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Factors Influencing the Adoption of Blockchain in the Construction Industry: A Hybrid Approach Using PLS-SEM and fsQCA

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Abstract: Blockchain is considered a breakthrough technology in the construction industry, with the potential to improve the trust environment and workflow of construction stakeholders. Although recent research offers hints regarding possible contributing elements to blockchain adoption in the construction industry, no specific study has addressed this topic. This knowledge gap hinders the adoption and promotion of blockchain in construction organizations. This study aimed to identify the determinants of blockchain adoption in the construction industry and verify the influence of the combination of various factors on adoption intention. Based on the technology–organization–environment framework, a conceptual model of blockchain adoption in the construction industry was constructed. Data were collected through the distribution of questionnaires, and 244 professionals in the construction field participated in this study. To evaluate the model hypotheses, we used a two-stage partial least squares structural equation modeling (PLS-SEM) and fuzzy-set qualitative comparative analysis (fsQCA) combination. The PLS-SEM revealed that factors such as compatibility, top management support, relative advantage, regulatory support, cost, competitive pressure, organizational readiness, and firm size significantly influence blockchain adoption. The fsQCA indicated that six causal conditions achieve high adoption intention. This is one of the first empirical studies on blockchain adoption in the construction industry, which can aid organizations, policymakers, and project participants in making informed decisions regarding the adoption of blockchain.

Keywords: blockchain; innovation adoption; construction industry; technology–organization–environment (TOE); PLS-SEM; fsQCA

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1. Introduction

In recent years, as an emerging technology, blockchain has attracted the interest of practitioners and scholars from different industries [1–3]. Blockchain is essentially a decentralized database, a novel application paradigm that integrates computer technologies such as point-to-point transmission, consensus mechanisms, distributed data storage, and encryption algorithms [3,4]. Because blockchain has the advantages of multiparty maintenance, non-tampering, openness, transparency, auditability, and security, it has begun to subvert many traditional business processes [4]. As a breakthrough technology, blockchain provides valuable opportunities for companies and organizations. In particular, it is expected to address difficult problems in the construction industry, such as trust among stakeholders [5], delayed payment [6,7], poor bidding information channels, opaque transaction processes [8,9], unclear rights and responsibilities [10], and poor process traceability [11]. Shojaei et al. [12] evaluated the current implementation of a circular economy and highlighted blockchain as a potential technique in a built environment. Perera et al. [13] conducted a critical analysis of current information regarding blockchain technology and its applications, demonstrating that blockchain has significant promise in the construction industry. Hunhevicz and Hall [14] emphasized that blockchain can provide opportunities to integrate smart contracts and digital information into management, thereby enhancing collaboration among stakeholders in the construction industry.

However, although blockchain can provide many benefits to the construction industry and is recognized as a disruptive innovation technology that changes the industry [13], its adoption speed has not reached market expectations [11,15]. Construction companies are still hesitant and adopt wait-and-see attitudes regarding whether to adopt blockchain. Although some scholars have investigated the drivers and obstacles of blockchain adoption, few studies have explored the determinants of blockchain adoption in the construction industry [1,15]. In addition, although some scholars have conducted quantitative research, most have focused on supply chain management in non-construction fields [16,17]. In other words, organizations in the construction industry know little about adopting blockchain decisions. Therefore, a more in-depth research is required to identify the factors that impact blockchain adoption in the construction industry. More importantly, although the use of structural equation models and software technology to prioritize the predictive indicators of technology adoption is efficient and effective [18,19], no research has been conducted on the integration of these methods in the construction industry.

To fill the gap, this study aimed to achieve the following objectives: (1) use the partial least squares structural equation model (PLS-SEM) method to identify the determinants of blockchain adoption in the construction industry; (2) combine the fuzzy-set qualitative comparative analysis (fsQCA) approach and the PLS-SEM method to explore the synergistic effect among these determinants. To achieve the research goals, we extracted 11 factors from existing blockchain adoption studies. A theoretical model was established based on the technology–organization–environment (TOE) framework. Then, to test the theoretical model, an integration of the PLS-SEM and fsQCA methods was used. The methods are complementary because fsQCA offers an in-depth comprehension of the complicated, nonlinear, and synergistic effects, whereas PLS-SEM gives an explanation of the net effect of linear connections between variables. Moreover, we demonstrated that the intention for blockchain adoption in the construction industry can be encouraged by configuring many causal indicators rather than signal causal indicators. This research was the first attempt in the construction field to combine PLS-SEM and fsQCA technologies to identify the factors that affect blockchain adoption and provide richer insight into the effects of complex trade-offs. The results provide valuable insights for industry practitioners and decision-makers in related departments.

2. Literature Review

2.1. Blockchain Technology

Blockchain technology can be defined as an open, secure, and immutable distributed ledger [20]. It enables transactions without third-party involvement, eliminating the need for third-party trust. It is a decentralized network that runs on top of Internet protocols and records transactions in an immutable manner using cryptography and distributed consensus algorithms among a distributed set of users [21]. Suppliers and demanders can conduct peer-to-peer transactions using a blockchain. In a blockchain system, every transaction is recorded on a ledger and then placed into a block. Each block is connected to another block before and after it. When a block is linked to a chain, it becomes immutable. The blockchain is verified using automation and governance protocols, which cannot be changed or deleted by a single participant.

Depending on the type of access mechanism, blockchains can be broadly classified into permissionless and permissioned blockchains [22]. In the first type of blockchain, every transaction is public and users do not need permission to transact and reach a consensus. The users remain anonymous at all times and the public network encourages participation in the latex network through incentives. In the second type of blockchain, participants must be invited to join a network. Many private blockchains are permitted to control the types of users that can transact.

Owing to the characteristics of blockchain technology, its advantages are relatively significant. First, the blockchain is transparent [23]. Based on blockchain hashes, the transaction records of the participants can be checked in real time and cannot be forged. Second, blockchain reduces third-party dependencies in decentralized peer-to-peer network transactions [21]. Third, blockchain technology improves security. This establishes a consensus of trust in the entire network, making it difficult for hackers to penetrate the internal network. Simultaneously, the information recorded in the database is permanent and cannot be easily manipulated [24].

2.2. Blockchain in the Construction Industry

Blockchain has been studied by scholars in the construction industry since 2015. In recent years, most scholars have either conducted research on theoretical methods or conducted literature reviews, and few studies have explored blockchain adoption in the construction industry [25].

Several review papers have been published on this topic. Xu et al. [26] provided a comprehensive review of the application of blockchain technology in the construction field based on bibliometric and content analysis methods and discussed key research topics and future research directions. Perera et al. [13] analyzed the advantages and challenges of blockchain technology and concluded that it has compelling promise in the construction industry. Li et al. [11] identified the main research areas of blockchain in the built environment by presenting the latest blockchain technologies and conducting literature reviews and compiled an extensive list of the challenges and opportunities related to blockchain, in addition to forming a roadmap for implementing blockchain in the construction sector. Scott et al. [27] used an exploratory approach to examine 33 application categories of blockchain applications in construction, which were organized into seven thematic areas. Mahmudnia et al. [28] reviewed the characteristics of blockchain and explored its important role in solving interaction issues in payments, documentation, and interaction in the construction industry.

