

Blockchain Applications for the Sustainable Management of High-Rise Buildings

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The application of blockchain technology is being identified in this construction industry revolution, particularly on high-rise projects. However, there is a significant research gap in understanding its applicability to enhance structural integrity, risk management, and sustainability. This study will try to bridge this gap by researching the impact of blockchain on these critical areas. Stakeholder data were obtained from a questionnaire of standard questions and analyzed using Partial Least Squares Structural Equation Modelling (PLS-SEM). The results show that blockchain adoption is positively correlated with significant improvement in data security (0.265, $p < 0.001$), structural integrity (0.358, $p < 0.001$), sustainability (0.301, $p < 0.001$), and risk management (0.318, $p < 0.001$). These findings suggest that the technology can lead to safer, more sustainable, and better-managed high-rise projects. In such implications, a considerable number of studies is put under consideration since they would present a new avenue through which advanced technologies would be brought into construction to achieve higher standards both in safety and environmental responsibility. Therefore, this present study adds to the existing knowledge on blockchain applications within construction, making valuable insights for industrial professionals and policymakers toward improving project outcomes through adopting technological innovation.

Keywords: Blockchain; Risk; Sustainability; Safety; Integrity.

1. Introduction

The Construction industry has, over a long time, been perceived globally as a vital component in economic growth and the development of metropolitan landscapes and skylines. The development of state-of-the-art technology and more ecologically friendly business practices also become increasingly important as demand for taller structures increases with the growth of metropolitan areas (C. Z. Li et al. 2021). However, construction has had its issues, from environmental and structural concerns over the impact

of the construction to cost escalation and project delays (Kim, Lee, and Kim 2020). The last few years have seen growth in the use of blockchain technology, which has become attractive to various sectors for the possibility to transform existing practices and deliver breakthrough solutions (Akinradewo et al. 2021; Waqar, Othman, Shafiq, and Mansoor 2023). The logic behind this is that with blockchain technology, traditional procedures can become tampered with (Sadeghi, Mahmoudi, and Deng 2022a). Blockchain has found enormous potential for application in every domain, like banking, supply chain management, and healthcare. It is, in general, a decentralized and unchangeable digital ledger. It now has the potential to entirely transform the construction sector, especially for high-rise projects where structural integrity and sustainability, among others, are of utmost importance (Chung and Caldas 2022).

This paper investigates the application of blockchain technology as an enabler of solution provision to vital emerging problems in a high-rise building design process. The goal is to pave the path for a future where building projects flourish with greater efficiency, transparency, and dependability by integrating the inherent qualities of blockchain technology with the skills of construction experts and advocates for sustainability.

The article digs into the difficulties encountered by the building industry, particularly in regards to high-rise projects, as well as the manner in which these difficulties have driven the quest for inventive solutions. It highlights how important risk management is to the construction sector and how important it is to identify, mitigate, and keep an eye on risks in order to ensure project success and stakeholder satisfaction.

The majority of the research that has already been done on the use of blockchain technology in the construction industry is on supply chain and payment system management; potential uses of blockchain technology in risk management have received very little attention. There is a gap in our understanding of the role that blockchain plays in ensuring project success and stakeholders' satisfaction since there hasn't been any specialized research on how blockchain can manage, monitor, and assess risks in high-rise projects (Figueiredo et al. 2022; Waqar, Khan, Shafiq, Skrzypkowski, Zagórski, et al. 2023).

Also, despite the growing popularity of sustainable building methods in the building sector, not much research has been done on how blockchain technology may support the development of sustainability in high-rise buildings (Hamma-adama, Salman, and Kouider 2021; Waqar, Qureshi, and Alaloul 2023). It is necessary, in order to push forward environmentally friendly activities in the construction sector, to investigate how blockchain technology may promote supply chain transparency, trace sustainable supplies, and measure environmental repercussions (Hamma-adama, Salman, and Kouider 2020).

