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Value-Chain Governance of Low-Carbon Supplementary Cementitious Materials (SCMs): Trust, Performance, and Blockchain Traceability in the Jordanian Construction Sector

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ABSTRACT

The need for a transition to a low-carbon construction industry is met with the need for a nonprofit intermediate system of trust plus institutional mechanisms plus transparency technology. In answering its gaps in knowledge, this study explored whether trust, system of governance, or the use of blockchain technology for transparency impacts performance in the value chain related to SCM-low carbon SCM in Jordan. The methodologies used in answering this issue are mixed methods. Data was obtained from 86 firms across the value chain in SCM. The data was obtained using

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questionnaires. The reliability and validity of the questionnaires were obtained using Cronbach's alpha coefficients. Regression analysis was used to establish the relationship between the identified constructs. Agent-based simulation analysis was used to evaluate system-level coordination. Visualization using Gephi was used to establish transparency. The results showed that trust had a strong positive influence on performance, but this was mediated only partially by governance structure. In addition, transparency moderated the relationship between trust and performance positively. Simulation and results analysis showed that transparency increased governance efficiency, which mitigated coordination problems in the SCM system. The results emphasize that behavioural trust and transparency enabled by blockchain technology are complementary mechanisms to leverage within SCM to make these systems more transparent, efficient, and sustainable. The study enhances the generation of socio-technical governance theories related to SCM systems.

Keywords: Low-Carbon Supplementary Cementitious Materials (SCMs); Blockchain Transparency; Trust and Governance; Sustainable Construction Value Chains; Agent-Based Simulation; Digital Traceability Systems; Circular Economy in Building Materials

1. Introduction

The construction industry has recently proved to be one of the key sectors that emit large amounts of carbon, estimated to be almost 39% of the entire carbon emission [1,2]. In such an environment, there has been an increase in the emphasis on low-carbon supplementary cementitious materials (SCMs), such as fly ash, Slag, Silica fume, and Natural Pozzolans, that are believed to be environmentally friendly alternatives to cement to construct buildings without increasing carbon emissions [3,4]. In such an environment, in order to successfully implement and manage such materials, there has to be innovative transformation in technology as well as within the area of the value chain. The complex and multi-tiered nature of construction supply chains is likely to pose inefficiency, trust deficits, and untracability [5]. The entities that participate in the SCMs process to test and certify them are impacted by asymmetric conditions with differing levels of veracity. These factors rank among the significant challenges to achieving sustainability [6,7]. Conventional contract-based modes of governance are found to be inadequate to address these issues since traditional modes promote regulate-and-control structures over developing cooperative trust networks and enabling visible transparency [8,9]. Due to these developments, there exists an increasing need to prefer a paradigm shift in favour of hybrid modes that comprehensively address behaviour, structure, and technology.

Turning to emerging technology applications, blockchain technology has been identified for its great promise

to improve traceability, transparency, and accountability in construction material handling [10,11]. The decentralized and immutable character of blockchain technology allows transaction data to be recorded, verified, and tracked by various participants in construction material life cycles to achieve "algorithmic trust" augmented with traditional human trust [5,12]. More recently, there are studies to suggest that blockchain technology has application in construction to improve purchase processes, waste management, and green labelling [13,14]. But few empirical observations are yet available concerning how transparency afforded by blockchain technology can shape trust and governance structure to improve value chain effectiveness in SCMs. In developing economies, with non-established institutional frameworks for governance yet to mature, there exists transformative potential for integrating digital mechanisms for transparency. Countries like Jordan are already implementing supportive governmental frameworks for environmentally sustainable construction methods and using minimal carbon contents [15-17]. But there are competing challenges yet to allow efficient implementation of SCM. In past studies related to Middle East-based construction sectors, there are identified barriers concerning incompatible data interoperability, insufficient digital preparedness or inadequate enforcement. Thus, to achieve sustainability in construction materials based on resilient construction material sectors leveraging behaviours based on trust, institutional frameworks for governance, and blockchain-based components for transparency, establishing an amalgamated framework for these components is vital.

The interrelationship between trust and construction project performance has been identified in previous studies^[18,19], highlighting that trust enhances teamworking and mitigates conflicts. Although the mediating role of construction project-level governance mechanisms in relation to trust interrelationship, moderated by the use of blockchain technology due to its transparency and traceability features, remains relatively unresearched. Notably, construction project-level value chain mechanisms are overlooked in previous construction sustainability literature^[20], creating an evident knowledge gap concerning the empirical relationship between inter-organizational networks and digital systems. This study uses three dimensions of governance trust (behavioural mechanism), governance structure (institutional mechanism), and blockchain transparency (technological mechanism), which are involved simultaneously in determining SCMs' value chains' outcomes. The method used in this study for analysis includes regression analysis, mediation model analysis, moderation model analysis, simulation model analysis using an agent-based simulation technique, and finally analysis using Blockchain Network Visualization.

2. Literature Review

Trust has been considered for a long period a behavioural basis for construction and supply chain cooperation. Trust enhances knowledge sharing in complex sectors like construction materials. It increases the efficiency of coordination procedures. Xu^[21] described trust as "confidence in partners' integrity, reliability, and competence." In construction contexts, according to Jiang et al.^[22] and Zhang et al.^[23], trust between contractors and suppliers was shown to result in improved collaboration, fewer disputes between them, and increased project success. Trust in material value chains is confronted with its own set of challenges owing to non-uniform structures, ill-defined documentation, or a lack of transparency^[24]. In SCM arrangements, there exists a lack of understanding pertaining to suppliers' material quality, origin, or compliance with environment-related parameters. As a result, there exists a lack of trust. Therefore, authors like Kambilo et al.^[25], or Qian and Papadonikolaki^[26] addressed the same concern pertaining to trusting arrangements being made within

formalized systems that are addressed in this study using blockchain technology to facilitate transparency.

"Governance describes institutionalized procedures to shape interactions between firms in a value chain. In the construction industry, risk, responsibility, and information flows are defined according to a construction system's governance structures. In conventional construction systems, risk, responsibility, and information are managed predominantly according to contract and hierarchy-based control^[27-29]. These instruments are less frequently effective within construction systems pursuing sustainability". There has been a recent move in literature to focus on 'hybrid' or 'relation-based' modes of governance that emphasize a combination of control and trust^[30,31]. Specific to 'sustainable construction' issues, Cantù et al.^[32] contend that 'governance' has to address not only 'resource coordination' but also 'actor goal-attunement pertaining to environmental dimensions.' Moreover, there was a focus recently on integrating 'digital modes' of governance to enable 'smart contracts' or 'traceability' to create sustainable green construction materials^[33].

Although these improvements have been made, project-level governance analysis remains more common than material-level governance analysis. As a consequence, there exists a theoretical and empirical gap concerning how a material supply-related governance structure functions. The issue raised in this study aims to fill that gap through analysing governance not only as a static control system but rather focusing upon its function as an intermediary between trust and performance in a sustainability-oriented material system. Blockchain technology has recently proven to be a crucial enabling technology for transparency and tracing within supply chain management. Described by its characteristics involving distributed ledger technology or immutable data, blockchain technology confirms diverse stakeholder access to real-time information related to product tracing, transaction certainty, and compliance^[34]. In the construction industry, blockchain technology adoption has been related to improvements in authentication processes related to building materials, waste management, and contract facilitation^[13,14]. Rejeb et al.^[35] proved that the adoption of blockchain technology increases the implementation of a circular economy in construction materials tracing.