In addition, few studies on the potential advantages of blockchain have recently been conducted. For example, Qian and Papadonikolaki [5] suggested that blockchain can provide data tracking, transferring resources, and contracting in construction supply chain management. Meanwhile, some studies [7,8] focused on secure construction payments and indicated that the application of blockchain might create a transparent and efficient platform to guarantee secure payments for construction projects. According to Wang et al. [29], blockchain technology may improve traceability and make it easier for participants to share information during precast construction. Lee et al. [30] used a case study to demonstrate that integrating digital twins with blockchain can aid in ensuring traceability.

Despite extensive research and the rapid spread of blockchain technology in the construction industry, many challenges and barriers remain to its adoption. Sharma and Kumar [31] argued that in the early stages of adopting blockchain technology, inadequate knowledge and experience are key challenges that must be addressed. Xu et al. [32] indicated that barriers to blockchain adoption in the construction industry are prominent, centered on insufficient information technology infrastructure and legal and regulatory ambiguity. Yang et al. [9] indicated that the fragmentation and uncertainty of construction projects complicate the widespread adoption of blockchain technology. Tezel et al. [33] and Toufaily et al. [1] stated that construction companies lack the IT infrastructure and servers required for blockchain applications. Compared with the significant potential of blockchain technology, its application and research are still in the preliminary stage. Overall, the widespread use of blockchain technology has not yet occurred in the construction industry.

2.3. Adoption Model

Owing to the various determinants that may affect innovation adoption in a wide variety of domains, various theoretical models have been presented to investigate and comprehend the adoption of innovation in organizations [34]. As a generic theory used for innovation adoption, TOE theory has guided scholars in identifying and determining the drivers of innovative technologies [35]. From a business development perspective, TOE indicates that a company's decision to adopt new technology is based on technological characteristics and organizational and environmental considerations. The context of technology describes the technical characteristics that can influence the adoption of innovation, the organizational context relates to the organizational attributes that may hinder or foster adoption, and the context of the environment refers to external factors relative to the organization, which may present opportunities and challenges for innovation adoption [36,37]. In several studies on construction innovation adoption, the three contexts of the TOE framework have focused on identifying the factors affecting new technology adoption by construction companies [38].

In the subsequent analysis, the TOE framework served as an overarching theoretical underpinning for this research. It presents an extensive analysis of technology adoption as decisions to adopt technology in the organizational dimension depend on factors in the context of technology, environment, and organization. Specifically, because the TOE framework combines human and non-human factors into one framework, it has better advantages than other traditional models, such as the technology acceptance model, diffusion of innovation, and unified theory of acceptance model [39]. It provides a suitable foundation for considering and understanding the appropriate determinants for the adoption of innovation, and many of the results of innovation adoption studies support this [40]. Wong et al. [17] mentioned that the TOE framework can be used to better examine blockchain adoption in organizations.

3. Model Construction and Hypotheses Development

The construction industry is generally regarded as structurally fragmented, with low productivity and a lack of improvements. Blockchain exhibits the basic properties of traceability, transparency, and immutability. Therefore, it can facilitate a paradigm shift towards cooperation and trust in the construction industry. With researchers developing blockchain-based solutions, specific issues in the construction industry are being addressed, such as construction quality, supply chain management, and construction payments. Based on the above literature review and analysis, a conceptual model for this study is proposed. It considers both the factors of technology and organization and the influence of the external environment. The framework includes 12 different constructs, with the willingness to adopt blockchain serving as the dependent variable, and the 11 determinants that are considered as independent variables being determinants in the TOE context. Figure 1 shows the proposed model.

3.1. Context of Technology

3.1.1. Relative Advantage

The degree to which the adoption of innovation may provide an organization with greater benefits than the status quo is described as a relative advantage [37]. Relative advantage is considered a fundamental indicator of innovation adoption [41], as observed for supply chains [42], cloud computing services [43], and business intelligence systems [44]. The construction industry is considered to be in a state of continual reengineering [45], and the adoption of new technologies will promote industry flourishing. As a primary use of blockchain technology, smart contracts may efficiently resolve construction payment delays and contractual disputes [46]. Blockchain technology can also provide construction companies with trusted partnerships, information sharing during the design and construction phases, foster collaboration, enhance traceability and transparency, reduce transaction costs, and address late payment challenges, thereby improving operational and management efficiencies [13]. Consequently, we propose the following hypothesis:

H1: *Relative advantage positively influences the willingness of blockchain adoption.*

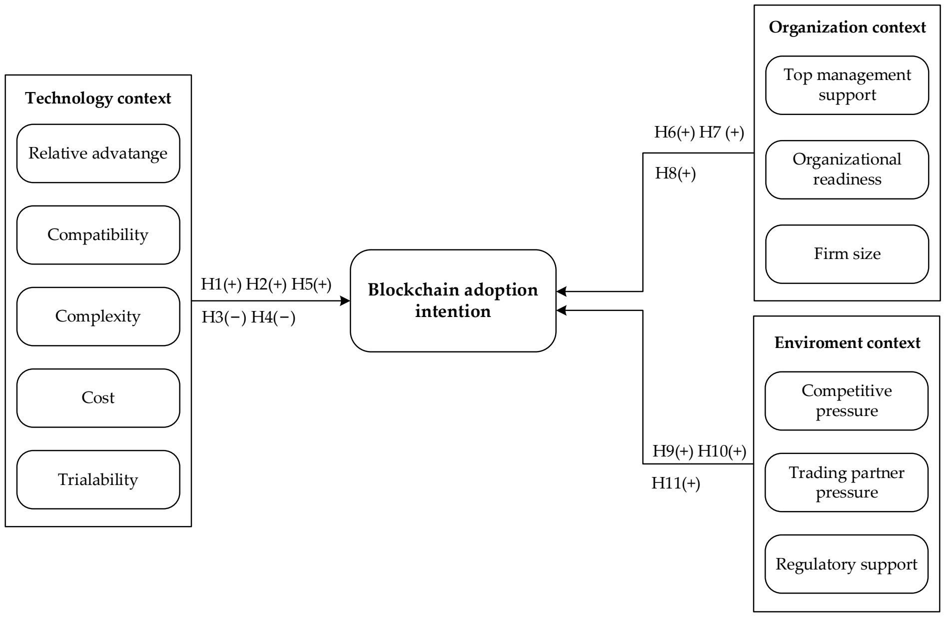

Figure 1. Research model of intention to adopt blockchain technology based on the TOE framework.

