

Article

The Catalyst of Culture: Unlocking Blockchain-Driven Digital Transformation in Saudi Construction

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Abstract

Saudi Arabia's construction industry is greatly impacted by rising costs and delays, causing project overruns and high financial pressures. In construction, blockchain technology is a decentralized and secure system that promotes transparency, trustworthiness and effective management of project data and transactions. This research is based on the Technology–Organization–Environment (TOE) framework, which develops and tests a conceptual model to investigate how supply-chain management, smart contracts, transparency and traceability, regulatory compliance and building information modeling (BIM) integration influence blockchain technology adoption, with organizational culture as a moderator. Data from 291 professionals in large Saudi contracting firms were analyzed employing a quantitative, cross-sectional design using SmartPLS. Results confirm all hypothesized factors significantly drive blockchain technology adoption. Organizational culture, acting as a key amplifier, positively moderates all relationships. The model explains 71.1% of the variability in blockchain technology adoption. In order to overcome project challenges and meet Vision 2030's goals, the results present a validated roadmap for Saudi's construction sector. The findings show that technical investments and promoting a culture of innovation, collaboration across departments and strong leadership are important for adoption blockchain technology.

Keywords: blockchain technology; BIM; organizational culture; PLS-SEM; regulatory compliance; smart contracts; supply-chain management; transparency and traceability

Academic Editor: Jorge Lopes

Received: 15 January 2026

Revised: 29 January 2026

Accepted: 3 February 2026

Published: 5 February 2026

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1. Introduction

Many countries are implementing digital innovation strategies to improve organizational effectiveness with the help of technological advancements and digital integration [1]. The construction sector stimulates economic growth, improves quality of life and promotes social advancement by providing a wide array of infrastructure and structures [2,3]. New technologies are driving the digitalization of construction and modernizing practices to improve performance, collaboration, and flexibility in meeting digital requirements [4].

Construction projects are highly complex, divided into various parts and highly risky in the global economy [5]. Construction projects face delays, disputes, and transparency issues due to complex stakeholder involvement and supply chains, leading to higher costs, project overruns and reduced stakeholder trust [5–7].

Saudi Arabia's economic diversification and development plans (e.g., Vision 2030) are underpinned by the construction industry [8]. Although the construction sector is massive, with great strategic value, there are many challenges in project implementation and completion, which include budget overruns, schedule delays and quality shortfalls [9]. The innovations in digital technologies are changing the construction environment in Saudi Arabia into efficient, affordable, and environmentally friendly projects, which is consistent with the objectives of modernization and innovation in the country's Vision 2030 [10].

The results of Saudi Arabian construction projects showed that 64% were overrun and 53% exceeded their budgets, mainly due to delays and poor cost management [11]. These problems in the execution of projects jeopardize the individual project's financial success and the overall development goals of the country [12]. Blockchain is a promising technology for addressing challenges in construction projects by offering a secure, transparent and efficient system with decentralized and immutable records, transparent transaction history and automated contract management using smart contracts [13]. The frequent occurrence of rising costs, delays and disputes in construction caused by stakeholder conflicts and trust issues makes these features valuable [14].

In construction, the use of blockchain technology is increasingly acknowledged. Multiple scholarly articles have discussed the individual advantages of blockchain in construction, e.g., automating payments through smart contracts [15,16], improving supply-chain management for resilience and sustainability [17], and the role of transparency and traceability in building stakeholder trust and ensuring accountability [18]. Additionally, using blockchain with BIM has been shown to reduce design cycles and construction delays, enhance site supervision [19,20] and streamline regulatory compliance through immutable record-keeping [21].

Smart contracts contribute to sustainable productivity and business success and can be adopted with the assistance of a positive organizational culture [22]. It significantly affects the ability of technological innovation (e.g., blockchain) to be utilized effectively in enhancing supply chain practices, where different cultural orientations either support or impede its impact on trust and sustainable integration [23]. The benefits of establishing an organizational culture that promotes willingness to embrace new ideas, lifelong learning, innovativeness, and a positive attitude towards risk-taking are essential for the successful implementation of blockchain technology [24].

The failure of projects in Saudi Arabia is high due to issues of transparency, inefficiency in teamwork and ineffective regulatory frameworks, which hamper the success of Vision 2030 [6,25,26]. Despite blockchain's potential to address these problems, its adoption is limited. This study introduces the first integrated framework, which examines BIM integration, supply chain management, smart contracts, transparency and traceability and regulatory compliance, while exploring how organizational culture influences their impact. It addresses industry needs and offers guidance on blockchain adoption in Saudi Arabia to promote transparency and efficiency and provide theoretical advancements and practical benefits for improved project delivery in the construction sector.

This study will answer the following questions related to Saudi contractors.

1. What impact do smart contracts have on blockchain technology adoption?
2. What impact does supply chain management have on blockchain technology?
3. What impact does BIM integration have on blockchain technology adoption?
4. What impact does transparency and traceability have on blockchain technology adoption?
5. What effect does regulatory compliance have on blockchain technology adoption?
6. What impact does organizational culture have on blockchain technology adoption?

7. To what extent does organizational culture shape the interactions between adoption of blockchain technology and
 - (a) Smart contracts;
 - (b) Supply chain management;
 - (c) BIM integration;
 - (d) Transparency and traceability;
 - (e) Regulatory compliance?

In order to investigate these questions, this study is grounded in the Technology–Organization–Environment (TOE) framework, which provides a structured lens to analyze the technological, organizational, and environmental factors influencing innovation adoption. This makes it well-suited to understanding the Saudi construction sector under Vision 2030.

1.1. Global Overview

In Chinese construction, Li et al. [27] revealed that organizational readiness, regulatory support, relative advantage, compatibility, firm size, top management support, cost, and competitive pressure play a crucial role in blockchain adoption. In Nigeria's built environment, Ebekozien et al. [28] revealed that implementing blockchain to automate payments, finance, and supply chains can reduce costs when properly applied. Based on Kang et al.'s [29] research in Hong Kong, blockchain technology can improve construction efficiency, decrease manual documentation and resolve communication barriers. In the context of Thai construction, Aksorn et al. [30] stated that employees' job functions, ranks, accountability and technological skills impact blockchain technology adoption. In Sri Lanka's construction sector, Bandara et al. [31] revealed that blockchain adoption can improve transaction speed, transparency, and security, aiding in reducing corruption and automating contracts. Kiu et al. [32] highlighted in the Malaysian construction industry that the adoption of blockchain is capable of creating trust and a collaborative spirit, enhancing transparency, expediting payment procedures, and improving the security and precision of data.

