises the backbone of the empirical analysis, with mean value ranking facilitating the assessment of factors that contribute most to each dataset. In other words, mean value ranking helps professionals categorize challenges related to transparency in descending order based on practitioner perceptions. In turn, based on mean scores, factors can be prioritized based on perceptions of supply chain practitioners about the most important characteristics in the adoption of blockchain technology in construction.

Comparative analysis represents another methodology segment, which concentrates on intercountry disparities in the factors affecting blockchain adoption between Indian and American respondents. Through comparison, it becomes clear how different developments in technology infrastructure, regulatory readiness, and industry adoption rates affect the relative importance of distinct factors facilitating or hindering blockchain adoption. These aspects are critical in formulating adoption recommendations tailored to the unique environments of different markets.

The integration analysis constitutes the most distinctively significant methodological contribution found in the current research since it corresponds to matching construction supply chain issues related to transparency with the capabilities of blockchain technology. It essentially involves matching

identified gaps in construction logistics data concerning transparency with corresponding characteristics found in blockchain technology adoption data. The analysis discusses how the characteristics of the technology, such as data integrity, real-time tracking capabilities, smart contract execution, or distribution of data in ledgers, can fare in countering individual issues such as the lack of quality data integrity, inaccuracy in deliveries, multi-party communication issues, and inefficiency in data forecasting.

3. Result

3.1 Results of Construction Supply Chain Transparency Problem Analysis

Data analysis obtained from the construction supply chain logistics dataset demonstrates there are many issues related to transparency in the management and organization of construction materials. Taking into consideration the data presented in Table 1 above, descriptive statistical analysis shows the issue of material acquirement transparency stands out as the most challenging issue experienced in the construction sector. Information asymmetry regarding construction quality scored the highest mean at 4.87, pointing to difficult verification of construction material quality characteristics before any purchases can occur. It can therefore be argued that construction practitioners face many challenges regarding proper cost comparisons from different suppliers, which was found to score the second-highest mean at 4.71 in the descriptive analysis. It was apparent from the data analysis that reputation verification from suppliers scored a mean of 4.15, showing construction practitioners do not have the means to verify the reputation of suppliers.

The analysis of the issues of material delivery transparency highlights that several sources of inaccuracy in deliveries exist in the construction supply chains. The data shows that the mean score of the supplier inaccuracy was 3.67, order inaccuracy had 3.58, and process alterations 3.47. These results imply that issues related to information exist at all stages in the material delivery process in construction, resulting in delays in projects and consumption of resources. The issues related to logistic coordination in construction projects show further issues exist at all stages. These issues show that the mean score in transportation considerations was 4.45, lack of storage space was 4.18, delays in delivery of materials was 4.13, and the issue of logistic failure was 4.02. These considerations related to construction supply chains can easily be identified in Figure 1. Importantly, it can be identified from the data that 78% of the population surveyed considered observation of work in progress at construction sites to forecast information, whereas 2% of construction companies use any logistical computerized software related to information management.

Table 1. Descriptive Statistics of Construction Supply Chain Transparency Problems

Category	Factor	Mean	Rank
Material Procurement Transparency	Quality information asymmetry	4.87	1
Material Procurement Transparency	Price transparency insufficiency	4.71	2
Material Procurement Transparency	Supplier reputation verification difficulty	4.15	5
Material Delivery Transparency	Supplier errors	3.67	7
Material Delivery Transparency	Order errors	3.58	8
Material Delivery Transparency	Process changes	3.47	9
Logistics Coordination Transparency	Transportation issues	4.45	3
Logistics Coordination Transparency	Storage insufficiency	4.18	4
Logistics Coordination Transparency	Delivery delays	4.13	6
Logistics Coordination Transparency	Coordination failures	4.02	7