There has been a focus on either the technological feasibility or conceptual structures rather than empirical analysis related to its governance effects. There are few studies that have actually quantitatively analysed how transparency in the blockchain system interplays with behaviour-based trust or intermediate structures in terms of its effects on its performance. This continues to remain a significant research gap that will be filled in this study in its specific context related to low-carbon SCM systems. SCM value chain performances are considered to involve three dimensions. These dimensions are the traditional cost, time, and quality parameters^[36]. The sustainability paradigm extends these margins to carbon reduction, use of resources, and material cycles^[37-39]. In terms of SCM applications, there are three elements that are crucial to its success: material innovation, collaboration with suppliers, and traceability^[36]. In fact, Juenger et al.^[40], as well as other studies like Yang et al.^[41], pointed out that for a successful low-carbon SCM system, its functionality cannot merely hinge upon material characteristics. Ineffective value chain collaboration specifically leads to less than desirable quality control processes, late delivery, and stakeholder participation.

There has been little investigation into how these mechanisms and trust relationships are interrelated to collectively shape low-carbon material system performance. Indeed, to date, there has been a lack of interdisciplinary synthesis between studies focusing separately upon either the ‘social’ (trust-related), or ‘technological’ (blockchain technology-related), dimensions. In other words, there has been little synthesis between these two to date. The literature survey shows that there has been great improvement in understanding the social, structural, and technological aspects related to construction governance. However, there are a few crucial gaps in these areas that need to be filled. Traditional studies tend to focus separately on trust issues, governance topics, or blockchain concepts without considering them simultaneously in one framework resembling real-world material system interactions. Secondly, although there are numerous conceptual debates involving blockchain traceability in construction, there are limited empirical pieces of evidence that quantify its interactions with trust and its impacts on construction performance. The majority of existing studies related to value-chain

governance are project or enterprise-oriented. In fact, few studies have explored value-chain-level material-level governance regarding low-carbon SCMs. Although there are few empirical studies in the Middle East or specifically in Jordan, there is an increasing interest in green building and digitalization.

In response to these gaps, a value chain approach to governance that incorporates trust (behavioural mechanism), governance structure (institutional mechanism), and transparency provided by blockchain technology (technological mechanism), to account for variations in performance (sustainability and efficiency), in the low-carbon SCM industry in Jordan. In fact, not only does our approach thus move the state-of-the-art concerning hybrid socio-technical governance system theories, but it also offers implementation methods to improve traceability, accountability, and sustainability in global building material supply chains, thereby directly meeting the objectives set forth by the *Journal of Building Material Sciences* to promote innovation, sustainability, and a circular economy approach to construction materials.

The conceptual framework (**Figure 1**) used in this study was designed to represent the inter-relationships between the central constructs that shape the issue of governance and value chain related to low-carbon supplementary cementitious materials (SCMs) in the context of value chain analysis in Jordan. The conceptual framework was based on institutional trust paradigm thinking and transaction cost economics. Later adjustments included the use of thinking based on blockchain technology transparency. The proposed framework stipulated that trust serves as a prime enabling mechanism driving coordination efficiency between producers, contractors, and regulators. As inter-organizational trust enhances, there are increased chances of sharing crucial information related to sourcing, testing, and delivery of SCMs. But trust does not cause performance directly. There exist mediating conditions based on which material transactions are executed. In conventional structures, trust-based governance occurs based on mutual expectancy or unwritten norms. In comparison, blockchain-based structures establish trust in terms of smart contracts based on verifiable transactions.

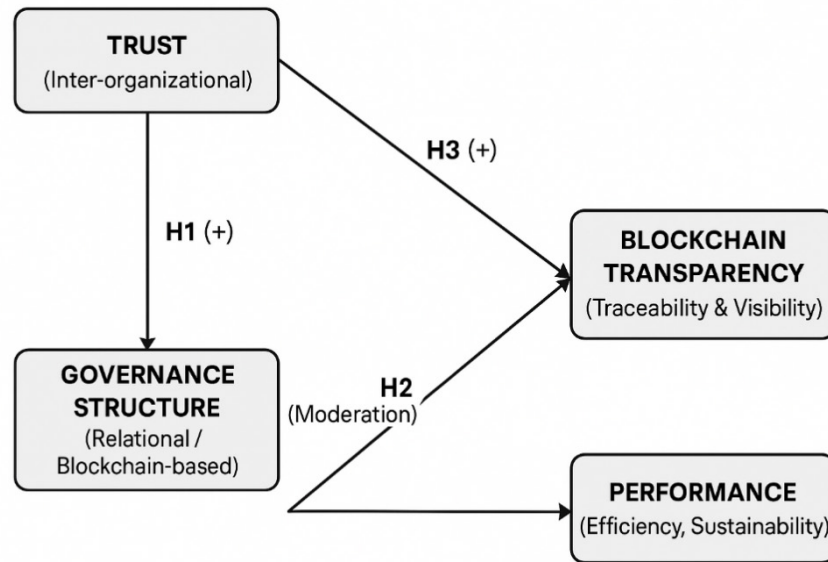


Figure 1. Conceptual Model of The Study.

Source: the authors.

Accordingly, the assumption made by the model was that the governance structure serves as a mediating variable that translates trust into performance outcomes. In addition to that, the framework considered blockchain transparency as a moderating variable. It made assumptions based on a hypothesis stating that digital traceability enhances the relationship between trust and performance because credibility, accountability, and real-time validation can be guaranteed in the value chain. In other words, technology enhances traditional trust to become digital trust because there are fewer asymmetry issues concerning information related to SCMs. The framework was to include performance as the dependent variable, which was to be measured through indicators like efficiency, timeliness of delivery, and sustainability indicators like carbon emissions. More effective governance was apparently expected to improve these indicators related to performance and aligned well with the journal's theme related to sustainable building materials.

The model proposed a hypothesis that trust positively impacts performance (H1), which was mediated by governance structure (H2). The transparency function of blockchain technology increases the strength of both trust and performance ties due to its mediating effects (H3), whereas increased levels of transparency improve the efficiency of governance directly (H4). These elements embrace a hy-

brid model describing both techno-social elements related to trust for improved construction material sustainability.

3. Methodology

In the current research, a mixed methods approach consisting of regression analysis, agent-based simulation for governance analysis, and using blockchain technology for traceability analysis was used. The choice for using the mixed methods approach was based on having a deeper understanding of trust in value chain performances in low-carbon supplementary cementitious materials (SCMs) in Jordan. The regression analysis focused on testing statistical associations between identified constructs. Meanwhile, using the agent-based approach allowed an understanding of how agents in charge of decision-making related to value chain structures made decisions based on well-defined structures using market-based structures, relationship-based structures, or structures based on blockchain technology. The use of blockchain analysis helped visualize SCM traces.

Data collection activities took place from January to June 2024. The data was directed at key stakeholders involved in the construction materials supply chain in Jordan. The data collection process was anchored with a mix of both structured research tools, such as online sur-

veys, to measure trust levels among stakeholders, joint productivity, and transparency. Other research tools include in-depth interviews to elicit data on governance structures and adoption processes. More specifically, data was attained from block chain transaction data in pilot nodes situated in three low carbon concrete projects. These three projects are set in Amman, Zarqa, and Irbid. The use of these three methods makes data collection reliable based on a combination of data obtained from a variety of sources. The population that was considered for study was made up of all those entities in Jordan’s construction industry involved in the processing or use of supplementary cementitious materials. These entities include cement manufacturers, ready mix concrete producers, construction contractors, testing agencies, and

standardization/control bodies. **Table 1** below shows the population composition.