The integration of blockchain technology with real-time structural monitoring systems and building information modeling (BIM) is yet largely researched, and this has implications for the improvement of structural integrity (Celik, Petri, and Barati 2023; K. Kang et al. 2022).

In essence, blockchain technology must be known for providing continuous structural monitoring and predictive maintenance to predict the possible structural breakdowns of high-rise structures and ensure integrity and safety (Sadeghi, Mahmoudi, and Deng 2022b; Suliman Eissa Mohammed and Jamal Salem Alharthi 2022). Supporting this, relatively few

real-world case studies show the effectiveness of applying blockchain technology in high-rise building development per se (Waqar, Andri, Qureshi, Almujiabah, Tanjung, et al. 2023). One of the barriers encountered is the industry's failure to visualize how blockchain technology could prove successful in risk mitigation, advancements toward sustainable practices, and improvements to the structural integrity of high-rise construction projects (Gajdzik, Wolniak, and Grebski 2024). Construction professionals, policymakers, and stakeholders who wish to become meaningfully cognizant of these research work enunciating the potential that blockchain technology holds within the high-rise sector of the construction industry will provide invaluable opportunities for research works to bridge those identified gaps. The use of blockchain would be facilitated by the completion of in-depth studies and empirical research in the fields above leading to the development of high-rise building procedures, which are more eco-friendly, sustainable, and sound at the structural level. Besides that, the text explores the growing awareness of eco-friendly building techniques in the building industry. Since construction hurts the natural world and human societies, environmentally friendly building through practices and materials used is increasingly necessary (Waqar, Houda, et al. 2024).

Sustainability in high-rise construction can be significantly improved via blockchain technologies in verifying the supply chain, carbon foot printing, and interchanging of renewable energies. Apart from this, the paper investigates how blockchain technology enhances structural integrity. Structures' failure could have disastrous consequences, and hence, there is a dire need to put in place trusted methods for their design, construction, and maintenance. The integrated use of blockchain technology, building information modeling (BIM), and real-time monitoring of structures makes it a reality that the structure's health is guaranteed at the highest level from construction to the end of its life. This study aims to contribute novel knowledge with a fresh treatment of the use of blockchain technology in high-rise buildings. This research will, therefore, aim to expose the revolutionary potential of blockchain technology through the means of empirical research, case studies, and practical demonstrations. This study attempts to provide unique insights into how blockchain technology might transform conventional construction procedures. The study aspires to pave the way for a more resilient, sustainable, and safe future for high-rise buildings by first identifying the problems encountered in high-rise projects and offering new solutions. In doing so, it hopes to contribute toward the general growth of the construction industry. Figure 1 The hypothesis of this study is presented.

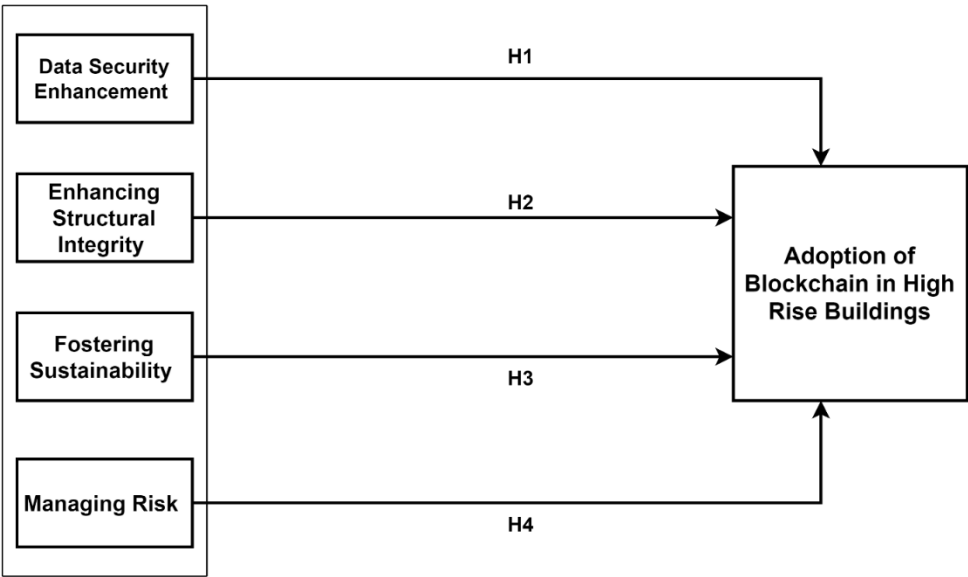


Figure 1 Hypothesis of the study.