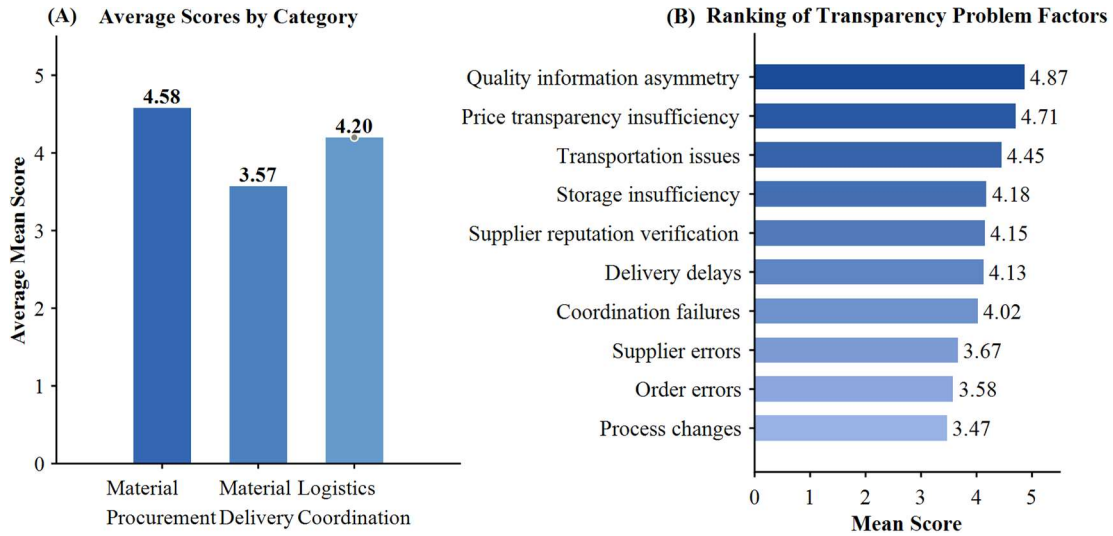


Figure 1. Construction supply chain transparency problems analysis.

3.2 Results of Blockchain Technology Supply Chain Adoption Factor Analysis

In examining the data from the adoption of the blockchain supply chain, there appear to be distinct tendencies in the perceptions of supply chain practitioners regarding factors that influence the adoption of blockchain technology. Notably from Table 2, the descriptive statistic analysis shows that factors relating to performance expectancy are fundamental issues in determining adoption intention in the context of the surveyed population. Enhancing supply chain visibility scored the highest mean at 4.72, showing that practitioners believe that enhanced visibility through using blockchain technology is the most attractive capability associated with blockchain technology adoption. Improving traceability scored 4.65, showing that practitioners are keen on the expectations associated with using blockchain technology in achieving traceability in the supply chains. Increases in operational efficiency scored 4.58, showing that practitioners believe that the efficiency benefits expected from using blockchain technology would come with significant increases in efficiency benefits.

Table 2. Descriptive Statistics of Blockchain Supply Chain Adoption Factors

Category	Factor	Overall Mean	India Mean	USA Mean
Performance Expectancy	Supply chain visibility enhancement	4.72	4.68	4.76
Performance Expectancy	Traceability improvement	4.65	4.61	4.69
Performance Expectancy	Operational efficiency gains	4.58	4.52	4.64
Facilitating Conditions	Technical infrastructure readiness	4.31	4.12	4.50
Facilitating Conditions	Organizational support	4.18	4.15	4.21
Facilitating Conditions	Industry standard availability	3.92	3.71	4.13
Social Influence	Partner pressure	3.85	4.02	3.68
Social Influence	Industry trend awareness	3.78	3.95	3.61
Social Influence	Policy promotion	3.62	3.74	3.50