In light of this fixed population, there was a need for a scientifically derived sample size to achieve representativeness, considering all value chain layers. The analysis focused on examining the role of governance mechanisms and trust processes in determining the performance of value chains in low-carbon SCM. The core variable was trust, which was used as an independent variable. Meanwhile, the dependent variable was performance. Then there was a mediating construct using the variable ‘governance model.’ Moreover, another significant variable was ‘blockchain transparency’ which acted as a moderator. Firm characteristics formed another set categorized under control variables. These are indicated in **Table 2**.

Table 1. Details of the Population of the Study.

Category	Estimated Population (N)	Examples of Entities
Cement producers	8	Lafarge Jordan, Northern Cement
Concrete manufacturers	52	Ready-Mix Co., National Concrete
Contractors and developers	37	Arabtech Jardaneh, MID Contracting
Government & regulatory bodies	6	Ministry of Public Works, JSMO
Material testing & R&D labs	9	Royal Scientific Society, UJ Materials Lab
Total Population (N)	112	

Source: the authors.

Table 2. Variable of the Study.

Variable Type	Variable	Operational Definition	Measurement Scale
Independent	Trust	Degree of perceived reliability and integrity among value chain partners	5-point Likert
Dependent	Performance	Efficiency, timeliness, and cost-effectiveness of SCM transactions	Continuous (Index)
Mediator	Governance Model	Nature of coordination mechanism (market, relational, hierarchical, blockchain-enabled)	Categorical
Moderator	Digital Transparency	Level of blockchain traceability and data sharing	5-point Likert
Control	Firm Size, Experience, and Sector	Structural characteristics of the organization	Nominal/Ordinal

Source: the authors.

These constructs are employed to assess the dimensions that are focussed on technology as well as those aligned with behaviour in correlation to the governance within value chains that entwine a concern with sustainability in SCM. To ensure validity, proven scales are utilized. The parameter trust was measured by utilizing the validated scale that comprises five items taken from Ngor-

suraches et al. ^[42], taking into account factors such as dependability, trustworthiness, competency, fairness Ness, and trust. The parameter Performance was defined by utilizing the aggregate index that comprises factors such as variability in quality of goods produced, timeliness of goods’ delivery, energy conservation measures adopted, and cuts in greenhouse gases. The organizational structure

has been defined by utilizing coding that comprises results from simulation to identify whether projects are defined as traditional models, hybrid models, and models that include blockchain technology. Blockchain transparency was defined by utilizing self-reported data and more technical criteria, such as reinforced transactions and traces-within-level. The scales had been pretested among ten experts to modify the terms to suit the values within the construction sector in Jordan.

At the time of data collection, blockchain applications in the Jordanian low-carbon SCM sector were confined to pilot nodes embedded in three low-carbon concrete projects (in Amman, Zarqa, and Irbid), rather than fully deployed, firm-wide production systems. Consequently, none of the 86 firms in our sample operated an enterprise-level blockchain ledger across all transactions. Instead, a subset of firms participated in project-based pilots that generated verifiable on-chain transaction records, while all firms relied on conventional digital traceability tools (e.g., ERP records, digital certificates, QR-coded batches).

To mitigate common-method variance and social desirability bias, we implemented several *ex ante* procedural remedies. Respondents were assured of anonymity and confidentiality, informed that there were no right or wrong answers, and that the survey was for academic purposes only. Items were distributed across different sections to create psychological separation between predictors and outcomes, and value-laden wording was avoided in sensitive constructs such as trust, governance, and transparency. *Ex post*, we conducted Harman's single-factor test, which showed that no single factor accounted for the majority of variance (the first factor explained < 50% of the total variance). In addition, full-collinearity VIFs for all latent variables were below 3.3, indicating that a single-method factor is unlikely to be inflating the observed correlations. These results suggest that common-method bias is unlikely to pose a serious threat to the validity of our findings.

Data analysis utilized statistical models and computational approaches. Regression analysis was carried out to confirm that trust had a certain impact on performance. Furthermore, hierarchical regression analysis was carried out to confirm that transparency within the blockchain moderated these influences to improve or dampen the impact of trust and performance. Governance structure was

measured as a latent construct using multiple Likert-type items capturing the extent of market-based contracting, relational coordination, hierarchical control, and blockchain-enabled transparency along the value chain. Respondents rated their agreement with each statement on a five-point scale (1 = strongly disagree, 5 = strongly agree). These indicators loaded on a single factor in the PLS-SEM measurement model, and the resulting factor scores (or mean-composite index in the robustness checks) were treated as an approximately continuous variable, consistent with common practice for multi-item Likert scales in linear regression and mediation analysis.

To attempt to reflect practical inter-organizational dynamics between the various agents within this practical setup, an agent-based model was designed utilizing the Net Logo simulation package. During model development, 100 agents represented producers, suppliers, contractors, regulators, and certifiers. At the same time, data analysis was carried out utilizing Gephi version 0.10 data analysis package for geophysics modelling. The results confirmed connections between entities, entity transparency between entities, and centrality analysis on the basis of actors. These approaches facilitated an inter-disciplinary perspective to shed insight on digital-based traceability influences on trust, performance, and sustainability within SCM's value flow processes.

4. Results

4.1. Overview of Data and Response Rate

A total of 110 questionnaires was distributed to the five main actor types that are delineated in the supplementary cementitious materials (SCM) supply chain in Jordan. These include producers of cement, concrete manufacturers, contractors, testing laboratories, and concerned regulatory authorities. Of these questionnaires, 88 were received, this resulted in a highly impressive 80% response rate that is satisfactory in empirical research endeavours carried out within the construction sector. Data screening was carried out to ensure data accuracy, completeness, and fitness for statistical analysis. The missing values stood below the acceptable cut-off level of 5%, and mean substitution techniques handled the values. The normality test, achieved through the use of skewness and

kurtosis analysis, showed that all the key variables were within the ± 2 range, indicating that the data was normally distributed. This made it possible to use the parametric regression analysis process as intended in the analysis design.

The use of Mahalanobis distance values to identify outliers led to the exclusion of two extreme values to increase the reliability of estimates. The results from tests for multicollinearity showed that variance inflation factors are below 3. The final data set (N = 86) thus formed a robust empirical basis to test hypotheses. The respondents covered a balanced proportion among the tiers in the value chain that is, 10.5% producers of cement, 38.4% manu-

facturers of concrete, 27.9% constructors, 12.8% testing laboratories, and 10.4% regulatory bodies. The average organizational experience among the respondents was 14.6 years that is, there was enough familiarity with SCM process operations, standards of performance, and new technology applications such as blockchain traceability. **Table 3** shows the descriptive statistics and Pearson correlation analysis results among the key study variables: Trust, Governance Structure, Blockchain Transparency, and Performance. From the descriptive statistics above, the means are moderately to highly positive, indicating that trust and transparency are viewed rather favourably in the Jordanian SCM environment.

Table 3. Descriptive Statistics and Correlations (N = 86).

Variable	Mean	SD	1	2	3	4
1. Trust	3.89	0.61	1.00			
2. Governance Structure	3.74	0.58	0.62**	1.00		
3. Blockchain Transparency	3.82	0.66	0.48**	0.55**	1.00	
4. Performance	4.01	0.53	0.69**	0.63**	0.57**	1.00

Note: SD = Standard Deviation; ** $p < 0.01$ (two-tailed).

The correlation analysis showed that there are positive and significant relations between trust and performance ($r = 0.69, p < 0.01$), and between governance structure and performance ($r = 0.63, p < 0.01$). Blockchain transparency was also found to have positive and significant relations with trust ($r = 0.48, p < 0.01$), and with performance ($r = 0.57, p < 0.01$). These results offer preliminary evidence to confirm the hypotheses that trust and digital transparency are essential components to optimize the efficiency and sustainability performance in the low-carbon SCM value chain in the Jordanian context. The fairly high average values with respect to performance and transparency (M = 4.01 and M = 3.82) represented the positive adoption trend with technology-based governance systems. The adoption trend was further supported by qualitative results received from the industry stakeholders that represented the increase in traceability and accountability, with the implementation of blockchain technology. As such, besides establishing data fitness for analysis with more sophisticated testing statistics, the descriptive analysis was further informative in understanding the culture development of trust-based and traceable governance processes in the ecosystem within Jordan’s sustainable con-

struction materials.