- H1: Data security enhancement has significant relation with adoption of blockchain in high rise buildings.
- H2: Enhancing structural integrity has significant relation with adoption of blockchain in high rise buildings.
- H3: Fostering sustainability has significant relation with adoption of blockchain in high rise buildings.
- H4: Managing risk has significant relation with adoption of blockchain in high rise buildings.

2. Literature Review

Industry supply chains and their partners depend on supply chain management. The efficiency of the project and its schedule are decided by the management of the prefabricated construction supply chain (PCSCM) (Qarnain et al. 2021). However, there are issues, such poor transmission and lack of transparency, with information sharing between departments in the management process. These problems result in overstock, early or delayed delivery, protracted construction periods, and—above all a deficiency in real-time information sharing (Jaskula et al. 2022). Other problems, such as higher supply chain costs, confusion on building sites, and longer project timetables, might occur in the absence of timely information exchange (Madakam, Holmukhe, and Kumar Jaiswal 2019). Emerging technologies like blockchain might potentially solve the challenges associated with PCSCM. A distributed ledger called blockchain can automatically store and disseminate transaction data. It offers a public platform where data may be recorded and examined, originally for two-party transactions. Information fragmentation, a lack of traceability and real-time data, *Nanotechnology Perceptions* Vol. 20 No.5 (2024)

as well as making sure component deliveries and payments are made on time, are some of the major problems facing PCSCM (J. J. Hunhevicz and Hall 2020). The industry and governments need to address the current issues with PCSCM to boost the usage of prefabricated buildings. Further investigation is required to enhance the prefabricated process, including the potential use of blockchain technology to provide safer and more effective information interchange across the supply chain lifespan. This should provide better coordination across the various phases of prefabrication.

Nonetheless, due to the rarity of the study topic, there is currently a research gap in implementing blockchain technology into PCSCM. Satoshi Nakamoto introduced blockchain technology in 2008. In 2009, Satoshi Nakamoto produced the first block and published the article "Bitcoin: A Peer-to-Peer Electronic Cash System," which formally started cryptocurrency (Amaludin and Bin Taharin 2018). Bitcoin, the first decentralized currency in history, is a prominent blockchain-based application. Transactions are made feasible by blockchain technology without the requirement for an intermediary. Blockchain's three important components in developing supply chain management are decentralization, security, and anonymity (Koc et al. 2020).

Since the emergence of blockchain technology in 2008, smart contracts have grown in popularity because they can be combined with it to perform peer-to-peer transactions in a secure environment. The emergence of smart contracts may be ascribed to the construction industry's digital revolution. These are computer software that can automatically develop, validate, and apply transaction conditions. Automation, digital environment development, and sensitive data security are their primary uses. Though the smart contract is often referred to as a blockchain feature, its relevance and function in the building sector is underappreciated. To investigate and illustrate the potential of smart contract applications in the construction industry within domain-specific constraints, extensive reviews of research publications published between 2014 and 2021 were conducted as shown in Table 1.