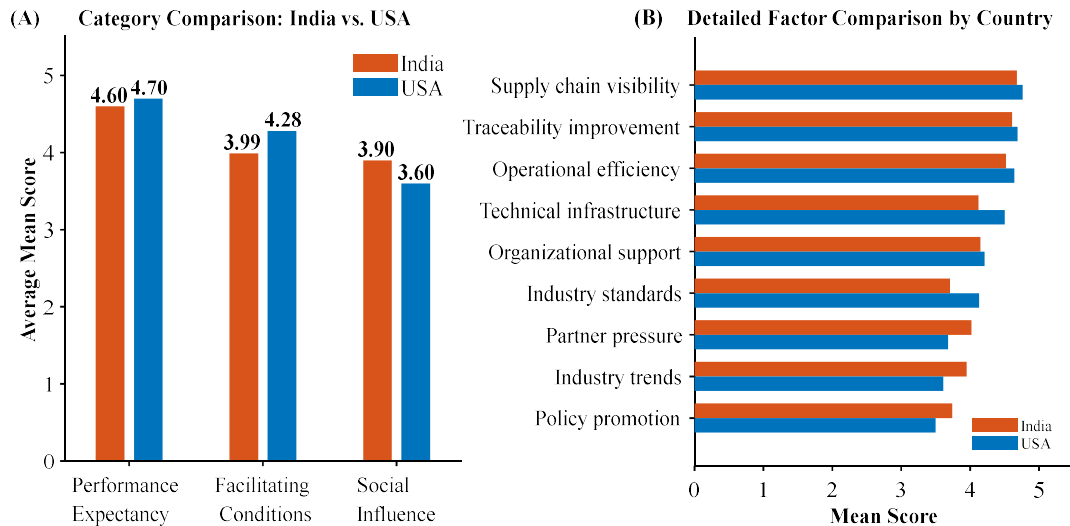


Figure 2. Blockchain supply chain adoption factors: India vs. USA comparison.

Facilitating conditions are another important factor in adoption, where technical infrastructure readiness has an average score of 4.31, organizational support has an average score of 4.18, and industry standard availability has an average score of 3.92. These results signify that although there are techno-feasibility capabilities in the adoption of blockchain technology in the global scenario, there has to be organizational support and cooperation at the industry level. Factors related to social influences moderately contribute to adoption intention, where partner pressure has scored an average of 3.85, industry trend awareness has scored 3.78, and policy promotion has scored 3.62. In Figure 2, the comparison of adoption factor priority differences between Indian and American professionals working in the financial sectors illustrates significant disparities in prioritized adoption factors. American professionals score greater in terms of technical infrastructure readiness and industry standard availability, due to the advanced techno-infrastructure in the United States. Indian professionals show greater reaction to factors related to social influences, such as partner pressure and industry trends, indicating market influences in driving the adoption of blockchain in emerging markets.

3.3 Results of Blockchain Technology and Construction Supply Chain Transparency Matching Analysis

The integration analysis correspondingly matches up the identified issues in the construction supply chain dataset with the capabilities in the adoption factor analysis of the blockchain technology. It can be observed in Table 3 that there are four main points where there can be alignments in terms of issues in construction supply chains and the technology that can help. The inability to modify or alter data, which is an aspect of the technology, resolves the issue of quality information asymmetry that was rated the most concerning issue in construction. By registering material characteristics, test reports, and quality inspections into an impermodifiable digital ledger, all parties in the construction supply chains can gain access to tamper-proof quality information, thereby overcoming the trust gap persisting in procuring based on the same.

The real-time tracking capability integrated in the blockchain technology solves the issues related to the delays in deliveries, order, and manufacturer discrepancies effectively. Using this feature, there will be constant tracking from the manufacturer locations to the construction sites, and the construction managers can detect any disruption risk early in order to prevent delays in construction. The smart contract automation capability solves the issues related to multi-party arrangements in construction supply chains. Using smart contracts, all the operations such as payment release, delivery confirmation, and acceptance of goods can easily take place without any kind of error.

As shown in Figure 3, the logistics information forecasting in the construction industry can therefore gain from the comprehensive solution provided by the distributed ledger sharing mechanism. It can

be seen from the analysis that although at present 78% of the construction industry workforce uses manual observation of construction work progress in logistics planning, through the application of blockchain technology, all construction industry stakeholders can enjoy simultaneous availability of construction material level, construction supply schedule, and construction demand forecast information. It can further be seen from the matching analysis result that there exist suitable solutions in the blockchain technology framework to handle all the identified construction industry transparency issues.