1.2. Digital Advancements in Saudi Construction

Saudi Arabia is at the forefront of digital innovation as a means of diversifying its economy, improving government services, and encouraging innovation, with the aim of becoming a regional technology center [33]. It is growing economically due to the rapid growth of the infrastructure and construction sector that is backed by investment, technological advancement, and innovative methods [17]. The construction industry is evolving due to economic transformation brought about by the decline in oil prices and regulatory demands, as part of the greater digitalization under Saudi Vision 2030, which presents significant challenges and massive future opportunities [34]. The Saudi construction industry is struggling to accept digital transformation compared to the tendencies in the rest of the world regarding automation and information communication technology [35].

1.3. Smart Contracts

A smart contract is a programmable and self-executing agreement that supports advanced transactions carried out in numerous industries [36]. The efficiency of corporate processes is improved by using smart contracts, which are usually secured with blockchain technology to reduce transaction risks, administrative and service costs and simplify operations compared to traditional contracts [37]. Smart contracts on blockchains automate payments, compliance and contractual obligations which facilitate project management, minimize delays and disputes and improve transparency and efficiency [38]. Smart

contracts provide a better solution by replacing the conventional processes of transactions in various business sectors [39]. In the Saudi context, smart contracts under Vision 2030 help resolve project delays and disputes by automating verification and payments, and improving cash flow and trust among stakeholders [15,40]. Table 1 demonstrates the key benefits used to operationalize the smart contracts construct.

Table 1. Expected benefits of smart contracts.

Dimension	Source
Improved Cash Flow from Automated Payments	[41]
Reduction in Contractual Disputes	[42]
Decreased Administrative Overhead	[43]
Encoding of Complex Contractual Clauses	[44,45]
Reduction of Counterparty Risk	[46]

H1a. *Smart contracts positively influence blockchain technology adoption.*

H1b. *Organizational culture positively moderates the relationships between smart contracts and blockchain technology adoption.*

1.4. Supply Chain Management

The major digitalization centers on modernizing construction supply chain management [47]. The main goals of supply chain management include lowering expenses, increasing productivity, optimizing resources and reducing sector fragmentation [48]. It focuses on facilitating the uninterrupted transfer of materials and services to sites by fostering collaboration among supply chain members [49]. The construction process, at each stage of the supply chain, is enhanced by incorporating blockchain technology [50]. Saudi Arabia's large-scale construction projects face supply chain delays and authenticity issues, but blockchain offers benefits such as transparent tracking of sustainable materials, real-time visibility for proactive management, and reduced administrative errors through digital reconciliation. Saudi Arabia's large-scale construction projects face supply chain delays and authenticity issues, but blockchain offers benefits such as transparent tracking of sustainable materials, real-time visibility for proactive management, and reduced administrative errors through digital reconciliation [17,51]. The operationalization of the supply chain management construct, based on expected benefits, is depicted in Table 2.

Table 2. Expected benefits of supply chain management.

Dimension	Source
Real-Time Supply Chain Visibility	[52]
Reduction in Logistics Paperwork	[53]
Enhanced Disruption Response	[54]
Verification of Material Authenticity	[55]
Automated Inventory Reconciliation	[56]

H2a. *The blockchain technology adoption is significantly driven by supply chain management.*

H2b. *Organizational culture strengthens the positive link between supply chain management and blockchain technology adoption.*

1.5. BIM Integration

BIM is a modern digital application that enhances collaboration and automates quantity take-off and clash detection. In the lifecycle of a building, it functions as a central

facility information database to support decision-making [57]. It enhances collaboration, data sharing and production by providing operators with real-time access to project information such as designs, locations, plans and costs through integrated models [58,59]. The integration of multidimensional data enables BIM to depict organizations, programs and projects in a visual and parametric format [60]. In construction projects, blockchain integrated with BIM can create new data-driven business opportunities and improve collaboration [61]. Integrating blockchain with BIM in Saudi Arabia enhances data security and accountability by creating a secure, auditable source of truth that locks critical design milestones and tracks changes [62–64]. The expected benefits used to operationalize the BIM integration construct are illustrated in Table 3.

Table 3. Expected benefits of BIM integration.

Dimension	Source
Tracking of Design Changes	[65]
Accuracy of As-Built Documentation	[66]
Trust and Accountability in Collaboration	[67]
Automated Milestone Payments	[68]
Integrity of Project Data History	[69]

H3a. *BIM integration positively influences blockchain technology adoption.*

H3b. *Organizational culture positively moderates the relationships between BIM integration and blockchain technology adoption.*

1.6. Transparency and Traceability

Traceability is the capability to observe and record information at every stage of the lifecycle, while transparency involves the timely, unbiased and accessible disclosure of related data without fee, interruption or discrimination [70]. Trust and transparency problems in the construction sector have hindered stakeholder collaboration [71]. The rise in the complexity of building data and object-based modifications has created a need for companies to implement transparent and traceable planning procedures [72]. Blockchain technology improves transparency and traceability in construction by enabling secure, immutable records of material provenance, lifecycle and supply chain transactions [55]. It also improves information sharing by increasing traceability and transparency, leading to improved monitoring and supporting sustainability performance [73]. Blockchain-enabled transparency in construction supports Saudi Arabia's Vision 2030 by providing an immutable, time-stamped record of transactions, enhancing auditability, preventing fraud, and enabling quick identification of quality issues [74–76]. Table 4 illustrates the operationalization of the transparency and traceability construct through its anticipated benefits.

Table 4. Expected benefits of transparency and traceability.