3.1.2. Compatibility

The extent to which an innovation system is considered compatible with the present system is referred to as compatibility [47]. Compatibility between the innovation and management requirements, as well as corporate culture and practices, is widely recognized as a critical factor in innovation adoption [37,48]. Fernando et al. [35] indicated that as the main motivation for technology adoption. Construction projects are highly fragmented and uncertain, and engineering changes during project implementation are common. Accordingly, construction companies are more likely to embrace and implement blockchain technology in various aspects of their operations if they believe that blockchain adoption is compatible with the current corporate culture and business practices. Thus, we formulate the following hypothesis:

H2: *Compatibility positively influences the willingness of blockchain adoption.*

3.1.3. Complexity

Complexity is the extent to which an innovation is difficult to comprehend and apply [49]. According to some studies, complexity is considered a key factor affecting innovation adoption [50]. Complexity is not positively associated with technology adoption as other elements of technology adoption, but rather negatively [51]. The blockchain's transaction mechanism is relatively complex and speed is a major problem to be considered; in addition, its implementation is challenged by its immature security properties [52]. Construction has long been considered a poorly performing and low-tech industry for innovation [53], and construction companies do not intend to adopt blockchain because of technical complexity. As construction companies move from traditional IT systems to blockchain-based ones, complex programming, integration challenges, and a lack of blockchain technology talent can hinder their adoption [54]. When the technology is complex, decision-makers consider whether to adopt it. Thus, construction companies have limited utility in participating in blockchain technology unless it can be readily incorporated into current building operating systems. Consequently, we propose the following hypothesis:

H3: *Complexity negatively influences the willingness of blockchain adoption.*

3.1.4. Cost

Various costs are associated with technology adoption, and costs influence the willingness to adopt technology. High costs discourage adoption [55]. The cost of obtaining and using blockchain technology is referred to as the cost of adopting blockchain [17]. Although digital technology has many benefits, its adoption in the construction industry remains quite low [56]. High costs are often a barrier for companies adopting new technologies [57]. Blockchain adoption requires the acquisition of the necessary hardware and software, which may be expensive for organizations. More importantly, several non-empirical studies on blockchain technology in the construction sector have indicated that cost is a significant factor that prevents construction companies from adopting blockchain technology [10]. Thus, the following hypothesis is proposed:

H4: *Cost negatively influences the willingness of blockchain adoption.*

3.1.5. Trialability

Trialability is the extent to which new technology can be attempted on a limited basis [58]. The likelihood of successful adoption increases when the organization has had the opportunity to test innovation before it is adopted [46]. Research has shown that trialability facilitates the successful adoption of innovations [47,59]. A high degree of trialability would make it less risky for companies to adopt the technology, which can increase the level of acceptance. Moreover, trialability is promising to enable companies to better understand the potential benefits and accurately determine the value of blockchain technology. Thus, we propose the following hypothesis:

H5: *Trialability positively influences the willingness of blockchain adoption.*

3.2. Context of Organization

3.2.1. Top Management Support

Top management support is the degree to which top management in an organization accepts and implements new technology [60]. The early adoption of blockchain inevitably encounters resistance, and top management support can motivate members of an organization by providing direction and satisfying the demand for resources and funding. Many studies related to the construction industry have highlighted the importance of adopting new technologies [61]. Top management support is essential for integrating emerging technologies into existing business processes to facilitate the learning and dissemination of innovative technologies [59]. Therefore, we propose the following hypothesis:

H6: *Top management support positively influences the willingness of blockchain adoption.*

3.2.2. Organizational Readiness

Organizational readiness is the capacity and intention of firms to adopt an innovation [62]. It denotes business management and investment readiness to invest in innovation technology, including cognitive readiness, resource readiness, and IT systems [59]. Pan and Pan [36] reported that organizational readiness positively influences the adoption of construction innovation. The awareness of change, financial resources, expertise, and technical capabilities of construction companies are the fundamental bases for ensuring the adoption and implementation of blockchain. Thus, we propose the following hypothesis:

H7: *Organizational readiness positively influences the willingness of blockchain adoption.*

3.2.3. Firm Size

Firm size is a critical condition in innovation adoption [55]. Many studies have indicated that firm size positively affects and controls the innovation process [35,40]. The adoption of blockchain technology involves a change from old to new systems and requires a large initial investment, the risks and costs of which may deter many small construction companies, whereas larger firms can often manage the costs of innovation and provide financial resources that occur in technology adoption. Meanwhile, larger firms have more skilled professionals to ensure that the implementation of innovation is smooth [63]. Accordingly, we propose the following hypothesis:

H8: *Firm size positively influences the willingness of blockchain adoption.*

3.3. Context of Environment

3.3.1. Competitive Pressure

Competitive pressure is the degree to which a company experiences pressure from competitors in the same field [17]. Intense competition among peers requires organizations to adopt innovation to improve quality, reduce costs, and increase effectiveness and efficiency [35]. As an emerging technology, blockchain can help early adopters to thrive in today's ultra-competitive market. The construction industry is competitive and fraught with challenges [64]. Competitive pressure is likely to increase construction companies' demand for blockchain technology, driving the aggressive adoption of blockchain. Thus, the following hypothesis is proposed:

H9: *Competitive pressure positively influences the willingness of blockchain adoption.*

3.3.2. Trading Partner Pressure

Trading partners influence the construction industry as project-based groups [65].

Pressure from partners has been proved to be a main factor in innovation adoption in various empirical investigations [40]. Badi et al. [46] indicated the beneficial role of partners in facilitating the adoption, implementation, and completion of projects. Wamba et al. [66] built a model to study the various factors influencing blockchain adoption in supply chain management, demonstrating that trading partner pressure significantly influenced blockchain adoption in India and the US. To facilitate collaboration between trading partners, construction companies would further decide whether to adopt blockchain technology, depending on whether blockchain is used by trading partners. Thus, the following hypothesis is proposed:

H10: *Trading partner pressure positively influences the willingness of blockchain adoption.*

3.3.3. Regulatory Support

Regulatory support is assistance offered by the government or its authority to encourage innovation adoption [37]. Regulatory policies and legislation, such as required rules or standards, have a crucial role in enabling blockchain implementation [57,61]. Interestingly, Gibbs and Kraemer [67] emphasized that regulatory support has a greater role in developing countries than in developed countries. Most studies suggest that social acceptance is a significant barrier to blockchain applications [68]. China is a developing country and the role of government regulations and guidance is critical for innovation adoption. Because of the novelty of blockchain technology, most construction companies have a wait-and-see attitude in the early stages of adoption, and blockchain adoption systems in construction would be further hindered by government regulation of what and how to regulate the process of adoption. Thus, we propose the following hypothesis:

H11: *Regulatory support positively influences the willingness of blockchain adoption.*

4. Research Design and Methodology

4.1. Measurement of Determinants

Owing to its accessibility and scientific nature, questionnaire research has been extensively adopted by researchers in the field of construction. To guarantee validity and reliability, we designed the questionnaire for this study by referring to well-established scales and reviewing the results of published literature in the context of blockchain adoption and the construction industry. Accordingly, three construction experts were invited to pretest the preliminary version of the questionnaire. The questionnaire was modified and utilized in the pilot research based on their feedback. Meanwhile, it was translated into Chinese by a language expert, considering that the study addressed blockchain adoption in the Chinese construction industry. Three other experts assessed the translated version to confirm that the content of the questionnaire was related to construction companies.

A questionnaire with 43 construct items was used to measure the variables within the TOE framework. To facilitate the judgment of respondents, we scored the questionnaire items on a five-point Likert scale, with values ranging from 1 (strongly disagree) to 5 (strongly agree). Respondents made judgments and decisions based on their experiences and were informed that there were no right or wrong answers and that they were used for academic research only. Technological factors included compatibility, relative advantages, cost, trialability, and complexity. Accordingly, the measurements of these five variables were adapted [17,36,46]. In addition, three organizational constructs—top management support, organizational readiness, and firm size—were adapted from [35,36,46]. Environmental factors included regulatory support, trading partner pressure, and competitive pressure. These three items were adapted from [17,46,63]. Appendix A presents a set of questions for each construct.

Moreover, this study used three variables, namely, years of experience, education, and job position. The years of experience and education could suggest a level of professionalism, which may be related to higher levels of self-efficacy [69], that has the potential to affect the dependent variable. Job position may influence the attitudes and behaviors of participants [70].