4.2. Reliability and Validity Analysis

The above step towards hypothesis testing was preceded by testing the reliability and validity of the measurement model to guarantee that each construct was correctly portraying the theoretical constructs defined by trust, governance, blockchain transparency, and performance. The internal consistency reliability was tested by Cronbach’s alpha and Composite Reliability (CR), while Convergent validity was tested with Average Variance Extracted (AVE) and standardized factor loadings. Each statistical test was followed by Kothari’s ^[43] prescription that data accuracy must be proved prior to testing analysis. The data shown in **Table 4** illustrates that Cronbach’s alpha values are above the recommended 0.70 acceptable level, therefore, the constructs had reliable internal consistency. The Cronbach’s alpha values ranged from 0.82 to 0.91, which confirms that each variable was comprised of items measuring the construct. The composite reliabilities had values that ranged from 0.84 to 0.93; hence, the values exceeded the suggested standard threshold of 0.70.

Table 4. Reliability and Validity of Constructs (N = 86).

Construct	Cronbach's α	Composite Reliability (CR)	Average Variance Extracted (AVE)	Range of Factor Loadings
Trust	0.89	0.91	0.68	0.74–0.88
Governance Structure	0.84	0.87	0.58	0.70–0.81
Blockchain Transparency	0.88	0.90	0.65	0.73–0.86
Performance	0.91	0.93	0.76	0.79–0.91

Source: the authors.

Convergent validity was evidenced by large factor loadings (all above 0.70) and AVE values ranging from 0.58 to 0.76, all of which exceeded criteria of 0.50. These findings supported that each construct shared sufficient variance with its indicators to ensure that the constructs had clear conceptual and empirical foundations.

The constructs proved to possess internal reliability as well as discriminant validity, that is, the constructs differed from each other empirically. The square root values of each construct's AVE exceeded the correlation values among constructs that is, no variable was similar to other variables conceptually. These results confirmed that trust, governance, transparency, and performance are related but distinct constructs within the SCM governance environment. The findings also proved the robustness of the survey instrument designed and employed in this research. For instance, trust factors such as reliability, mutual respect, and integrity had the strongest loadings, indicating that these factors are critical to the relational aspect that affects SCM governance. Performance factors such as delivery efficiency and the reduction of carbon footprint also had good internal validity, indicating alignment with the sustainability needs of the construction materials sector in Jordan.

The relatively high values of reliability and validity coefficients strengthened the confidence that credible results would be produced after carrying out further analysis

such as regression analysis. These results further strengthened the confidence that quantitative variables used in this study had aptly captured the essence related to the management aspect represented by the value chain of low-carbon supplementary cementitious materials.

4.3. Regression Analysis: Trust and Performance Relationship (H1)

In testing the first hypothesis, the analysis employed a linear regression analysis. The aim was to establish if trust within the Jordanian SCM sector was predictive of performance with respect to efficiency, timeliness, and sustainability measures. Before moving to the analysis, assumptions about regression models were tested. The normal probability plot of the standardized residuals confirmed that it was free from any violation of linearity. The values of VIF (1.38) and Tolerance (0.72) suggested that there was no problem of multicollinearity. The Breusch-Pagan test ($p = 0.27$) was performed to check homoscedasticity to confirm that there was no violation in the uniform distribution of residuals. Results are shown in Table 5 below, with trust (independent variable) regressively analysed to determine its impact on performance (dependent variable). The analysis showed that 47% of the variations in the dependent variable ($R^2 = 0.47$) are explained by the independent variable trust.

Table 5. Regression Results for Trust and Performance (H1).

Model	Unstandardized Coefficient (B)	Standard Error	Standardized Beta (β)	t-Value	Sig. (p)	R ²	F-Value
Constant	1.57	0.24		6.54	0.000		
Trust	0.63	0.07	0.69	8.91	0.000**	0.47	79.4**

Note: Dependent Variable = Performance; ** $p < 0.01$; N = 86.

The regression coefficient ($\beta = 0.69, p < 0.001$) reflected the strong and significant positive correlation that exists between trust and performance. The result verified

that there was an enhancement in the level of performance upon increased inter-organizational trust in the low-carbon SCM value chain. Organizations that placed more trust in

the reliability, integrity, and competence of supply partners performed better in terms of delivery efficiency, transaction delay, and adherence to the standard of low-carbon materials. $R^2 = 0.47$ indicated that trust explained about 47% of the variability in performance. This highlights the critical role that trust has to play in establishing the underlying governance structure within sustainable construction material management. The strength of this variable's effect has also supported findings in earlier research that trust has to play a decisive role in establishing coordination efficiency and innovation diffusion in supply chain networks. From an application perspective, these results imply that trust development among stakeholders by means of communication and quality assurance can greatly improve operational and sustainability results. This is particularly true in the context of the Jordanian construction industry, which faces challenges in terms of the adoption of low-carbon SCM due to collaboration and accountability considerations.

4.4. Mediation Analysis: Role of Governance Structure (H2)

The second hypothesis (H2) suggested that gover-

nance structure mediated the process by which trust impacted the performance within the value chain relative to low carbon supplementary cementitious materials (SCMs). The hierarchical regression method was utilized to confirm the mediating role to ensure that the process met the standard procedure, further verified by the use of bootstrapping with 5000 resamples to ensure that the indirect effect was robust. In the first step, trust was regressed on performance (Model 1) to establish the significant total effect. In the second step, trust was regressed on the governance structure (Model 2) to verify that the predictor had a significant effect on the mediator. In the third step, trust and the governance structure were introduced concurrently to the regression equation that predicts performance (Model 3). Mediation was concluded if (a) trust was significant in predicting the governance structure, (b) the governance structure was significant in predicting performance, and (c) there was an attenuation in the coefficient representing trust after the inclusion of the governance structure in the model. The regression results are presented in **Table 6** below.

Table 6. Mediation Analysis: Governance Structure as Mediator (H2).

Model	Dependent Variable	Independent Variables	Standardized β	t-value	Sig. (p)	R ²
Model 1	Performance	Trust	0.69	8.91	0.000**	0.47
Model 2	Governance Structure	Trust	0.62	7.42	0.000**	0.39
Model 3	Performance	Trust	0.41	4.89	0.000**	0.59
		Governance Structure	0.45	5.28	0.000**	

Note: ** $p < 0.01$, N = 86. All coefficients standardized.

The findings showed that trust was a significant predictor of governance structure ($\beta = 0.62, p < 0.001$), meaning that as inter-organizational trust increased, there were higher chances of more collaborative and open governance structures. When governance structure was placed as the mediator in Model 3, the direct impact of trust on performance declined from $\beta = 0.69$ to $\beta = 0.41$ but still was significant ($p < 0.001$). The mediator (governance structure) had a significant positive impact on performance ($\beta = 0.45, p < 0.001$), and the explanatory power of the model increased from $R^2 = 0.47$ to $R^2 = 0.59$. To further confirm the mediated effect, a bootstrapping analysis with the PROCESS macro (Model 4) was carried out. The indirect effect of trust on performance mediated by the governance struc-

ture was 0.28, with a 95% confidence interval [0.15, 0.46], which did not contain zero, thus confirming the partial mediated effect. This shows that trust has a direct positive effect on performance but also has an indirect effect through the quality and form of governance structures that shape relationships among firms.