Dimension	Source
Unified Stakeholder Access to Information	[77]
Material Provenance Tracking	[78]
Deterrence of Fraudulent Documentation	[79]
Efficient Quality Issue Isolation	[80]
Improved Stakeholder Confidence and Audit Ease	[81]

H4a. *Transparency and traceability have a positive impact on blockchain technology adoption.*

H4b. *Organizational culture strengthens the positive link between transparency and traceability and blockchain technology adoption.*

1.7. Regulatory Compliance

Regulatory compliance is crucial in blockchain architecture because it guarantees that transactions are legally valid, illicit transactions are avoided and innovative privacy measures are designed to balance transparency and privacy of users [82]. The emerging markets, where industrial, global and technological changes occur swiftly, demand high compliance with regulations to facilitate economic stability and sustainable growth [83]. Regulatory compliance assists business entities to conduct business within the legal framework, safeguard stakeholders and encourage a culture of trust and honesty [84,85]. In the construction sector, the implementation of regulatory compliance measures increases operational efficiency and leads to cost savings [86]. The Saudi construction regulatory landscape is rapidly evolving with new rules on Saudization, environmental standards, and permit approvals. Blockchain technology can automate compliance checks and streamline reporting by providing secure, transparent access to verified project data [87,88]. Table 5 illustrates the operationalization of the regulatory compliance construct based on expected benefits.

Table 5. Expected benefits of regulatory compliance.

Dimension	Source
Ease of Compliance Reporting	[89]
Automation of Compliance Checks	[90]
Streamlining of Permit Approvals	[91]
Adherence to Saudization and Local Content	[92]

H5a. *Regulatory compliance positively influences blockchain technology adoption.*

H5b. *Organizational culture strengthens the positive link among regulatory compliance and blockchain technology adoption.*

1.8. Organizational Culture

Culture defines the distinctive nature of an organization, in terms of environment, core values, prominent heroes, etiquette, rituals, and cultural network [93]. Building effective organizational culture is central to long-term employee engagement and organizational excellence [94,95]. Organizational culture determines the manner in which employees share and manage knowledge, which affects the success of the organization [96]. Change management relies on organizational culture, which impacts common beliefs, behaviors and attitudes that determine how employees receive and respond to change initiatives [97]. The road to operational success is paved with the alignment of technology, such as blockchain solutions, to organizational culture [98]. In order to operationalize organizational culture in Saudi context, eight key dimensions were identified, reflecting a culture of innovation and agility within the organization, as outlined in Table 6.

Table 6. Operational dimensions of organizational culture.

Dimension	Source
Culture of Technological Experimentation	[99]
System for Rewarding Innovation	[100]
Agile and Adaptable Decision-Making	[101]
Leadership Support for Digital Transformation	[102]
Effectiveness of Cross-Departmental Collaboration	[103]

Availability of Technical Expertise and Infrastructure	[104]
Confidence in Managing Organizational Change	[105]
Strategic Alignment of IT and Innovation Goals	[106,107]

H6. *Blockchain technology adoption is positively driven by organizational culture.*

1.9. Blockchain Technology Adoption

The transformative power of blockchain technology can reshape the workflows, trust systems, and purchasing procedures in the built environment [108]. In construction, its application aids in eliminating the problem of low efficiency, lack of cooperation, and poor administration of contracts [109]. Blockchain technology automates workflows, improves intelligent project management and reduces the reliance on manual labor [110,111]. Management workflows are improved through blockchain technology, which boosts security and trust, and reduces expenses [112]. Table 7 illustrates the operationalization of blockchain technology adoption.

Table 7. Blockchain technology adoption.

Dimension	Source
Intention to Launch Pilot Projects	[113]
Willingness to Allocate Financial Resources	[114]
Senior Management's Strategic Belief in Blockchain Technology	[115]
Perception of Blockchain Technology as a Competitive Necessity	[116]
Proactive Pursuit of Partnerships and Knowledge	[117]
Existence of a Strategic Integration Roadmap	[118]

1.10. Theoretical Background

The TOE framework, developed by Tornatzky and Fleischer [119], explains how organizations adopt and implement technological innovations by considering the technological (available technologies), organizational (the company's structure and resources), and environmental (external factors, e.g., regulatory compliance) context. Internal and external technologies are represented by technological dimensions within the organization. The organizational dimensions represent various aspects of a company, such as its scale, reach, level of formal procedures, degree of centralization, management complexity, internal redundancies and human resource quality. An organization's environmental dimensions encompass its industry landscape, competitors, alliances, and regulatory policies or objectives [119,120].

2. Methodology

2.1. TOE Framework

This research is founded on the TOE framework, which analyzes the impact of environmental, technological and organizational factors on blockchain technology adoption [119,121]. The technological dimension is reflected through BIM integration, supply chain management, smart contracts and transparency and traceability. The environmental dimension is captured through regulatory compliance. Organizational culture (moderating construct) forms the organizational dimension that amplifies or hinders the influence of these technological and regulatory factors. In Figure 1, the visual representation of the conceptual framework is shown.

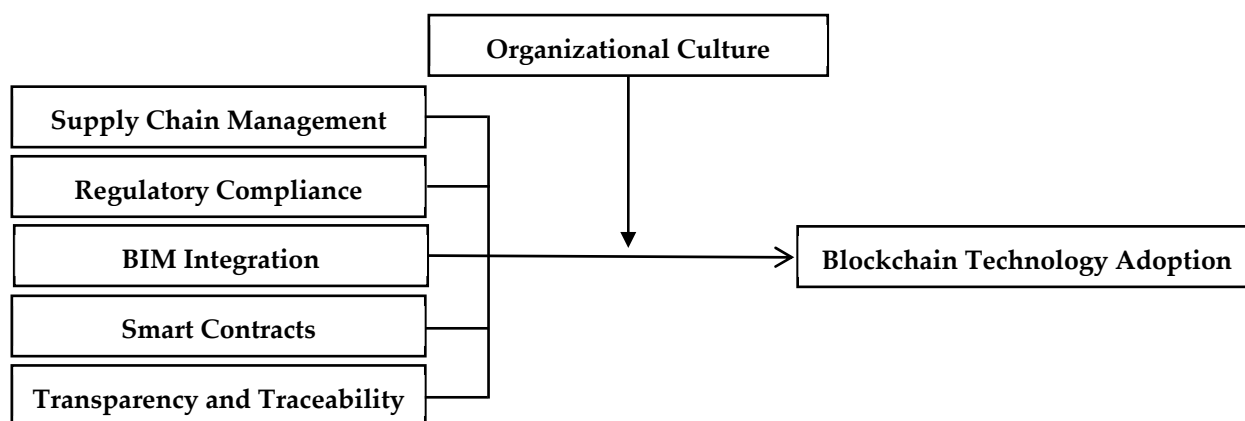


Figure 1. Conceptual Framework.