4.2. Sample and Data Collection

Because blockchain is an emerging technology in China's construction industry, this study adopted a snowball sampling technique to obtain more valid and extensive responses. The questionnaires were distributed in WeChat groups of relevant conferences and forums of engineering management majors, focusing on topics related to intelligent construction, digital transformation of construction companies, and blockchain, in which the participants were more aware and concerned about emerging technologies in the construction industry. We selected eligible experts, senior managers, directors, and chief executive officers in the conferences and forum as our key informants and they were encouraged to forward the questionnaire. To further increase the enthusiasm of the respondents, the research group promised to send the research conclusions to the respondents in the form of a report after the end of the study to enable the respondents to adopt and apply blockchain technology in the entire construction industry. Due to the pandemic of COVID-19, the survey lasted five months in total, and finally, 244 valid surveys were received after removing disqualified questionnaires, such as partial answers and nonsensical responses.

The demographic information of the participants is presented in Table 1. To test for non-response bias, we used a t-test to compare the early and late participants. The findings demonstrated that there were no significant differences between the two groups, indicating that nonresponse bias was not a problem in this study. Statistically, we used Harman's single-factor test to evaluate the common method bias (CMB) problem [71], which accounts for the vast majority of the model variance. Because only a signal factor accounted for 38.2%, which was less than 50%, the result revealed no substantial CMB. Additionally, each correlation coefficient was less than 0.90, which also indicated that there was no issue with CMB [17]. Meanwhile, variance inflation factors (VIFs) were used to check for multicollinearity. All VIFs in this study were lower than the threshold of 5, indicating that linear correlation was not a problem.

Table 1. Profiles of questionnaire participants.

Demographic	Categories	Frequency	Percentage (%)
Years of work experience	<5 years	11	4.5
	5–9 years	88	36.0
	10–15 years	89	36.5
	>15 years	56	23
Education	High school degree or below	3	1.2
	College degree	103	42.2
	Undergraduate degree	117	48.0
	Graduate degree	21	8.6
Job position	Senior manager	44	18.0
	Department manager	53	21.7
	Project manager	56	23.0
	Chief engineer	58	23.8
	Other	33	13.5
Employee number	Less than 100	56	23.0
	100–200	100	41.0
	More than 200	88	36.0

4.3. Analytical Approaches

A multiple-method approach was applied to validate the proposed model. First, data retrieved from the questionnaire were analyzed using PLS-SEM via SmartPLS software to test the model and hypotheses, and the Statistical Package for Social Sciences (SPSS) was used for descriptive analysis. SEM employs a confirmatory approach to analyze the phenomenon-based structure and could account for the measurement error, thereby providing valid conclusions on the structural patterns of multiple indicator variables than other analytical approaches such as linear regression [63]. PLS-SEM was chosen for this study for the following reasons: (1) PLS-SEM is a contemporary multivariate analytic approach that is capable of estimating theoretically proven causality models; (2) PLS-SEM is more favorable than covariance-based structural equation modeling techniques to determine the connection variance between dependent and independent variables [36]; (3) PLS-SEM is more suitable for research involving non-normally distributed data, such as the data of this study; and (4) PLS-SEM has been applied to solve construction management problems in recently published articles [72]. The data were then analyzed in two steps using SmartPLS. To ensure the goodness of the model, stage one examined the measurement model to determine its validity and reliability. Subsequently, the proposed hypotheses were tested using a bootstrapping procedure in phase two.

Second, fsQCA was conducted to obtain knowledge of the components that constitute adequate combinations for blockchain adoption. fsQCA leverages Boolean logic to uncover several paths that result in a common outcome [73]. It is an asymmetric approach different from traditional symmetric approaches, such as regression and structural equation modeling, which only permit the analysis of a single path of antecedent factors. Although synergies exist in the factors influencing blockchain adoption, using fsQCA can capture decision-making complexity in construction companies. The following phases were included in the modeling process when using the fsQCA software: Phase one involved calibrating the data from the survey into a fuzzy set (0 to 1) with three main points: full set membership, crossover point, and full non-membership. Phase two was the analysis of the necessary condition, which identified the determinants that may influence the achievement of the target outcome. Subsequently, a truth table algorithm was constructed to draw the study's suggested conclusion in the third phase.

5. Results

5.1. Results of PLS-SEM

5.1.1. Measurement Model

The quality of the research model was assessed in terms of convergent validity, reliability, and discriminant validity. These three aspects are discussed next, as suggested in [36] and [63]. To verify convergent validity, we applied the average variance extracted (AVE) and factor loadings. Table 2 shows that every AVE was above the 0.5 benchmark, and all factor loadings were above the 0.7 benchmark, which indicated satisfactory convergent validity. The constructs' reliability was examined by jointly analyzing Cronbach's alpha and composite construct reliability (CR). The tests both had acceptable values exceeding 0.7, as shown in Table 2, indicating that the reliability of the construct was validated. The cross-loadings and Fornell–Larcker criteria were used to estimate the discriminant validity. Figure 2 shows that the correlation coefficients were less than the square root of the AVE, which satisfied the requirements of the Fornell–Larcker criterion. Additionally, all cross-loadings were below each construct loading, which satisfied the cross-loading criterion in this study, and discriminant validity was further established. The results of validity and reliability are presented in Figure 3.

Table 2. Convergent validity and reliability results.

Constructs	Items	Loadings	Cronbach's α	CR	AVE
BI	BI1	0.926	0.889	0.931	0.819
	BI2	0.915			
	BI3	0.872			
RA	RA1	0.816	0.873	0.905	0.613
	RA2	0.833			
	RA3	0.748			
	RA4	0.747			
	RA5	0.786			
	RA6	0.762			
CB	CB1	0.897	0.897	0.929	0.765
	CB2	0.872			
	CB3	0.875			
	CB4	0.854			
CX	CX1	0.927	0.937	0.955	0.841
	CX2	0.920			
	CX3	0.921			
	CX4	0.902			
CT	CT1	0.916	0.942	0.959	0.853
	CT2	0.941			
	CT3	0.909			
	CT4	0.928			
TA	TA1	0.823	0.782	0.866	0.685
	TA2	0.908			
	TA3	0.743			
TMS	TMS1	0.902	0.912	0.938	0.790
	TMS2	0.880			
	TMS3	0.898			
	TMS4	0.875			
OR	OR1	0.862	0.863	0.907	0.709
	OR2	0.854			
	OR3	0.845			
	OR4	0.805			
FS	FS1	0.920	0.890	0.932	0.820
	FS2	0.915			
	FS3	0.881			

Table 2. *Cont.*

Constructs	Items	Loadings	Cronbach's α	CR	AVE
CP	CP1	0.741	0.799	0.869	0.624
	CP2	0.819			
	CP3	0.824			
	CP4	0.771			
TPP	TPP1	0.874	0.821	0.894	0.738
	TPP2	0.904			
	TPP3	0.797			
RS	RS1	0.828	0.848	0.898	0.687
	RS2	0.843			
	RS3	0.825			
	RS4	0.819			

Notes: BI: behavioral intention; RA: relative advantage; CB: compatibility; CX: complexity; CT: cost; TA: trialability; TMS: top management support; OR: organizational readiness; FS: firm size; CP: competitive pressure; TPP: trading partner pressure; RS: regulatory support.