To assess the robustness of the mediation analysis, governance structure was additionally specified as a set of dummy variables representing the four ideal-type categories (market, relational, hierarchical, blockchain-enabled), with market governance as the reference group. Re-estimating the mediation model with these dummy variables yielded a positive and significant indirect effect of trust on performance via governance, with the signs and signif-

icance levels of the main coefficients remaining substantively unchanged. We also estimated a multinomial logit model with governance type as the outcome and trust as a predictor; higher trust was associated with a greater likelihood of more coordinated (relational/blockchain-enabled) governance forms. These alternative specifications support the robustness of our main results.

The partial mediation effect implies that trust and governance structure are more like complements rather than substitutes in functioning as governance mechanisms. Trust to a large extent promotes relational governance that is characterized by adaptive flexibility and coordination. Blockchain-integrated governance mechanisms, on the other hand, introduce formality in terms of validation and smart contracts as well as possibility due to automated traceability that ensures better results. They form a blend wherein social capital and digital accountability are combined to form the essential components in the fulfilment of sustainability criteria within the SCM value chain. In terms of management implications, these results highlight that trust development is by no means sufficient to ensure that complex material supply processes improve their performance. Companies with trust-embedded governance models that include blockchain validation systems are more likely to display greater accuracy, lower conflict rates, and

better achievement levels with regard to low-carbon performance criteria.

4.5. Moderation Analysis: Blockchain Transparency (H3)

The third hypothesis (H3) argued that blockchain-based transparency has a positive moderating effect on the trust-performance relationship among the actors within the low-carbon SCM value chain. The rationale behind this hypothesis was that blockchain technology, with its immutability features such as automated verification and tracing capabilities, was believed to reinforce the trust-performance nexus. In testing the moderation effect, a hierarchical multiple regression analysis was conducted. The continuous variables (trust, blockchain transparency, and performance) were centered to reduce multicollinearity among them, and an interaction term (Trust × Blockchain Transparency) was generated. The analysis was conducted in three stages:

- (1) entry of control variables (firm size, sector type),
- (2) entry of the main effects (trust and blockchain transparency),
- (3) entry of the interaction term. The results of the moderation test are shown in **Table 7**.

Table 7. Moderation Analysis of Blockchain Transparency (H3).

Model	Independent Variables	Standardized β	t-Value	Sig. (p)	R ²	ΔR^2
Model 1	Control Variables	0.18	2.01	0.048*	0.06	
Model 2	Trust	0.42	4.96	0.000**		
	Blockchain Transparency	0.39	4.58	0.000**	0.54	0.48**
Model 3	Trust × Transparency	0.27	3.84	0.000**	0.61	0.07**

Note: Dependent Variable = Performance N = 86 * $p < 0.05$, ** $p < 0.01$.

To address multicollinearity, trust and blockchain transparency were mean-centered prior to computing the interaction term, and several diagnostics were examined. The correlations between the interaction term and the centered predictors remained below conservative thresholds, tolerance values were above 0.20, and the largest condition index was below 30, while all VIFs were below 3, indicating that multicollinearity is unlikely to bias the estimated moderation effect. The inclusion of the interaction term increased the explained variance in performance from $R^2 = 0.54$ to $R^2 = 0.61$ ($\Delta R^2 = 0.07$, $p < 0.01$). Using Cohen’s

(1988) formula, the incremental effect size for the interaction is $f^2 = (0.61 - 0.54)/(1 - 0.61) \approx 0.18$, which corresponds to a moderate effect in this context. The standardized coefficient for the interaction term is $\beta = 0.27$ ($t = 3.84$, $p < 0.01$), confirming that higher blockchain transparency appreciably strengthens the positive impact of trust on performance.

The results (**Table 7**) showed that the presence of the interaction variable (Trust/Blockchain Transparency) added statistically significant explanatory power to the model by raising R^2 from 0.54 to 0.61 (delta $R^2 = 0.07$, $p < 0.01$).

The result was supported by the positive sign ($\beta = 0.27$, $t = 3.84$, $p < 0.001$) and statistical significance of the interaction variable. To understand the results of the interactive effect, a simple slope analysis was carried out. The results suggested that with higher blockchain transparency, trust was strongly linked to performance ($\beta_{\text{high}} = 0.71$, $p < 0.001$), while with lower transparency, the linkage was substantially diminished ($\beta_{\text{low}} = 0.38$, $p < 0.05$). This interactive effect is presented in **Figure 2** below, it shows that blockchain transparency has an amplification effect that encourages trust with added traceability and accountability within the SCM network.

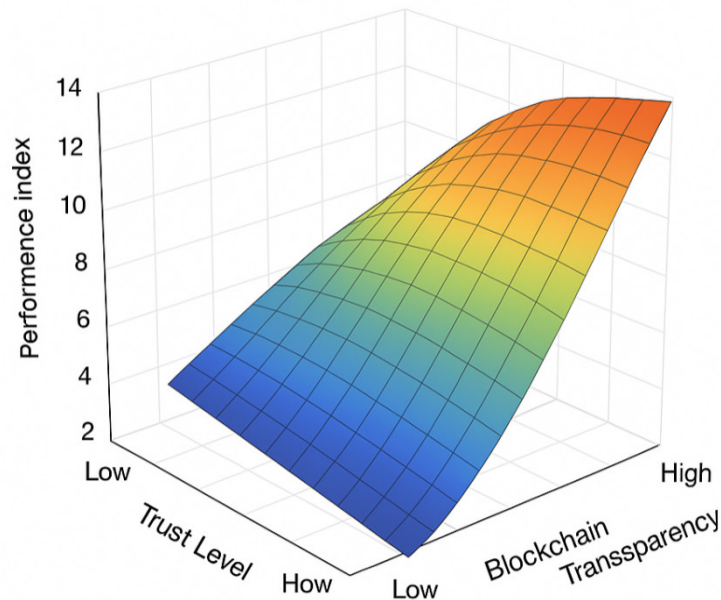


Figure 2. 3D Surface Plot of the Moderating Effect of Blockchain Transparency on the Trust–Performance Relationship.

Source: the authors.

A three-dimensional surface plot (**Figure 2**) was generated to visually represent the combined effects of trust and blockchain transparency on performance. The 3D visualization provides a more comprehensive depiction of the interaction surface, showing how performance progressively increases when both trust and transparency rise simultaneously. The curvature of the surface confirms that blockchain transparency strengthens the positive impact of trust on performance, supporting the moderating effect proposed in H3. The graphical analysis showed that the slope increased in situations with greater levels of blockchain transparency, indicating that digital traceability heightens the efficiency benefits that occur due to trust. Additionally, there was a less significant relationship between trust and trustworthiness-performance in settings with lower levels of transparency, indicating that trust has less potential without verifiable digital traceability.

In terms of governance, these results illustrate that blockchain technology is complementary to relational trust since it offers a structural trust assurance mechanism that

limits opportunistic activities and offers data integrity capabilities to empower real-time provenance validation in SCM. The adoption of blockchain technology thus offers trust institutionalisation whereby trust becomes an objective digital trust that was previously realized as an intangible relational construct. The role of the moderating effect had significant management implications. The companies that adopted blockchain traceability platforms had shorter delivery cycles, quality control documentation was higher, and there was lower dispute activity within transactions compared to companies that adopted only traditional governance practices. This confirms the use of trust and transparency to reinforce sustainable governance practices within the construction commodity sector in Jordan.