2.2. Population and Sampling

This research is cross-sectional (quantitative) and uses a close-ended questionnaire for data collection [122,123]. The Saudi Contractor Authority registers 769 large companies with employee counts ranging from 501 to 3000, comprising 11.65% Saudi nationals, 83.35% non-Saudis, 7.73% females and 92.27% males [124]. The selection process involved simple random sampling from the target population, ensuring that each contractor was equally likely to be selected [125]. The occupation includes project managers, construction managers, QA/QC managers, human resource managers, information technology managers, procurement managers, contract administrators, engineers, and other professionals. The companies specialize in building construction, landscaping, civil engineering and specialized construction activities. This research requires no fewer than 264 participants [126].

2.3. Survey Instrument and Data Collection

Using closed-ended questionnaires (Supplementary Materials), this study ensures effective data gathering, enhances understanding for participants, reduces confusion and obtains measurable and reliable data with a higher rate of responses [127,128]. Advance notice was given by email to employees of large contracting firms. The questionnaires were distributed using a mixed-mode approach. Physical questionnaires were handed to selected employees where direct access was available, while email-based questionnaires were shared with respondents who preferred digital participation. Each questionnaire was accompanied by a cover letter outlining the study objectives, voluntary participation, anonymity and data confidentiality. Follow-up reminders were issued by email and WhatsApp 2.2587.9.0 messages at regular intervals to improve response rates. Participants responded using a five-point Likert scale, with questions carefully crafted for clarity and proper formatting. Continuous follow-up efforts were made to improve response rate and to ensure the data accuracy [129–132]. After distributing 395 questionnaires, 316 were returned; 25 of these were invalid, leaving 291 valid responses, which amounts to a completion rate of 73.67%.

2.4. Analysis

SmartPLS 4.1.1.5 served as the tool for analysis in this research. It is known for its powerful capabilities, reliable performance, user-friendly interface and ability to handle non-normal data with complex structures [133–135].

3. Results

3.1. Demographics

The demographics shows that males constitute 93.81% with a small female representation (6.19%). Most are non-Saudis (88.66%) compared to Saudis (11.34%). In terms of occupation, engineers (36.08%) comprise the largest group, followed by procurement managers (13.40%), construction managers (10.65%), project managers (4.81%), QA/QC managers (7.56%), IT managers (8.25%), human resource managers (3.09%), contract administrators (2.75%), architects (1.03%), quantity surveyors (0.69%) and other roles accounting for 11.68%. Employee experience varies, with the largest group having 10–14 years of experience (29.55%), while the smallest group has over 20 years of experience (12.71%). The main area of contractor activity is building construction at 30.58%, followed by landscaping (25.43%), civil engineering (23.71%) and specialized construction activities (20.27%). Demographics are shown in Table 8.

Table 8. Demographics.

	Category	Frequency and Percentage
Gender	Male	273 (93.81%)
	Female	18 (6.19%)
Nationality	Saudi	33 (11.34%)
	Non-Saudi	258 (88.66%)
Occupation	Project Manager	14 (4.81%)
	Construction Manager	31 (10.65%)
	QA/QC Manager	22 (7.56%)
	Human Resource Manager	9 (3.09%)
	IT Manager	24 (8.25%)
	Procurement Manager	39 (13.40%)
	Contract administrator	8 (2.75%)
	Engineer	105 (36.08%)
	Architect	3 (1.03%)
	Quantity Surveyor	2 (0.69%)
	Others	34 (11.68%)
Employee Experience	1–4	39 (13.40%)
	5–9	76 (26.12%)
	10–14	86 (29.55%)
	15–19	53 (18.21%)
	>20	37 (12.71%)
Division	Buildings Construction	89 (30.58%)
	Landscaping	74 (25.43%)
	Civil Engineering	69 (23.71%)
	Specialized Construction Activities	59 (20.27%)

3.2. Measurement Model

In SmartPLS, the way observed indicators measure latent variables is outlined in the measurement model [136]. Its validation includes evaluating indicator reliability (indicators reliably measure the construct), construct reliability (measures the internal consistency), convergent validity (indicators converge to represent their construct) and discriminant validity (constructs remain empirically distinct) [137–139]. Figure 2 depicts the measurement model.

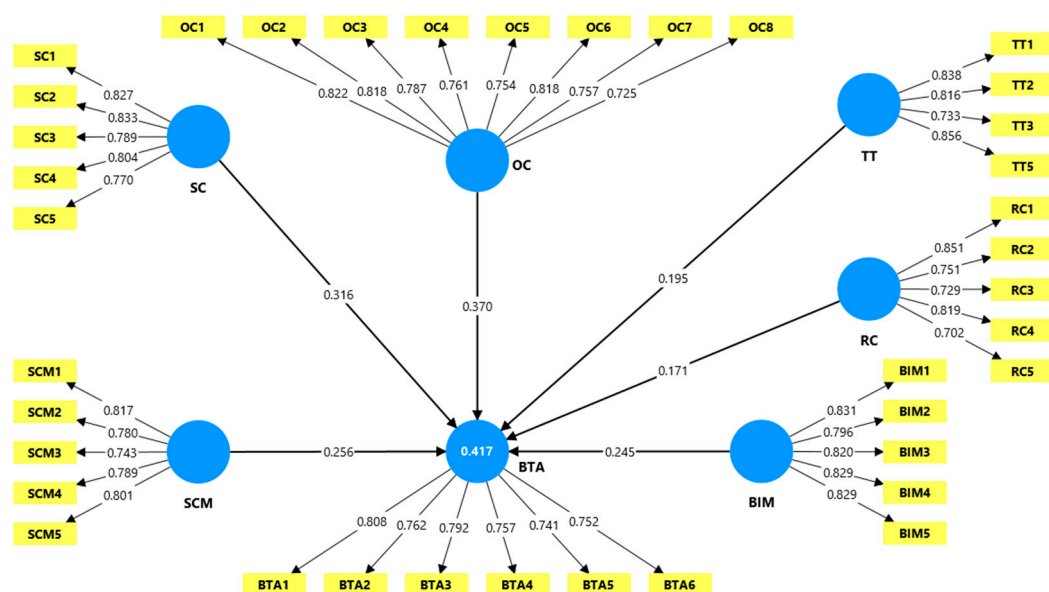


Figure 2. Measurement model.