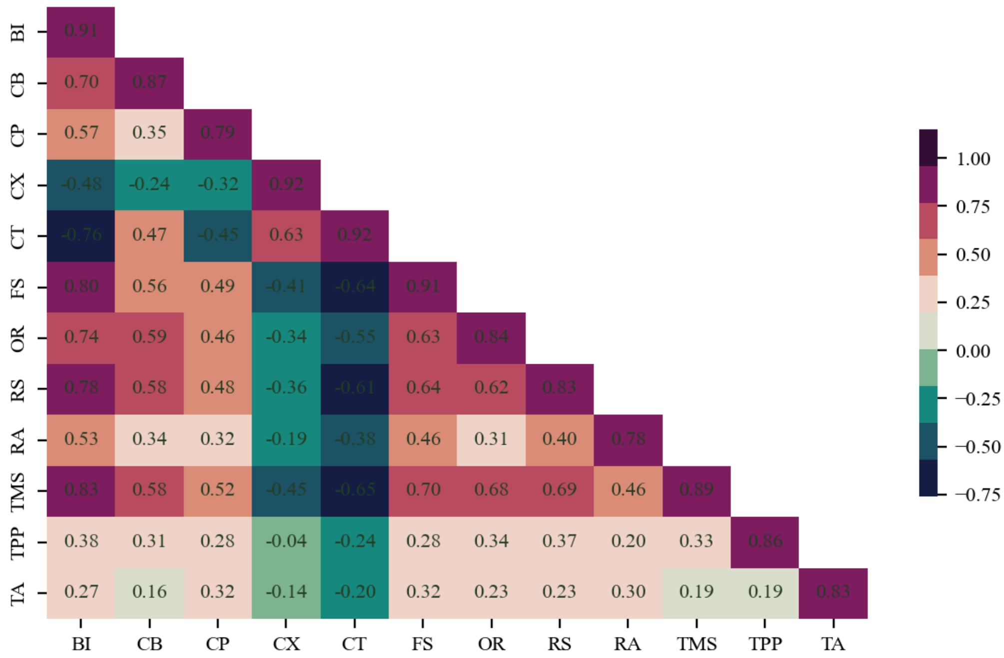

Figure 2. Fornell and Larcker criterion for discriminant validity results.

5.1.2. Structural Model

In this step, the proposed hypothesized relationships were examined using a bias-corrected bootstrap procedure with 5000 subsamples. As Table 3 and Figure 4 show, complexity, trialability, and trading partner pressure were non-significant factors at the 0.05 level. Among the remaining eight accepted relationships, compatibility, top management support, regulatory support, organizational readiness, relative advantage, firm size, and competitive pressure significantly positively influenced construction companies' willingness to adopt blockchain technology, whereas cost was negatively correlated with adoption. In addition, the R^2 value of 0.88 in Figure 4 indicates that the entire research model fits the survey data well. Moreover, we assessed the control variables' relevance by adding them separately to a model that includes all main variables. According to the results, none of the control variables exert a significant effect on blockchain adoption, thus all the control variables were excluded from the final model.

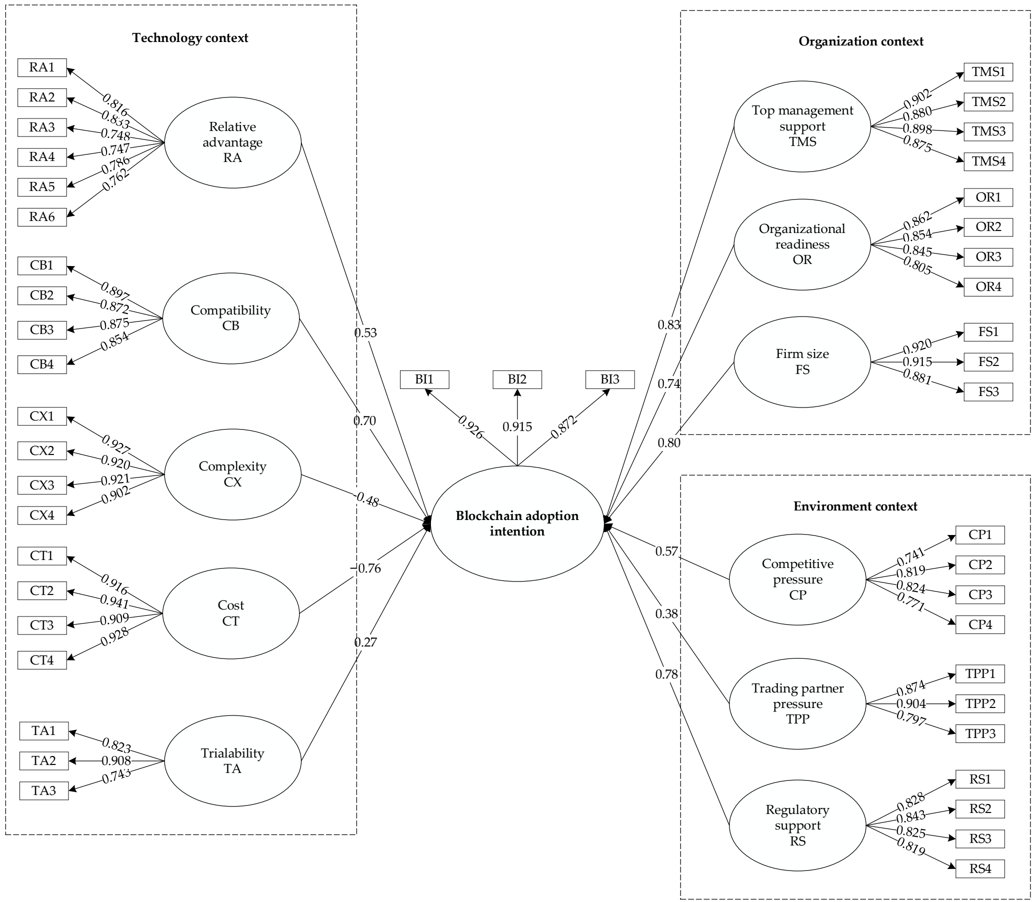

Figure 3. Measurement model.

Table 3. Path analysis results.

Hypotheses (Effects)	Hypothesis	Path Coefficient	t-Value	Conclusions
H1 (+)	RA → BI	0.102	3.960 ***	Supported
H2 (+)	CB → BI	0.166	4.314 ***	Supported
H3 (−)	CX → BI	−0.013	0.459	Not Supported
H4 (−)	CT → BI	−0.205	3.605 ***	Supported
H5 (+)	TA → BI	−0.013	0.579	Not Supported
H6 (+)	TMS → BI	0.207	4.208 ***	Supported
H7 (+)	OR → BI	0.112	2.489 **	Supported
H8 (+)	FS → BI	0.170	3.406 **	Supported
H9 (+)	CP → BI	0.064	2.367 **	Supported
H10 (+)	TPP → BI	0.030	1.175	Not Supported
H11 (+)	RS → BI	0.155	3.679 ***	Supported

Notes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

5.2. Results of fsQCA

The fsQCA, as a supplementary analysis, was further used to investigate the synergistic impact of numerous factors that may influence the willingness of construction companies to adopt blockchain. Some steps were necessary to perform an fsQCA analysis. The first step was data calibration. Ordinary data must be transformed into fuzzy sets with three meaningful thresholds: setting the original values from Likert scales to full membership, crossover anchors, and full non-membership. The 5th, 50th, and 95th percentiles were respectively used to show the level of membership among variables [74]. After calibration, the necessary conditions analysis (NCA) was performed to detect the conditions that might influence the achievement of the desired result. Table 4 lists the calibration and NCA results. Because all the consistency scores were below 0.90 as presented in Table 4, none of the conditions are necessary for high levels of blockchain adoption. In the next step, a truth table was constructed based on consistency and frequency. The number of cases threshold was set to five [75], and the lowest acceptable observation consistency was set at 0.9 [63].