4.6. Agent-Based Simulation Results (H4)

To test Hypothesis 4, an agent-based simulation model was built in NetLogo 6.3 to simulate the transactions between the governance entities in Jordan's low-car-

bon SCM value chain. The simulation modelled an agent network with five types of agents: producers, contractors, regulators, laboratories, and certifiers that interacted with each other through behavioural rules. The simulation was set to run with 1000 transactions, which represented one year with weekly transactions. In each simulation run, the effect of differing degrees of transparency made possible by the use of blockchain technology was tested on the outcome variables that are efficiency in governance processes, success in coordination processes, and material flow process. In the simulation process, there were three types of governance models tested the: A (Low Transparency), B (Moderate Transparency), and C (High Transparency), which entail no use of blockchain technology, partial use of blockchain technology principles to improve data verifications processes and data immutability respectively. In each case, the initial settings allowed trust levels to be similar during the simulation process.

The results shown in **Table 8** are the simulation output averages over 20 Monte Carlo trials for each case. The critical KPIs taken in this simulation are Governance Efficiency (GE), Coordination Failure Rate (CFR), and Trans-

action Delay Index (TDI).

The simulation outcomes (**Figure 3**) showed that there was a significant positive correlation between the transparency features of blockchain technology and governance efficiency. Blockchain traceability was shown to reduce the rates of coordination failure from 34% to 7% amidst significant improvements in governance efficiency by over 50%, from 0.58 to 0.88. Additionally, the Transaction Delay Index (TDI), which is the proportion that shows delay in transactions due to either info asymmetry or doc error, was seen to reduce by 67% over the three scenarios. The average trust level in the network was also shown to steadily improve over time. Each transparency scenario was simulated over 300 iterations and replicated 20 times. During the runs, we monitored network density, average path length and degree distribution, and defined convergence as a change of less than 1% in density and average path length over the final 50 iterations across the Monte Carlo trials. The indicators reported in **Tables 8** and **9**, and the visual networks in **Figures 3** and **4**, are computed from these post-convergence averages to reflect equilibrium, self-adjusting governance states rather than transient dynamics.

Table 8. Simulation Results under Different Transparency Scenarios.

Scenario	Governance Efficiency (GE)	Coordination Failure Rate (CFR)	Transaction Delay Index (TDI)	Average Network Trust Level
Low Transparency	0.58	0.34	0.27	0.61
Moderate Transparency	0.72	0.18	0.19	0.73
High Transparency	0.88	0.07	0.09	0.82

Source: the authors.

Table 9. Blockchain Network Metrics under Different Transparency Scenarios.

Metric	Low Transparency	Moderate Transparency	High Transparency
Network Density	0.26	0.47	0.71
Average Degree Centrality	0.18	0.32	0.55
Modularity Index	0.46	0.29	0.12
Average Path Length	2.9	2.2	1.6
Network Diameter	7	5	3

Source: the authors.

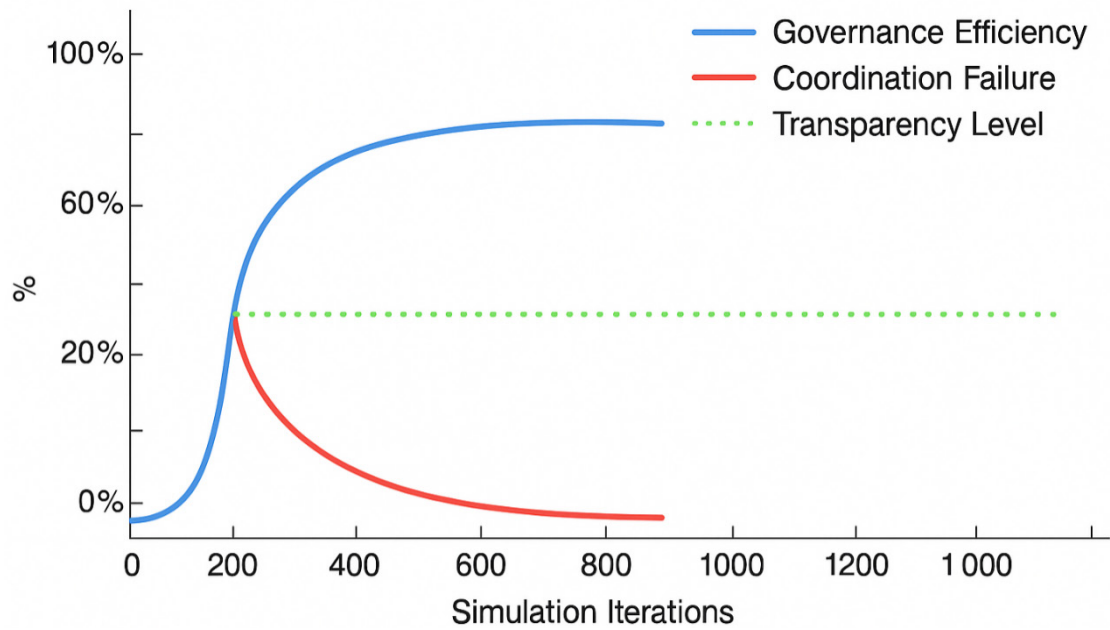


Figure 3. Agent-Based Simulation Trajectories of Governance Efficiency and Coordination Failure under Varying Transparency Conditions.

Source: the authors.

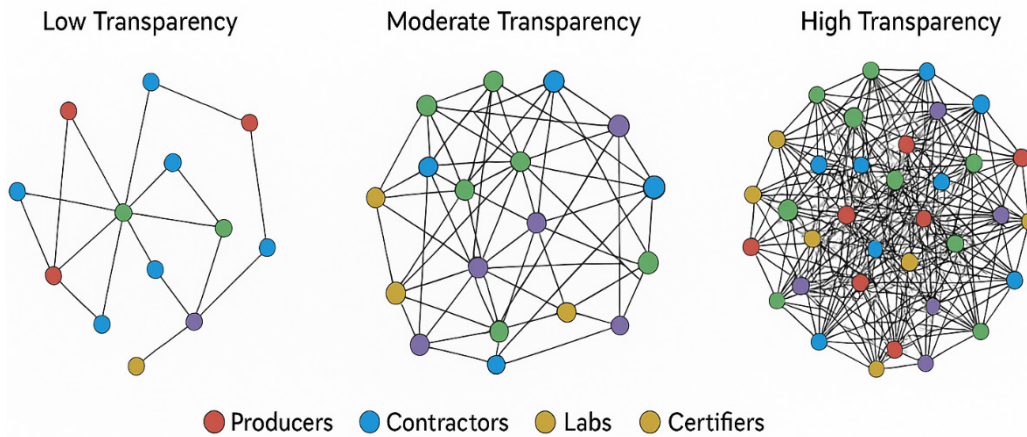


Figure 4. Blockchain Network Visualization across Transparency Scenarios (Generated using Gephi 0.10.1).

Source: the authors.

The system-level phenomena that emerged from the simulation activity attested to the existence of governance processes. In environments with low transparency, the heavy use of relational trust caused instances of cooperation and failed coordination due to unforeseen disruptions. As transparency was increased to reflect the use of blockchain verification processes that brought about reliability to the structure, confidence was cemented among the agents without relational trust. In the High Transparency

scenario (Scenario C), the agents' governance activities displayed self-organizing tendencies with stable collaboration clusters and are characterized by large transaction numbers and low conflict. The simulation also shows that there are shorter adaptation times due to the increased transparency made possible by blockchain technology with regards to the trustworthiness among partners. The network-level performance function converged after 300 iterations. Data logs at the agent level also revealed that

the changeover from traditional governance (Scenario A) to hybrid governance (Scenario B) resulted in almost 22% lower decision latency. When complete implementation of blockchain verification was realized (Scenario C), there was a 46% decline in the values of total decision latency.