A threshold of 0.708 for outer loadings signifies indicator reliability [140]. Indicator TT4 was removed (loading < 0.708), while all outer indicator loadings exceeded 0.708. Table 9 shows that Cronbach's alpha (>0.7) and CR (>0.7), confirming internal consistency reliability and AVE (>0.5), shows established convergent validity [137].

Table 9. PLS algorithm results.

Construct	Indicator	Loading	Cronbach's Alpha	CR	AVE
Supply Chain Management (SCM)	SCM1	0.817	0.847	0.864	0.618
	SCM2	0.780			
	SCM3	0.743			
	SCM4	0.789			
	SCM5	0.801			
Smart Contracts (SC)	SC1	0.827	0.864	0.866	0.648
	SC2	0.833			
	SC3	0.789			
	SC4	0.804			
	SC5	0.770			
Transparency and Traceability (TT)	TT1	0.838	0.832	0.857	0.660
	TT2	0.816			
	TT3	0.733			
	TT5	0.856			
Regulatory Compliance (RC)	RC1	0.851	0.837	0.923	0.596
	RC2	0.751			
	RC3	0.729			
	RC4	0.819			
	RC5	0.702			
Building Information Modeling (BIM)	BIM1	0.831	0.880	0.886	0.674
	BIM2	0.796			
	BIM3	0.820			
	BIM4	0.829			
	BIM5	0.829			
	OC1	0.822	0.909	0.917	0.610

Organizational Culture (OC)	OC2	0.818	0.862	0.863	0.591
	OC3	0.787			
	OC4	0.761			
	OC5	0.754			
	OC6	0.818			
	OC7	0.757			
	OC8	0.725			
Blockchain Technology Adoption (BTA)	BTA1	0.808			
	BTA2	0.762			
	BTA3	0.792			
	BTA4	0.757			
	BTA5	0.741			
	BTA6	0.752			

3.3. Structural Model

Structural model evaluation involves examining how unobserved constructs relate to latent constructs and its ability to predict and explain relationships among these constructs [136]. In this study, a VIF (<3) depicts no multicollinearity issue [141]. Figure 3 shows the structural model.

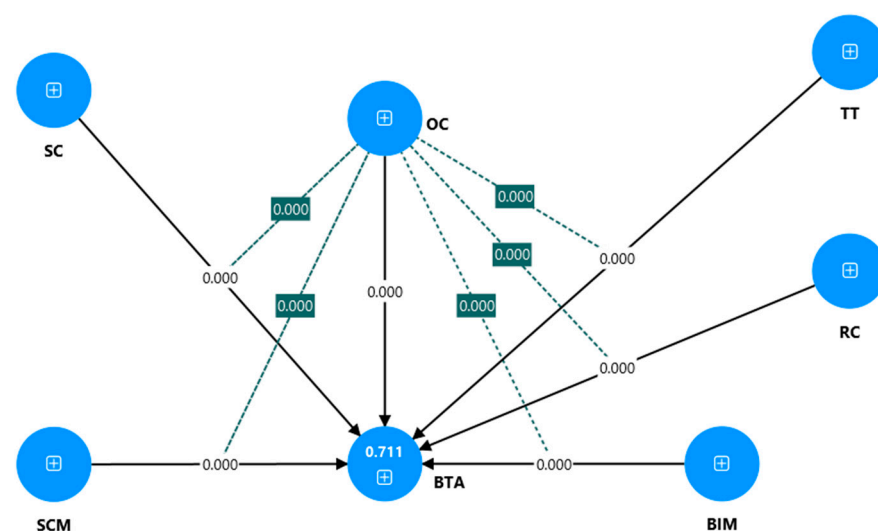


Figure 3. Structural model.

As illustrated in Table 10, the bootstrapping with 5000 subsamples was used to determine estimate robustness, with BCa confidence intervals at 5% significance obtained through a two-tailed test [140].

Table 10. Bootstrapping results.

	Relationship	Original Sample	Standard Deviation	T Statistics	p Values
H1a	SC → BTA	0.312	0.036	8.728	0.000 *
H1b	OC × SC → BTA	0.304	0.035	8.596	0.000 *
H2a	SCM → BTA	0.245	0.039	6.317	0.000 *
H2b	OC × SCM → BTA	0.250	0.041	6.159	0.000 *
H3a	BIM → BTA	0.238	0.037	6.471	0.000 *
H3b	OC × BIM → BTA	0.259	0.039	6.714	0.000 *
H4a	TT → BTA	0.212	0.052	4.081	0.000 *

H4b	OC × TT → BTA	0.250	0.064	3.904	0.000 *
H5a	RC → BTA	0.139	0.038	3.615	0.000 *
H5b	OC × RC → BTA	0.220	0.044	4.955	0.000 *
H6	OC → BTA	0.300	0.047	6.366	0.000 *

* All hypotheses are supported.

Coefficient of determination (R^2) reflects the model's ability to explain the variability in the outcome construct, with a range of 0 to 1 indicating its in-sample predictive strength [137,142,143]. Following Chin's [144] guidelines, R^2 is categorized as $0.19 > R^2$ (extremely poor), $0.33 > R^2 \geq 0.19$ (weak), $0.67 > R^2 \geq 0.33$ (medium) and $R^2 \geq 0.67$ (strong). The estimation reveals that 71.1% of the variation in blockchain technology adoption is attributed to the collective impact of smart contracts, supply chain management, BIM integration, transparency and traceability and regulatory compliance, which are moderated by organizational culture, signifying a highly robust model. Using PLS predict/CVPAT analysis, the study showed positive Q^2 values (0.366–0.435) for six blockchain technology adoption indicators and demonstrated that strong out-of-sample predictive power, with RMSE and MAE values of PLS-SEM lower than the benchmark. Furthermore, The PLS-SEM model's prediction error (loss = 0.736) was lower than the LM benchmark by 0.347 ($t = 8.246$, $p < 0.001$) and the IA benchmark by 0.483 ($t = 8.545$, $p < 0.001$), which demonstrates its superior predictive performance over the linear regression and indicator averages models [145–147]. PLS predict/CVPAT analysis data is shown in Table 11.