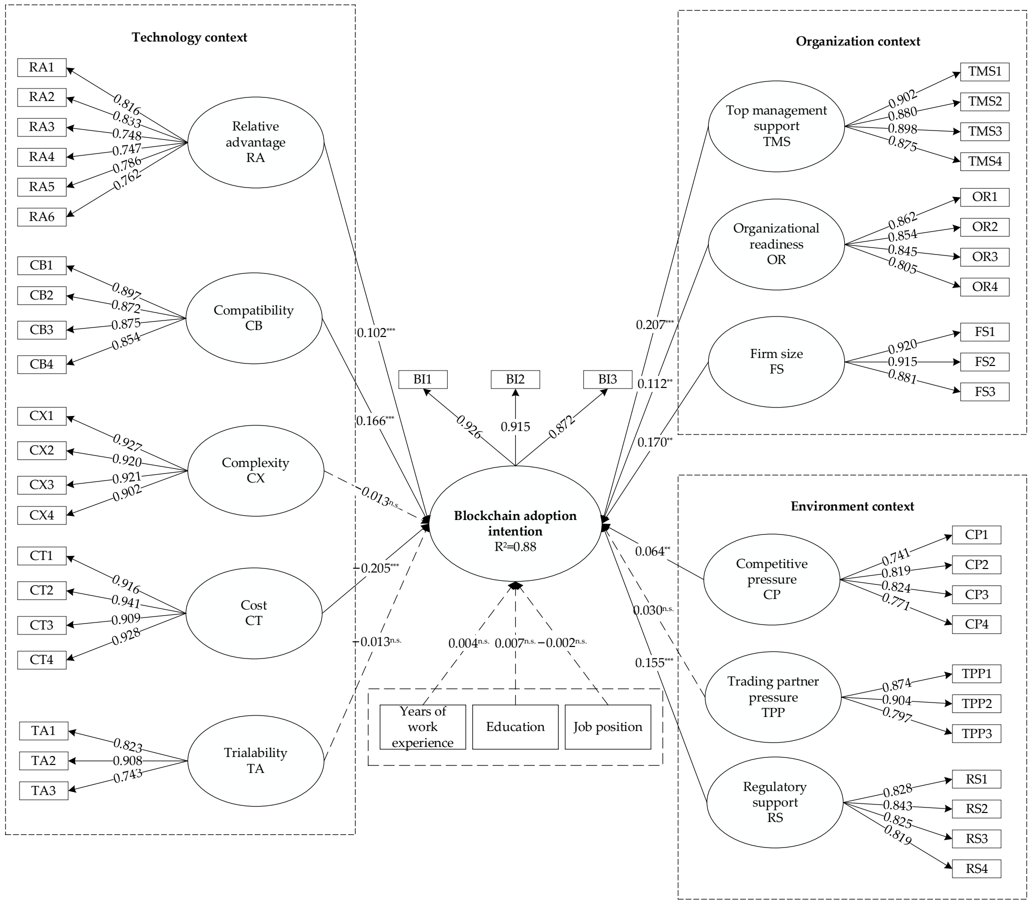

Figure 4. Structural path diagram for the hypothesized relationships. Notes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant.

Table 4. Calibration thresholds of the measures and causal necessary conditions test.

Construct	Full Membership	Cross-Over	Full Non-Membership	Consistency	Coverage
RA	4.33	3.50	2.50	0.768	0.775
CB	4.50	3.25	2.00	0.868	0.836
CX	4.75	3.25	2.00	0.515	0.544
CT	4.46	3.00	2.00	0.380	0.459
TA	4.67	3.67	2.33	0.692	0.703
TMS	4.00	3.25	2.00	0.863	0.853
FS	4.33	3.33	2.00	0.867	0.899
OR	4.00	3.25	2.00	0.856	0.830
CP	4.33	3.00	2.00	0.760	0.807
TPP	4.25	3.50	2.04	0.765	0.717
RS	4.28	3.33	1.72	0.884	0.856

A parsimonious solution, a complex solution, and an intermediate solution were used through the fsQCA software. Considering the superiority over the other two solutions [75], intermediate solutions were selected to conduct the fsQCA analysis of high blockchain adoption intention. Two combinations of causal conditions resulting in a high willingness to adopt blockchain are listed in Table 5. According to the raw coverage, solution 1 accounts for 21.7%, and solution 2 accounts for 28.7% of cases associated with the outcome. The overall solution coverage in Table 5 indicates that the two solutions covered 34.6% of cases that had the willingness to adopt blockchain. The consistent values for the two solutions are above 0.8, which means the two solutions have achieved technology innovation with sufficient consistency [76]. Factors including compatibility, top management support, relative advantage, regulatory support, firm size, and organizational readiness are considered the main conditions for blockchain adoption because they appeared in both solutions, which indicated that these six factors together strengthen adoption willingness. Solution 1 suggested that high blockchain adoption can be attained through the six main conditions listed above: low levels of complexity and cost and low levels of trialability and trading partner pressure. Solution 2 revealed that the six main conditions listed above—low levels of complexity and cost, combined with trialability, trading partner pressure, and competitive pressure—can achieve high blockchain adoption.

Table 5. Configurations for high blockchain adoption intention.

Configuration	**Solution**	
	1	**2**
The context of technology		
RA	•	•
CB	•	•
CX	O	O
CT	O	O
TA	O	•
The context of organization		
TMS	•	•
OR	•	•
FS	•	•
The context of environment		
CP	O	•
TPP	O	•
RS	•	•
Consistency	0.999	0.999
Raw coverage	0.217	0.287
Unique coverage	0.059	0.130
Configuration	**Solution**	
Overall solution coverage	0.346	
Overall solution consistency	0.9995	

Notes: The black circles "•" indicate the presence of an element. The black circles "•" indicate the presence of an auxiliary condition. The circle "O" represents the absence of an element.

5.3. Comparing PLS-SEM and fsQCA Results

The PLS-SEM analysis indicated that compatibility, top management support, relative advantage, regulatory support, cost, firm size, organizational readiness, and competitive pressure can significantly influence the intention of blockchain adoption for construction companies in order of decreasing influence, whereas complexity, trialability, and trading partner pressure can inhibit the intention to adopt. The fsQCA results indicated that compatibility, top management support, relative advantage, regulatory support, firm size, and organizational readiness are considered core elements for adoption because the six variables mentioned above were included in both solutions. These results indicated that the fsQCA and PLS-SEM analyses agreed.

However, some differences were observed between the fsQCA and PLS-SEM analyses. FsQCA complemented the PLS-SEM analysis by revealing more than one complex configuration of antecedents to achieve a high adoption of blockchain. Corresponding to the concept of causal asymmetry, fsQCA indicated that factors such as trialability, competitive pressure, and trading partner pressure have opposite impacts on the willingness to adopt blockchain, based on how they are combined or interact with other attributes. For example, solution 1 indicated that, although the level of complexity, cost, trialability, competitive pressure, and trading partner pressure is low, the six core conditions can increase organizations' willingness to adopt blockchain. Similarly, solution 2 indicated that trialability, competitive pressure, and trading partner pressure as the auxiliary conditions can contribute to the high intention of blockchain adoption, as long as the level of complexity and cost is low and the levels of six core elements are high.