The simulation results proved that a more transparent blockchain network has had a significant positive effect on the efficiency and coordination aspects of governance within the low-carbon SCM in Jordan. The trust-through-blockchain effect functioned as a trust amplifier and risk reducer to ensure that there was a self-reinforcing process within the governance mechanism. Although relational governance had difficulties with its scaling challenges, the blockchain trust process had an algorithmic effect that helped to ensure sustainability through stable interactions. This means that the use of blockchain technology in traceability within the low-carbon SCM would increase efficiency from 0.58 to 0.88.

The above **Figure 4** shows the blockchain transparency networks among the producers, contractors, regulators, laboratories, and certifiers constructed to correspond to low, medium, and high transparency levels within the low-carbon SCM supply chain. The entities are represented by each node, the connections represented by each edge are the authenticated transactions that take place in the blockchain. The visual representation was designed using Gephi 0.10.1 and shows higher connectivity and lower modularity with increased transparency. In the low transparency environment, the graphics depict that the network is fragmented with loosely linked nodes, signifying that there is little exchange and greater risk in coordination. In the moderately transparent environment, there is greater density with higher connectivity with clustered nodes. This shows that there is partial use of blockchain technology that has improved coordination as well as minimized information asymmetry. In the highly transparent environment, there are strongly linked nodes with full connectivity, which depicts that the entire governance structure is blockchain-ready with maximized trust as well as traceability. The transition across the scenarios shows how more transparency in the blockchain results in higher connectivity, more efficient governance, and lower coordination failures to empirically confirm Hypothesis 4 (H4).

4.7. Blockchain Network Visualization Results

To validate the results obtained from the simulation study, the data generated from the traceability nodes of the transactions in three large construction projects in the kingdom were analysed utilizing Gephi 0.10.1 to obtain visual illustrations on the structure formed by transparency networks. The nodes in the visual representation corresponded to organizational actors in the SCM value chain producers, contractors, regulators, laboratories, and certifiers. The edges signified blockchain transactions among the actors. The visual representation produced graphs illustrating the level of transparency as shown in **Figure 3** with low, medium, and high levels. Network statistics are used to determine the transparency and connectivity within the network, with the aim of analysing three parameters that include density, average degree centrality, and modularity. The density determines the level of connectivity among the actors within the network, centrality determines the coordinators in the network, while modularity determines the level to which the network is clustered. The results are presented in **Table 9**.

The values of network density increased steadily from a low transparency environment with 0.26 to 0.71 in the highly transparent environment. The result represented significant cooperation among the various organizations with respect to data sharing. This was evident in the creation of a more tightly linked environment in which transactions took place in more direct and verifiable manners. At the same time, the average degree centrality that measures the relative importance within the key organizations increased from 0.18 to 0.55. The modularity index declined from 0.46 to 0.12 with the increase in transparency values, suggesting that the network shifted from a disintegrated layout consisting of isolated clusters to an integrated ecosystem. In environments with higher transparency values, the network's clustering coefficient declined substantially, signifying less granularity within the ecosystem among those in the value chain and more uniform data verification processes. Additionally, values declining in average path length (from 2.9 to 1.6) and network diameter (from 7 to 3) indicate that validation processes among any two entities took fewer steps with the increased speeds and efficiencies within traceability validation.

The results of the visualization further supported the

simulation results and proved that blockchain transparency leads to better coordination and governance within the network. Working under the normal scenario with low transparency, the network was modular in its structure with producers and contractors working in isolated pockets and without any regulatory control. Asymmetric information was also widespread with delays in verification and unorganized documentation. The onset of blockchain-based traceability (moderate transparency level) resulted in more balanced node distribution with fewer redundant intermediaries. It marked the beginning of a digitally governed environment wherein transactions were automatically verified by means of smart contracts. In the high level of transparency, the network reached an equilibrium state that was self-adjusting, regulators and laboratories took active roles in real-time validation processes to form closed loops that successfully thwarted potential frauds.

The key position taken over by producers and regulators in the highly transparent network reinforced their position as trust nodes within the value chain. The entities with the largest degrees in the network represented the entities that had taken over the governance role after the adoption of the blockchain technology within the supply chain. The adoption had implications that brought about

equity in the governance and collaboration within the supply chain, supported by international best practices. The quantitative data analysis supported Hypothesis 4 (H4), indicating that greater blockchain transparency contributes to higher connectivity within the network, decreases modular fragmentation within the supply network architecture, and improves governance efficiency. The data empirically confirmed that trust and performance in sustainable material supply networks are structurally facilitated by digital traceability.

4.8. Hypothesis Testing

This section provides an integrated summary of results from testing all four hypotheses that had been postulated in the research study. In essence, this section provides an integrated summary on the impact of various factors that might be classified within the realms of Behavioural Governance and Technological Governance that might act as influencers within the low-carbon supplementary cementitious materials (SCM) supply chain in Jordan. In **Table 10** below is a summary of the results from carrying out hypothesis testing with respect to each hypothesis.

Table 10. Summary of Hypothesis Testing Results.

Hypothesis Code	Statement	Statistical Technique/Analytical Method	Key Findings	Decision
H1	Trust has a positive and significant effect on performance among actors in the low-carbon SCM value chain.	Simple Linear Regression	Trust positively predicted performance ($\beta = 0.69, R^2 = 0.47, p < 0.001$).	Supported
H2	Governance structure mediates the relationship between trust and performance within the SCM value chain.	Hierarchical Regression and Bootstrapping	Governance structure partially mediated the trust–performance link (Indirect Effect = 0.28, 95% CI [0.15, 0.46]).	Supported
H3	Blockchain transparency positively moderates the relationship between trust and performance.	Hierarchical Moderated Regression	Interaction term significant ($\beta = 0.27, \Delta R^2 = 0.07, p < 0.01$), strengthening the trust–performance relationship.	Supported
H4	Higher blockchain transparency levels are associated with improved governance efficiency and reduced coordination failures.	Agent-Based Simulation and Network Visualization	Governance efficiency increased (0.58 → 0.88) coordination failure decreased (0.34 → 0.07) network density rose (0.26 → 0.71).	Supported

Source: the authors.

The results obtained confirm that *there is an efficient governance process within the low-carbon SCM supply chain in Jordan that promotes trust to improve its results*

(H1), and trust is translated into results through various governance processes (H2). The role of blockchain transparency in magnifying trust is further reinforced by data ac-

curacy and monitoring (H3), and simulations indicate that with effective transparency, weak processes are strengthened to form strong networks (H4). In summary, the results confirm that combining processes that include behaviourally governed structures with technology results in sustainable results. It is recommended that policymakers and firms use blockchain technology to improve traceability.

5. Discussion

The interrelation between trust, institutional structure, and information transparency in governing construction materials for sustainability has long been defined in the context of dynamic value chain systems. The empirical contribution this study makes to that literature agenda is an examination of these features' joint impacts on value chain coordination in specific areas related to low-carbon supplementary cementitious materials in Jordan. In contrast to prior literature streams that focus separately on these three features, there are interdependent layers identified in extending existing theoretical foundations. The inter-relationships identified between trust and governance are highly reminiscent of previous studies concerning relational contracting and supply chain collaboration. In specific examples, Xu ^[21], for example, posited that trust between construction entities can serve to promote knowledge sharing between these entities. In a similar vein to Jiang et al. ^[22] and Zhang et al. ^[23], for example, pointed to the fact that the 'social' aspect of trust mitigates against 'hard' contract enforcement to promote construction supply chain collaboration. In light of these observations, the task presented to this research seems to affirm these related strands to suggest trust not only has a 'social' function but serves to promote 'collaborative' adaptability.