Table 11. PLS predict/CVPAT results.

	Q^2 Predict	PLS-SEM_RMSE	LM_RMSE	PLS-SEM_MAE	LM_MAE
BTA1	0.426	0.81	1.002	0.658	0.812
BTA2	0.399	0.846	1.03	0.683	0.833
BTA3	0.435	0.858	1.048	0.718	0.856
BTA4	0.366	0.886	1.046	0.725	0.835
BTA5	0.379	0.878	1.058	0.71	0.875
BTA6	0.373	0.868	1.061	0.704	0.872

Figure 4 depicts a two-way interaction influencing blockchain adoption through smart contracts and organizational culture. Organizations with a strong organizational culture experience a greater positive impact on blockchain adoption when increasing smart contract usage. When the perceived benefits of smart contracts are high, the predicted level of blockchain adoption is significantly greater in organizations with a strong culture than in those with a weak culture. This shows that an innovative, agile culture is critical for leveraging smart contract potential to drive adoption.

Figure 5 depicts a two-way interaction influencing blockchain adoption through supply chain management and organizational culture. A strong culture enhances the influence of supply chain demands on blockchain adoption, leading to greater implementation of blockchain solutions for supply chain improvements. The positive effect of supply chain management needs on blockchain adoption is much stronger for firms with a supportive culture. In a weak culture, even high supply chain pressures lead to only a marginal increase in adoption intentions.

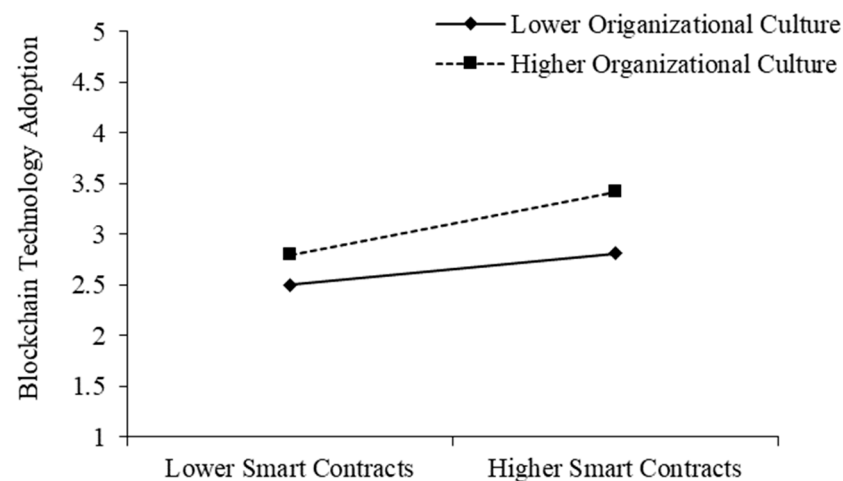


Figure 4. Two-way interaction influencing blockchain adoption through smart contracts and organizational culture.

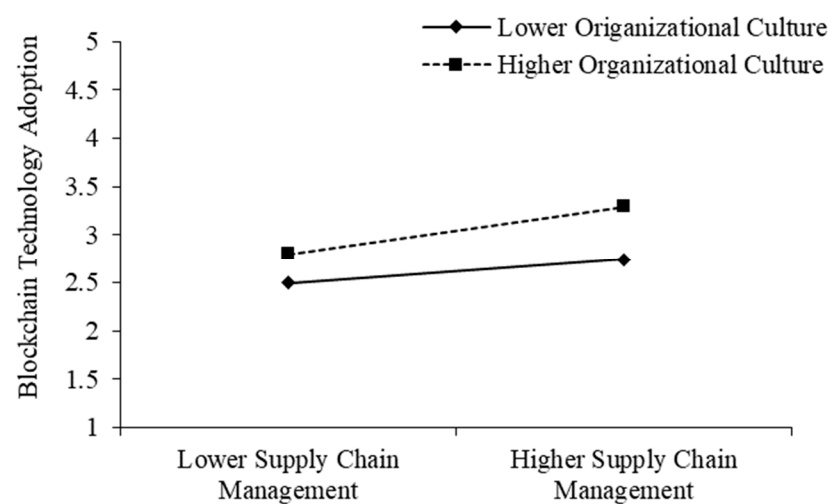


Figure 5. Two-way interaction influencing blockchain adoption through supply chain management and organizational culture.

Figure 6 depicts a two-way interaction influencing blockchain adoption through BIM integration and organizational culture. A strong organizational culture enhances the positive effect of BIM integration on blockchain adoption, which results in increased adoption efforts. The slope is markedly steeper under high organization culture, indicating that a culture promoting collaboration and technical expertise is essential for translating the data integrity benefits of BIM integration into concrete blockchain adoption strategies.

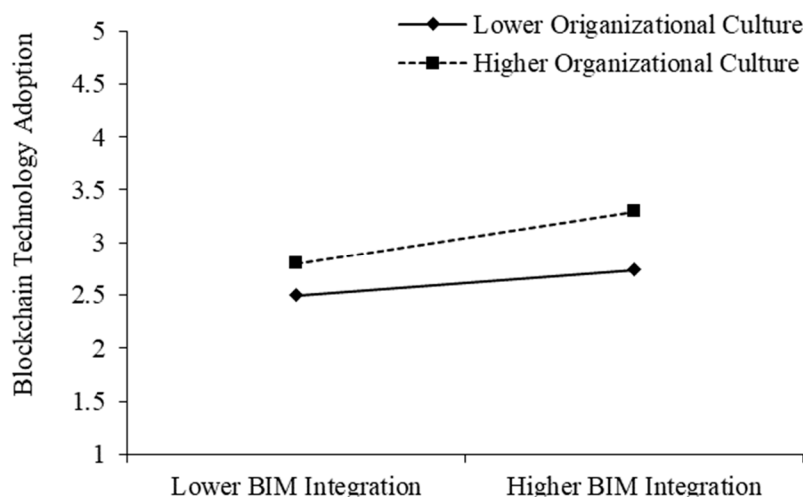


Figure 6. Two-way interaction influencing blockchain adoption through BIM integration and organizational culture.