Table 3. Matching Analysis of Blockchain Technology and Construction Supply Chain Transparency Problems

Construction Supply Chain Problem	Problem Mean Score	Blockchain Solution	Solution Capability	Matching Mechanism
Quality information asymmetry	4.87	Data immutability	Tamper-proof records	Material certificates and quality data permanently recorded on blockchain
Price transparency insufficiency	4.71	Distributed ledger sharing	Synchronized information access	Real-time price data shared across all network participants
Delivery delays	4.13	Real-time tracking	Continuous monitoring	GPS and IoT integration enables live shipment visibility
Order errors	3.58	Smart contract automation	Automatic verification	Order specifications automatically validated against contract terms
Supplier errors	3.67	Real-time tracking	Exception alerting	Immediate notification when deviations from planned delivery occur
Coordination failures	4.02	Smart contract automation	Automated workflows	Multi-party approvals and handoffs executed automatically
Information forecasting difficulty	Traditional methods (78%)	Distributed ledger sharing	Data synchronization	Shared demand and inventory data enables collaborative planning

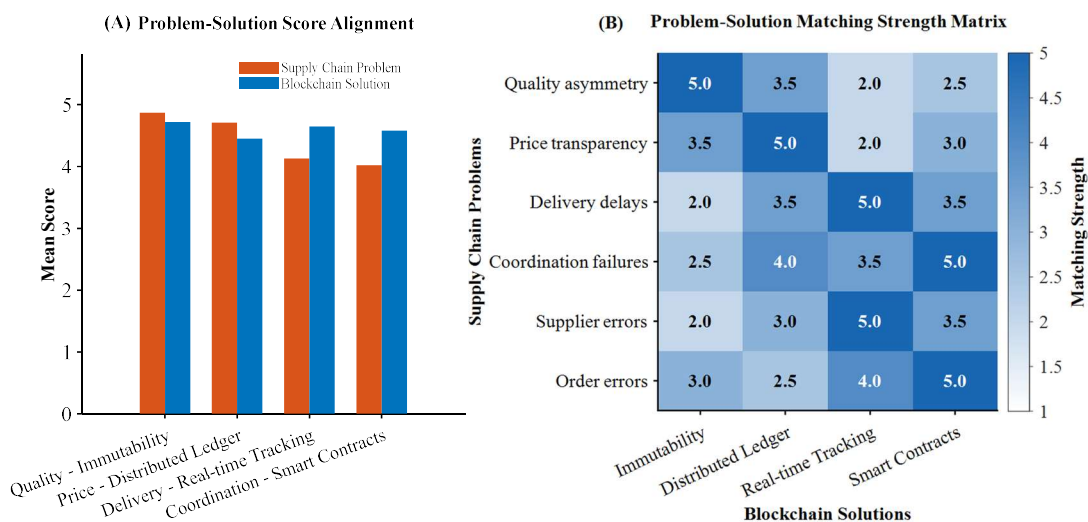


Figure 3. Blockchain-supply chain transparency matching analysis.

4. Discussion

Empirical evidence from the current research confirms the viability of Blockchain technology in overcoming challenges related to the transparency of construction supply chains, while at the same time highlighting critical aspects worth consideration in practical implementations [11]. The result from the matching analysis confirms the strength of correspondence between the characteristics of Blockchain technology and construction supply chains' challenges, thereby verifying the viability of Blockchain technology in providing optimal solutions to challenges in the construction industry. These current research outcomes can therefore verify the arguments presented by Hijazi et al., which insisted that there was need for convergence of Blockchain technology and Building Information Model technology to offer improvements in supply chains data transfer [12]. Identifying quality information asymmetry as the challenge with the most potential in the construction industry, while at the same time recognizing the high value placed on data immutability in Blockchain technology, indicates that construction companies need to embrace Blockchain technology in material source and quality verification first.

Construction supply chain transparency enabled by the blockchain technology works through three interrelated levels. At the level of information, the creation of an unrecordable record of construction material qualities, quality certifications, and transaction data in the form of an unalterable ledger allows all the construction supply chain stakeholders to gain knowledge about legitimate facts that can eliminate the current issue of information asymmetry in construction procurements. Indeed, recent studies by Waqar et al. have shown that the empowerment of the construction supply chains through the application of the blockchain technology can increase efficiency and sustainability in the construction industry [13]. At the process level, the construction supply chains can automate the triggering of payment and transfer of goods confirmation based on the satisfaction of specified criteria that can eliminate human error in construction transaction processing. On the other hand, chatbot technology applied to the construction blockchain networks developed by Adel et al., can offer a practical solution in ensuring that the current automated construction transaction process can easily be applied by construction professionals [14]. By applying the construction ledgers, all construction supply chains can get rid of communication channel siloing between construction stakeholders.