6. Discussion

This study identified significant factors of blockchain adoption across technological, organizational, and environmental dimensions, which can provide the foundation for promoting blockchain adoption in the construction industry. Consequently, these key results contribute to a deeper understanding of blockchain adoption in the construction industry. By combining PLS-SEM with fsQCA, we also gained a better understanding of the overall adoption process. According to an evaluation of the research model, compatibility, top management support, and relative advantage were observed to be the top three important determinants to influence the intention of blockchain adoption, whereas complexity, trialability, and trading partner pressure received no meaningful statistical support at a significant level. Next, all findings related to the hypotheses are discussed.

Within the technology dimension framework, relative advantage (H1) is positively correlated with construction companies' intentions to adopt blockchain. Previous studies on innovation adoption also support this conclusion [17,36]. For example, relative advantages such as enabling efficiency gains, cost reductions, instant tracking and tracing of assets, and automated contract enforcement have been demonstrated to be potential benefits in the construction industry. Compatibility (H2) has a considerable impact on the adoption of blockchain by construction companies. Several studies supported this finding [35,77]. Blockchain adoption would be facilitated if the existing business operating model of an organization is compatible with blockchain technology. The internal systems of the construction industry are complex, and if the blockchain application matches the existing information infrastructure, construction companies would be more active in implementing blockchain. Studies have shown that the effect of complexity (H3), which was considered in earlier studies, does not have a significantly negative influence on blockchain adoption [36,78]. The relationship between the complexity and intention to adopt blockchain technology was not supported by the data we collected. Although somewhat unusual, this insignificant relationship may be due to the following reasons. On one hand, most construction companies have no ability to develop blockchain technology on their own, and they purchase it directly from high-tech companies. To some extent, companies do not care much about the complexity of blockchain but more about its usefulness, highlighting the significance of the relative advantage. On the other hand, with the advent of the digital age, construction companies could acquire technology in multiple ways, and technical barriers no longer play a crucial role in a company's competitive advantage. Cost (H4) has a significantly negative impact on the intention to adopt blockchain, which is consistent with the findings of earlier research that identified high costs as a primary barrier to innovation adoption [17,36]. The construction industry is a collaborative stakeholder with a complex network of relationships. A significant advantage of blockchain technology is the elimination of third-party-related costs in the network. Additionally, based on interviews with professionals working in the construction industry, it is anticipated that blockchain technology will reduce the costs associated with data processing and management by 70% through the automation of compliance checks, payments, and project performance analyses [5]. Even with such cost savings, the adoption of blockchain will increase hardware and facility costs, and the costs of operation and maintenance will remain significant. Construction companies may make comprehensive decisions to weigh the costs of blockchain adoption against the cost savings. Many construction companies are reluctant to adopt blockchain technology, considering the large initial investment and uncertainty on whether the expected benefits could be achieved. Trialability (H5) was confirmed to have no effect on blockchain adoption for construction companies, which was consistent with the findings of [46] and [77]. The present relative immaturity of blockchain technology could explain this result. The construction industry is recognized for its lack of innovation, and anxiety about using emerging technology systems could discourage the adoption of blockchain technology. Although trialability was not a significant factor in this study, its significance may change if blockchain technology is applied more broadly in the construction industry.

Within the organizational context framework, this study revealed that top management support (H6) has a crucial role in the adoption of blockchain in construction organizations. It has been an essential component of the implementation of various technological advancements [36,47]. It had the second-highest path coefficient value of all the examined factors, confirming the significance of top management in innovation adoption in construction. The significant effect of organizational readiness (H7) on blockchain adoption corresponds with the findings of [35]. Blockchain adoption by construction companies that lack sufficient technical, financial, and trained human resources may be challenging. A company may not implement blockchain technology if it does not have the necessary resources and competencies. Corresponding with the findings of [40] and [35], firm size (H8) emerged as a critical factor affecting adoption. Combined with the characteristics of the construction industry, larger firms intend to adopt blockchain technology because their capabilities and sources are sufficient to utilize and implement blockchain technology.

Regarding the framework of the environmental context, competitive pressure (H9) was confirmed to have a significant positive impact on the blockchain adoption intentions of construction companies. Competitive pressure has been shown to be a crucial facilitator of technology adoption across a broad variety of businesses, as previous studies have shown [35,46]. Firms under intense competition are more likely to use and implement blockchain technology to increase their market share. A construction company may explore effective strategies to gain a long-term competitive edge. This shows that competition exists and that the ability to remain at the forefront of technical advancement influences decisions. Trading partner pressure (H10) was confirmed to have no significant effect on blockchain adoption, similar to the study conducted in [36]. This may be because blockchain is still a relatively new technology, with most companies involved being start-ups. Chinese construction companies currently have minimal adoption of blockchain, and it is difficult to assess the difficulty of using blockchain technology in new construction projects. It is impossible for trading partners to fully adopt blockchain within a short period. Consequently, companies are less sensitive to pressure from trading partners in the construction industry. Regulatory support (H11) has a significantly positive influence on blockchain adoption, similar to the conclusions of [63] and [78]. The significance of this link results from the fact that construction companies consider the adoption of blockchain technology to be a large investment, and regulatory support is essential for legitimizing adoption and implementation. The reason for this significant relationship is that construction companies consider blockchain adoption a significant investment and regulatory support as necessary to ensure smooth implementation across the board.

6.1. Theoretical Implications

As blockchain research is still in its early phases in terms of empirical testing, theoretical processes, and methodological diversity, this paper provides timely important theoretical and methodological contributions. Although there are many previous qualitative studies on blockchain in construction [11,27], there is a lack of quantitative studies in this investigation. Based on the theoretical perspective of the TOE framework and empirical evidence from Chinese construction companies, the results of this study provide researchers, practitioners, and policymakers with relevant guidance for the construction industry by investigating the relationship between various determinants and the willingness to adopt blockchain. The results of the study revealed that factors such as compatibility, top management support, relative advantage, regulatory support, cost, competitive pressure, organizational readiness, and firm size significantly influence the intention of blockchain adoption whereas complexity, trialability, and trading partner pressure have no effect. These findings are in line with those reported by the vast majority of earlier studies on the process of technology innovation diffusion [36,46]. The inconsistency of these findings with the results of previous studies about the application of blockchain to other fields reflected the characteristics of the construction industry [17,35]. More importantly, a comprehensive analysis of the fsQCA and PLS-SEM results deepens our understanding of the adoption process. Furthermore, this research can provide organizations or businesses with a clearer picture of the factors influencing blockchain adoption, which can enhance the transformational capabilities of construction companies and provide insights into the impact of emerging technologies on the construction industry.

6.2. Practical Implications

With the rapid development of smart construction, the construction industry has experienced unprecedented disruptive innovation in recent years. Blockchain is recognized as an emerging technology that promises to solve pain points in the construction industry. It promises to have a significant impact on operations, trust management among stakeholders, and business processes. This study evaluated various factors that influence the intent to adopt blockchain, and our findings have many practical implications. Overall, these conclusions can help practitioners make better blockchain adoption decisions. This study evaluated the causes and situations that drive the migration of the construction industry to blockchain.