Figure 7 depicts a two-way interaction influencing blockchain adoption through regulatory compliance and organizational culture. Strong organizational culture shows a greater impact of regulatory compliance on blockchain adoption, with higher compliance leading to increased blockchain technology adoption efforts. The graph indicates that firms with a proactive, digitally aligned culture are significantly more likely to adopt blockchain as a strategic compliance tool in response to regulatory pressures, whereas firms with a weaker culture tend to have a muted reaction to regulatory drivers.

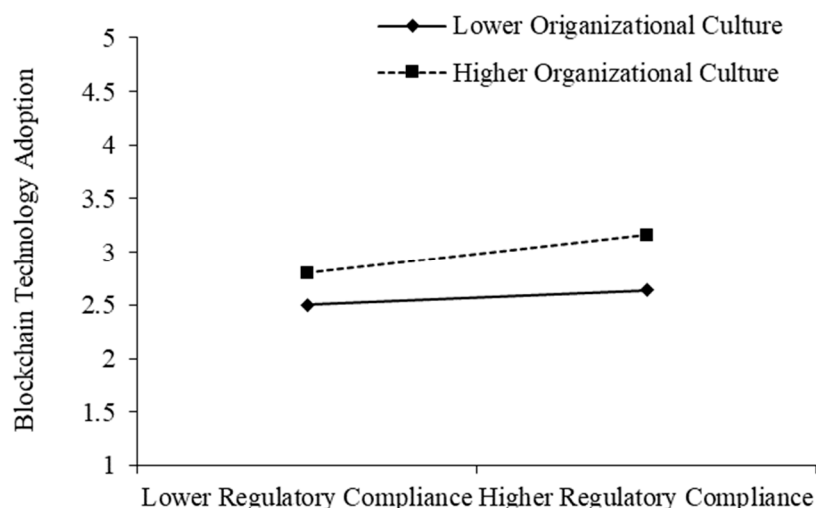


Figure 7. Two-way interaction influencing blockchain adoption through regulatory compliance and organizational culture.

Figure 8 depicts a two-way interaction influencing blockchain adoption through transparency and traceability and organizational culture. A stronger organizational culture amplifies the impact of transparency and traceability on blockchain implementation. The drive for transparency and traceability is most strongly translated into adoption in a high-trust, open culture, while a weak culture significantly diminishes this relationship.

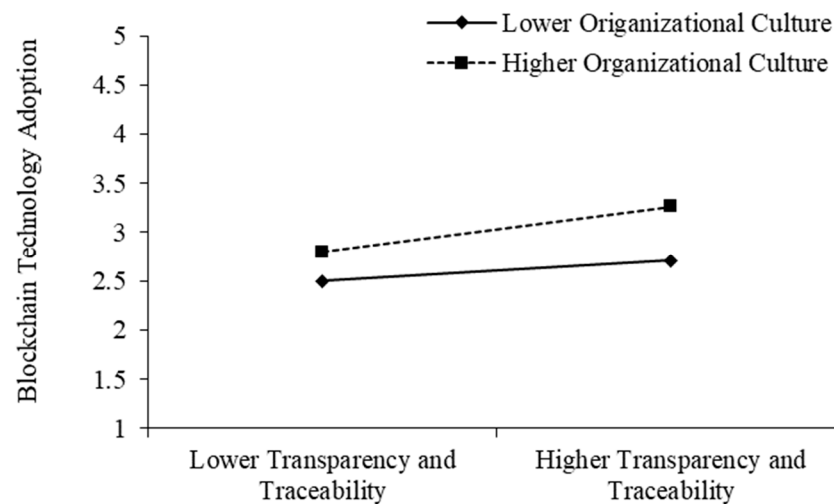


Figure 8. Two-way interaction influencing blockchain adoption through transparency and traceability and organizational culture.

The strength of predictor and dependent construct relationship is quantified by the effect size (f^2) [140]. Based on Cohen's effect size guidelines, with thresholds set at 0.02 (weak), 0.15 (moderate) and 0.35 (strong), an f^2 of 0.228 for blockchain technology adoption reflects a moderate effect [148]. The f^2 of blockchain technology adoption is calculated using Equation (1), where R^2 (OC included) = 0.417 and R^2 (OC excluded) = 0.284.

$$f^2 = \frac{R^2 \text{ (OC included)} - R^2 \text{ (OC excluded)}}{1 - R^2 \text{ (OC included)}} = \frac{0.417 - 0.284}{1 - 0.417} = 0.228 \quad (1)$$

This study demonstrates that organizational culture has a moderate and meaningful contribution to blockchain technology adoption, reinforcing its role as a catalyst rather than a peripheral factor.

4. Discussion

Smart contracts are considered to be one of the leading reasons to implement the blockchain by Saudi contractors. Their reasons are feasible benefits in terms of improved cash flow, reduced conflicts and minimization of administrative expenses. This reacts to industry issues that include delayed payment and high cost of litigation. Contractors view blockchain as an efficient means of controlling liquidity and contract-related risks, as opposed to speculation. Its ability to encode intricate clauses and reduce counterparty risk makes it attractive for large, high-stakes projects and contractual governance. Organizational culture moderates the relationship between smart contracts and blockchain adoption, with an innovative culture seeking to maximize the utilization of smart contracts through cross-departmental communication and leadership support. On the other hand, cultures that are inflexible and risk-averse may hinder adoption in cases where their efficiency advantages are evident, proving that technical potential alone cannot be fully realized unless there is an enabling organizational environment capable of managing them to their full potential. The results correspond to Shang et al. [149], Singh et al. [150], Vedapradha and Ravi, [151] Clohessy and Acton [152] and Weerapperuma et al. [153].

Supply chain management's positive influence underscores the importance of blockchain technology in large Saudi projects to overcome supply chain logistics challenges. It provides real-time visibility, checks the authenticity of materials, provides less paperwork, and automates inventory reconciliation, which leads to a reduction in costs and delays. Blockchain technology is also useful in enhancing responses to disruptions and ensuring that contractors are able to respond promptly to shortages and bottlenecks using

a trusted supply chain source. An important aspect of blockchain technology in supply chain management is its moderating effect, which involves the active participation of partners and a culture of technological experimentation. Internal isolated culture hinders coordination, whereas technical knowledge and infrastructure are needed to apply blockchain technology. The findings align with the study of Karakas et al. [154], Munir et al. [155], Okanlawon et al. [156] and Sunmola et al. [157].