Whereas trust was previously considered mainly from static perspectives within the study of Sociology, more contemporary research within digital construction risk management has appreciably recognized trust's more dynamic technological form. Inasmuch as technology itself has come to play a more fundamental role within current construction risk management approaches and applications, most notably within the study by de Vries et al. ^[24], and more recently by Kambilo et al. ^[25], in relation to algorithmic trust-confidence within construction material trac-

ing applications mediated by blockchain technology itself, evidence has been forthcoming that similar observations from those made within the present study itself also affirm such similar construct types, whereby the societally-embedded variable represented by blockchain transparency works to mitigate trust deficits within SCM transactions. In similar manner to above-stated observations, Saberi et al. ^[44], among others, found that accountability within supply chains was supported by virtue of immutable data record constructs mediated by blockchain transparency.

In addition, incorporating the role of governance structure with a mediating function enhances a comprehensive approach to understanding the issue of trust's influence on sustainability value chain performance. In prior research, Carson et al. ^[45] and Krishnan et al. ^[46] identified that trust-based governance structures raise cooperative efforts only if managed within supportive institutional settings. The above-mentioned research develops a similar approach in a digital environment because it proves that blockchain-based structures institutionalize trust using verified procedures and smart contracts embedded in invisible yet open audit trails. Removing barriers between relationship-based conventional construction methods and data-based digital construction procedures represents a progression in construction management paradigm shifts away from collaborative procedures based on construction experience. From a system dynamics point of view, the simulation approach used in the study supports both the behaviour observed in earlier agent-based modelling exercises related to construction networks. For example, Doroudi et al. ^[47] found in an agent-based model that 'trustful decision-making in project networks follows a sequence of cooperative interactions rather than being based on single-shot trust arrangements.' In a similar vein, another study using agent-based model simulation found that 'agents who used transparent structures are less prone to face coordination problems in multi-agent projects' ^[48,49]. The result obtained in this study related to a system dynamic point of view supports these observations.

The further explanation of the Blockchain technology network shows that these changes are representative of an amalgamation or integration process that is proceeding from society to technology. Taking past research that has been carried out by various individuals, such as Chang et al.

^[34], and others, such as Rejeb et al. ^[35], the impact that these types of decentralized networks that are generated through the use of Blockchain technology have on supply chain logistics sets higher levels of transparency. In other words, there is greater traceability with respect to sustainable materials. The pre-eminence of this study is that it does not only prove these facts but proves that there is also a redistribution process that takes place with respect to the issue of communication within the processes of value production that has to do with the redistribution process with regard to communication. Impacts related to these trends go beyond technical efficacy. The encouragement of trust to deliver transparency represents the overarching shift towards the adoption of circular material management systems. Researchers like Adams et al. ^[50] emphasize that transparency within these systems must achieve circulating construction material if there are to be valid shifts to a circular economy. Connecting these trends involving tracing materials using blockchains to building trust to enable collaboration represents how applying low carbon SCM to run a circular economy in emerging nations like Jordan is quite feasible.

The synergy between behavioural and technological mechanisms of governance that was observed in this study adds to the expanding domain of building a socio-technical system theory. The mutual development of trust between actors and transparency based on blockchain technology serves to demonstrate that technology can improve relationships between actors instead of displacing them. Apparently, Patil et al. ^[51] are correct in stating that blockchain technology benefits when incorporated into networks where there are well-developed relationships based on mutual values. In other words, instead of creating a merely mechanical system of governance, basically raising the level of resilience in relationships based on innovation (SDG 9), blockchain technology increases resilience based on industry (SDG 12). With respect to regional studies, there are few empirical studies on digital transformations in construction sectors in the Middle East. In earlier regional studies, there was a focus on the hindrances to adopting state-of-the-art technology in governance. In other words, this study will serve to illustrate that there are practical digital frameworks for tracing SCM in the Jordanian market, which promote using technology for sustainability objectives.

6. Conclusion

The shift to using lower carbon and more sustainable building materials has thus prompted a need to review how value chains are managed. The aim of this paper was to analyse value chain management in lower carbon supplementary cementitious materials (SCMs) in the construction industry in Jordan with specific focus to explore linkages between trust value chain management structures and value chain management using blockchain technology. An analytical framework was used to enable comprehensive understanding to simulate improvements influenced by technology for value chain management. The paper highlighted that trust becomes unimportant at no point in time but rather becomes an essential pre-condition to capitalize on the efficacy of coordination and the competency of value-creation in supply chains linked with construction materials. At the same time, the practicality of trust gets conditioned upon the construct defined within terms of collaboration and accountability. Together with the capability to be made more transparent within blockchains, trust does not locate itself only within the interpersonal and bilateral relations spheres but gets embedded within the blockchains. In this sense, the constructs ‘trust’ and ‘blockchain’ are more-or-less complementing to each other’s technology. They set up a ‘tough’ environment resistant to ‘opportunism’.

In terms of systems thinking, analysis using agent-based simulation techniques and graphical representation of blockchain networks suggests the development of a hybrid system that blends trust in both the social realm and digital environment to create self-optimizing networks that are transparent. Hybridization increases system efficiency in terms of construction governance. In other words, these results are crucial for lowering carbon emissions in construction. These results tend to stretch a construction system’s traditional bounds in managing construction materials to incorporate digital technology adapted to sustainability goals based on the construction agenda in transition to a circular economy. From a theoretical point of view, the contribution that this study makes to the development literature related to construction management lies in its focus on the topic of socio-technical governance. The study connects well-established constructs of ‘relationally

governed' construction processes with recently emerging scholarship around 'blockchain-enabled' traceability. In this process, resilience brought about by algorithmic transparency paired with human trust is an added element within the process that accelerates the transformation of the construction sector towards 'eco-friendly' SCMs. The research provides valuable insights that can be utilized by policymakers, industry stakeholders, and regulators within the Jordanian context and other similar emerging economies. The adoption of blockchain tracing platforms and relational governance education within the SCM sector may introduce more transparency within the sector.

A methodological limitation is that blockchain use in the sector was at a pilot, project-level stage rather than a fully scaled production system. Accordingly, our blockchain transparency construct reflects a combination of perceived digital traceability and pilot-level blockchain traces, and should be interpreted as an indicator of blockchain-enabled transparency rather than a census of all on-chain transactions at the firm level. Beyond the present focus on survey- and transaction-level data, future research could enrich the governance framework by integrating computer-vision models that analyse on-site images of SCM materials and concrete deliveries. Vision-based deep-learning architectures such as DeepLab, which perform semantic segmentation of complex scenes at pixel level, can be used to detect and delineate defects, material boundaries and surface conditions in field imagery (see, for example, the study of Song et al. ^[52]). In parallel, EfficientNet-style convolutional networks offer parameter-efficient yet highly accurate backbones for extracting quality-related features from large image datasets, as illustrated by recent work on automated estimation of cementitious sorptivity via computer vision ^[53]. Feeding such automatically derived, image-based quality and compliance indicators into the blockchain ledger would provide an additional, objective layer of traceability to support low-carbon SCM governance.

Author Contributions

Conceptualization, F.A.F.A. and S.I.M.; methodology, S.A.A. and A.V.; software, B.A.O.; validation, T.M.A.-F. and S.A.A.; formal analysis, A.V.; investigation,

B.A.O.; resources, S.I.M.; data curation, F.A.F.A.; writing—original draft preparation, F.A.F.A.; writing—review and editing, T.M.A.-F. and S.A.A.; visualization, A.V.; supervision, S.I.M.; project administration, F.A.F.A.; funding acquisition, S.I.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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