In the context of technology, construction companies should actively recognize the benefits of blockchain as the first step in its adoption. Our findings suggest that the relative advantages that blockchain brings to construction companies can incentivize them to adopt blockchain. The positive correlation between the comparative advantage and adoption intentions can help decision-makers recognize the value of blockchain in construction businesses; moreover, compatibility is a significant predictor of blockchain adoption. If blockchain technology is compatible with a firm's business philosophy and operating system, it contributes to the smooth operation of the firm. Compatibility: Our findings suggest that compatibility has a greater impact on the willingness to adopt blockchain than top management. For strategic deployment, executives first assess a company's compatibility before adopting blockchain technology. Additionally, cost is a key concern for construction companies, and can influence their willingness to adopt blockchain technology. Although the cost is negatively correlated with the willingness to adopt blockchain, construction companies still comprehensively decide whether to adopt blockchain technology in a dialectical and systematic way.

In the organizational dimension, the attitude of the top management is critical to the willingness of construction companies to adopt blockchain. Our findings suggest that, for senior managers to conclude that adopting blockchain will bring relative advantages, they should focus on improving the technical capabilities of R and D personnel to meet the company's needs for blockchain technology. Blockchain adoption is not a simple technology implementation process and involves various aspects of organizational readiness to create a foundation for adoption and application. Construction companies should focus on improving their technological capabilities to successfully implement blockchain adoption. More scientists with relevant knowledge must be recruited to facilitate the implementation of blockchain. Large-scale firms are more willing to change their adoption of new technologies than smaller ones. Large-scale companies can use blockchain for business expansion to solve their business challenges. Even with the uncertainties and risks associated with blockchain technology adoption, large construction companies are actively adopting big data analytics to gain a competitive advantage and open up new business opportunities.

In an environmental context, competitive pressure compels the construction industry to adopt blockchain technology to enhance the strength of companies. Learning and applying blockchain technology is gaining popularity as companies seek to gain a competitive advantage over their competitors. In an increasingly competitive market, our findings suggest that companies should adopt blockchain. Regulatory support is indispensable, and the improvement of relevant laws and regulations will provide effective protection for the construction industry to adopt blockchain. Governments play a pivotal role in encouraging the development of new technologies, and the adoption of blockchain technology requires the support of government entities.

7. Conclusions and Limitations

Based on the TOE framework, this paper attempted to fill a knowledge gap by identifying the determinants of blockchain adoption and presenting an empirical foundation for future blockchain adoption in the construction sector. The survey data for this study were obtained from Chinese construction companies, and 11 components in three different contexts were examined using a hybrid approach of PLS-SEM and fsQCA. The PLS-SEM findings show that factors such as compatibility, top management support, relative advantage, regulatory support, cost, firm size, organizational readiness, and competitive pressure significantly influence adoption. In addition, three factors (complexity, trialability, and trading partner pressure), because the relevant hypotheses did not receive support from the evidence, were confirmed to have no statistically significant influence. Further research on these three factors is required to obtain a clearer understanding. From the fsQCA results, a combination of compatibility, relative advantage, top management support, regulatory support, organizational readiness, and firm size achieves the highest level of blockchain adoption intention. These findings are intended to assist researchers, developers, and decision-makers in better comprehending the key blockchain adoption factors in the construction industry and addressing negative adoption factors more effectively.

This study had some limitations. First, the data were cross-sectional rather than longitudinal and the sample size and diversity were limited. However, the adoption of blockchain is a dynamic process and blockchain technology is constantly evolving. Thus, more studies should be conducted to extend the generalization of the findings in the current study. For example, involving more stakeholders in the progress of adopting emerging technologies; using different research methods, such as using multiple case studies or a system dynamics approach to replicate this study and verify the findings obtained from it. Second, except for those identified in this study, the research cannot be exhaustive because of many other technical, organizational, and environmental factors that may influence blockchain adoption; more precisely, some of the factors cannot be used to differentiate the construction industry from others. In the future, we will consider factors that are more specific to the construction industry, such as security and privacy issues. Furthermore, this study only considered the impact of factors on adoption decisions, and linkages may exist between factors, for example, whether the factors in the environmental dimension moderate the factors in the dimensions of technology and organization to impact adoption decisions. Additionally, the sample used in this study was from China. Because of the cultural differences between China and other countries, the study model should be further examined and contrasted using samples from other nations to offer more credible support for the hypotheses.

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Appendix A

Table A1. Survey items.

Construct	Measurement Items	Adapted From
Relative advantage	Adopting blockchain can enable my company to accomplish project tasks more efficiently and effectively Adopting blockchain can enhance the traceability of my company's projects Adopting blockchain can increase the transparency of my company's projects Blockchain can increase trust among stakeholders in construction Adopting blockchain can improve deferred payment issues	[17]
Compatibility	Blockchain can provide privacy protection and security of my company Blockchain is compatible with the business operating model in my company Blockchain is compatible with the management requirements of the company Blockchain fits with the existing values of my company Blockchain is compatible with my company's existing infrastructure	[36,46]
Complexity	Blockchain would be too complex for my company to use Learning how to use blockchain in my company is not easy It will take considerable time and effort for my company to learn how to use blockchain My company believes that blockchain adoption requires many skills	[17,36]
Cost	Adopting blockchain in my company will increase the cost of facility and hardware Adopting blockchain in my company will increase the cost of operations and maintenance The cost of adopting blockchain will be expensive for my company The cost of adopting blockchain is unknown and difficult to comprehend	[17,36]
Trialability	My company intends to try out some blockchain technology in a small scope before fully adopting and implementing it A trial period before blockchain adoption will reduce risks The ability to experiment with blockchain adoption is critical in deciding whether to adopt it	[46]
Top management support	Top management in my company will be responsive and attentive to blockchain adoption Top management in my company could take the risks associated with blockchain adoption My top management will provide the necessary human resources, finances and materials for blockchain adoption My top management will look at blockchain as strategically important	[35,46]
Organizational readiness	My company has resources necessary to use blockchain My company has possessed the necessary expertise and skills to adopt blockchain The technology staff in the company have the sufficient experience and skills to conduct the adoption of blockchain My company's existing technologies support blockchain adoption	[36,46]
Firm size	My company's capital is higher than others in the construction industry My company's revenue is higher than others in the construction industry My company has more competent staff than others in the construction industry	[35,36]
Competitive pressure	The adoption of blockchain will offer my company a stronger competitive advantage My company believes it is important to adopt blockchain to be competitive My company is forced to adopt blockchain due to competitive pressure My company believes that competitors have recently started exploring blockchain technology	[17,63]

Table A1. *Cont.*

Construct	Measurement Items	Adapted From
Regulatory support	The government or competent agencies provide financial assistance for blockchain development The government or relevant authorities provide technical guidance for adopting blockchain technology Blockchain technology can be implemented with the current set of laws and regulations Government encourages the adoption of blockchain in procurement and projects	[17]
Trading partner pressure	My company's major trading partners recommend blockchain adoption My company's major trading partners encourage blockchain adoption My company's major trading partners request blockchain adoption	[46,63]
Behavioral intention	My company intends to adopt blockchain technology actively in the future My company intends to digitally transform management My company is willing to utilize blockchain technology in various projects	[17,46]

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