The trust layer for digital construction collaboration is built using blockchain technology. BIM creates rich data, but there are still issues regarding responsibility, data ownership, and version history. Contractors regard it as a channel to protect data integrity, provide an unalterable audit trail, and connect design changes to automatic payments, which connect both the physical and digital aspects of the project. This contributes to building trust and accountability with various stakeholders. The combination of blockchain and BIM is complicated and relies on the organizational culture. It entails information-based cooperation and digital workflow integrity. An organizational culture that does not openly collaborate or lacks technical confidence will regard this integration as complicated, which will impede blockchain implementation. The results align with An et al. [158], Celik et al. [159], Dounas et al. [160] and Zhang et al., [57].

Contractors consider blockchain technology adoption in Saudi projects an important way to solve critical issues, such as accountability, efficiency, compliance and stakeholder confidence. In organizations with poor cross-departmental collaboration and low confidence in managing change, a strong need for transparency tends to result in minimal solutions such as upgraded legacy systems, hindering effective traceability and limiting the blockchain technology potential for transformation. A culture of technological experimentation, combined with agile decision-making and proactive partnerships, allows the firm to quickly develop blockchain pilot projects addressing material provenance tracking and stakeholder access. A strong organizational culture amplifies this process by effectively converting problems into solutions through structured support and resources. The results correspond to Basheer et al. [161], Brandín and Abrishami [162], Khan et al. [70] and Wu et al. [163].

The Saudi regulatory environment is complex, involving Saudization (local content requirements), multi-layer permitting, and stringent environmental and safety codes. Regulatory pressures for accuracy and automation serve as a motivator for contractors to adopt blockchain technology solutions. Contractors with weak culture handle regulations in a reactive manner, addressing compliance issues only after they arise, which can lead to delays, penalties or increased costs. In contrast, contractors with innovative culture have the intention to adopt blockchain technology to proactively automate compliance and turn it into a strategic advantage. The findings support Akinradewo et al.'s [164] and Kumi et al.'s [165,166] research.

5. Conclusions

This study uniquely shows that organizational culture is a key catalyst that strengthens the influence of environmental and technological variables on implementing blockchain technology. It offers the first validated roadmap for the Saudi construction sector that emphasizes the importance of cultural change alongside technological investment for successful digital transformation.

Using the TOE framework, this presents a comprehensive and validated model for understanding blockchain adoption among large contractors in Saudi Arabia. This research underscores that blockchain technology adoption is impacted by interconnected factors across all three TOE domains. Technologically, the perceived blockchain advantages, e.g., enabling smart contracts and integrating supply chain management and BIM are key drivers. Organizationally, a culture supportive of innovation, agility and

digital transformation functions as key amplifier, strengthening the effect of technological factors on adoption. Environmentally, regulatory pressures (e.g., Saudization) have a significant direct influence, demonstrating how institutional mandates shape strategic technology choices. The actual implementation of blockchain technology relies on a strategic choice that is rooted in the organization's culture, and it involves actively considering and integrating technological advantages and regulatory requirements rather than responding passively to internal or external pressures.

Although the empirical context is Saudi Arabia, the study is grounded in the TOE framework, which supports cautious generalization to other construction markets facing similar regulatory pressures, project complexity and digital transformation challenges, particularly within the GCC and emerging economies. Future comparative studies across different geographical and regulatory landscapes are encouraged to establish the boundary conditions and further extend the generalizability of these findings.

Building on this validated model, future research could include longitudinal studies to examine how TOE factors influence change over time, comparative studies across GCC countries or regulated industries to understand contextual differences, deeper analyses of organizational culture components (e.g., leadership and incentives) to identify key catalysts, and exploration of barriers such as complexity, security concerns, or distrust that may hinder blockchain technology adoption.

The focus on large Saudi contractors limits the scope of this research, which may not apply to smaller firms or different regions and by its cross-sectional approach. The model is comprehensive but may not include all relevant factors such as the role of external consultants, client demand or the maturity of blockchain solutions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/buildings16030672/s1>. (Questionnaire attached).

Author Contributions: Conceptualization, M.A.R. and D.A.A.; methodology, M.A.R. and D.A.A.; software, M.A.R.; validation, M.A.R. and D.A.A.; formal analysis, M.A.R. and D.A.A.; investigation, M.A.R. and D.A.A.; resources, M.A.R. and D.A.A.; data curation, M.A.R. and D.A.A.; writing—original draft preparation, M.A.R. and D.A.A.; writing—review and editing, M.A.R. and D.A.A.; visualization, M.A.R. and D.A.A.; supervision, D.A.A.; project administration, D.A.A.; funding acquisition, D.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research is financially supported by the Deanship of Scientific Research at King Khalid University, Saudi Arabia, through Research Grant RGP.2/484/45.

Institutional Review Board Statement: Ethical review was not required for this study, as it constituted a non-interventional, anonymous survey with minimal risk to participants and involved no collection of personal identifiers or sensitive data.

Informed Consent Statement: The informed consent requirement was waived because participation was anonymous and involved minimal risk.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors extend their appreciation to the Deanship of Scientific Research at the King Khalid University of Saudi Arabia for funding this work through the Large Groups Research Project under Grant no. RGP.2/484/45. We gratefully acknowledge the cooperation of employees from large contracting firms registered with the Saudi Contractors Authority who contributed by completing the questionnaire.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AVE	Average Variance Extracted
BCa	Bias-Corrected and Accelerated (confidence interval)
BIM	Building Information Modeling
BTA	Blockchain Technology Adoption
CR	Composite Reliability
f^2	Effect Size
GCC	Gulf Cooperation Council
IA	Indicator Averages (benchmark model)
IT	Information Technology
LM	Linear Model (benchmark model)
MAE	Mean Absolute Error
OC	Organizational Culture
PLS-SEM	Partial Least Squares Structural Equation Modeling
QA/QC	Quality Assurance/Quality Control
Q^2	Stone–Geisser Predictive Relevance Indicator
R^2	Coefficient of Determination
RC	Regulatory Compliance
RMSE	Root Mean Square Error
SC	Smart Contracts
SCM	Supply Chain Management
TOE	Technology–Organization–Environment
TT	Transparency and Traceability
VIF	Variance Inflation Factor

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