The cross-country analysis of factors affecting the adoption of blockchain technology highlights that the adoption process needs to factor in differences in technology infrastructure and market characteristics. The tendency of American respondents to record higher scores in terms of technology readiness and availability of industry standards implies that developed countries are poised to embrace the technology at a faster pace. By contrast, the greater emphasis placed by Indian respondents on the pressure from trading partners and industry trends implies that emerging countries can harness the adoption process through associations and trading partners' requirements in the industry. These aspects cover the research work undertaken by Xu et al., who developed the adoption constraints of blockchain technology in the Architecture, Engineering, and Construction industry [15]. The constraints related to supply chain transparency and sustainability, presented by Singh et al., highlight the need to maintain wider stakeholder engagement [16].

The adoption of blockchain technology in construction supply chains needs to factor in organizational and industry-level issues. At the technology level, the choice of suitable blockchain platforms can be an important consideration, where consortium blockchains can offer the benefits of public blockchains in terms of transparency, while at the same time meeting the privacy needs of commercial transactions. The research undertaken by Das et al. regarding the security of interim payments using blockchain framework technologies can offer important lessons in terms of considerations in technology selection [17]. At the organizational level, staged adoption strategies starting with the development of material procurements applications can help construction companies develop technology capabilities and generate value addition in order to tackle complex scenarios. Zhang et al. underlined the same factors in understanding the role of systematic review in construction contract management using blockchain technology [18]. At the industry level, development of industry

standards regarding protocols and readiness of suppliers in terms of using blockchain technology will have important implications in achieving network effects in terms of adoption. The important solutions outlined in the critical assessment undertaken by Okafor et al. to overcome supply chain management issues in the construction industry in Nigeria can offer important lessons in terms of organizational-level considerations [19].

The conceptual frameworks presented in the papers by Groschopf et al. on smart contract sustainability assessment can be considered useful tools in assessing the development level of construction supply chains pre-blockchain adoption [20]. Nevertheless, in recognizing the scope of the current analysis, there are several limitations cited in the presented discussion. The two data sets explored in the analysis come from two different geographical settings, in which the construction logistics data was gathered in Nigeria, whereas the data regarding the adoption of blockchain technology was gathered in India and the US. These two geographical settings could potentially generate discrepancies in the adaptability of the matching analysis in terms of cultural, economic, and environmental settings. The data sets explored in the analysis cover the realms of construction logistics and blockchain technology adoption in two distinct settings, rather than interacting with the realms in terms of assessing blockchain technology adoption in construction settings.

However, future studies need to consider these points and collect data from primary sources in order to conduct an in-depth analysis of the application of blockchain technology in construction supply chains. Exploratory studies of projects undertaking the implementation of blockchain technology could help understand the challenges and benefits arising from such applications in the long run. In fact, as was identified in the research agenda outlined in the works of Xu et al. in their discussion about applying blockchain technology in the AECO sector, there appears to exist an important knowledge gap in validating applications of such technology [21].

5. Conclusion

In this paper, the use of blockchain technology in boosting the management of construction supply chain transparency is explored based on an integrated analysis of construction logistics and factors of adopting blockchain technology. Results obtained show that information quality asymmetry (4.87), insufficiency of price transparency (4.71), and transport management issues (4.45) are the most pressing factors in construction supply chains regarding transparency, but 78% of surveyed construction professionals lack dependence on advanced work progress observation methods in terms of information forecasting. The analysis result shows that the corresponding factors of data immutability, real-time tracking capability, smart contract automated execution, or mutual sharing of construction construction data using the blockchain technology offer corresponding technical answers for these identified issues. It has been found in comparison that American construction professionals are ready in terms of technical-infrastructure readiness (4.50 vs. 4.12) in the adoption process of the technology, but Indian construction professionals respond better under social influence factors such as dealer pressure (4.02 vs. 3.68). In this paper, the critical issue in construction supply chains regarding transparency deficits corresponds to an innovative, task-oriented construction framework providing matching answers based on actual evidence about the adoption readiness of construction technology like the blockchain technology.

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