Table 1: Smart Contract Benefits and Challenges Across Construction Domains

Factors	Design	Procurement	Construction	Operations	BIM Integration	Data Management	Security & Privacy
Potential Benefits of Smart Contracts in Construction	✓	✗	✗	✗	✗	✓	✓
Reduced transaction costs	✓	✓	✗	✗	✗	✗	✗
Increased transparency and traceability of data	✓	✓	✓	✓	✓	✗	✗
Facilitated project coordination and collaboration	✓	✗	✓	✗	✗	✗	✗
Integrated change management functionality	✗	✗	✗	✓	✓	✗	✗
Automated payment scheduling/release	✗	✗	✓	✓	✓	✗	✗
Performance monitoring/warranty enforcement	✗	✗	✗	✓	✓	✓	✓

Supply chain optimization	✗	✓	✗	✓	✗	✓	✓
Potential Challenges of Smart Contracts	✗	✗	✓	✓	✓	✓	✓
Inflexibility to changes in project scope	✓	✓	✓	✓	✓	✓	✓
High costs of testing and ensuring security/reliability	✓	✓	✗	✓	✓	✓	✓
Skill/training requirements for implementation	✓	✗	✓	✓	✗	✓	✗
Standardization and integration challenges	✓	✓	✓	✓	✓	✗	✓
Legal/regulatory uncertainties	✓	✗	✓	✓	✓	✓	✓
Data privacy and security risks	✗	✓	✓	✗	✗	✓	✓

PCSCM (prefabricated construction supply chain management) is now afflicted by a variety of challenges, including bulk stock, early or late delivery, extended construction durations, and, most importantly, a lack of real-time information exchange (Plevris, Lagaros, and Zeytinci 2022). Furthermore, a lack of real-time information interchange increases the likelihood of future difficulties such as supply chain cost increases, construction interruptions, and delayed project timetables. The emerging technologies, like bitcoin, may answer the emerging technological trends of the future and thus are a practical solution to many of the PCSCM challenges (Srivastava et al. 2022). Blockchain is a highly safe, traceable, and unalterable distributed ledger that can automatically record and relay the data or transaction information it has. This shows that blockchain can handle the challenge posed by PCSCM (Qarnain et al. 2021).

With all these qualities, it is evident that the supply chain challenges in the construction industry can be tackled if blockchain technology is adopted. The rise of smart contracts may be attributed to the digital transformation in the construction industry (Brandín and Abrishami 2021). Although smart contracts have various applications, their main uses are in the built digital environment, information security, and automation. They are programmable applications that create, verify, and implement transaction conditions on their own.

Currently, there are many problems with prefabricated construction supply chain management (PCSCM), such as bulk stock, early or late delivery, extended construction times, and most notably, a lack of real-time information exchange. Also, the possibility of future problems like supply chain cost hikes, construction disruptions, and extended project schedules is increased when there is a lack of real-time information exchange. Today, emerging technologies like blockchain may show the way for future technology trends, and they can offer workable solutions for PCSCM issues. Blockchain is an ultra-secure, distributed, traceable ledger capable of automatic data or transaction information storage and sharing. This means that it can effectively solve PCSCM problems (Bakhtiarizadeh et al. 2021). A Study, however, argue that the blockchain technology used together with BIM could make the latter more viable since it makes BIM data more transparent, and any history

of data change is followable by each building partner (Mee San Kiu et al. 2022). The following section analyzes how smart contracts merge with other new concepts and state-of-the-art technology. It discusses the applications, benefits, and problems of using innovative contract technology for several research fields.

3. Identification of Factors through Literature

As interest in using blockchain technology for high-rise buildings grows, researchers are looking at how it can improve sustainability, maintain structural integrity, and manage risks more skillfully. A blockchain uses a distributed ledger to keep records of transactions (Waqar and Almujibah 2023). Various studies have proven that technology like a blockchain provides a transparent and tamper-proof ledger, which assures the authenticity and quality of construction materials used in a project (C. Li, Zhang, and Xu 2022). This results in the building having extra structural stability. This is to ensure that the building has already been adherent to all the regulations and standards, hence reducing the chances of structural failure. Besides, the capability of real-time checking and auditing of structures brought by blockchain technology fosters transparency and timely identification of problems (Waqar and Othman 2023).

About promoting sustainability in high-rises, blockchain has been considered one way in which carbon footprints can be measured—a vital tool for changing upon improvements in sustainable processes (Graham and Hailer 2019). This contributes to projects promoting sustainable buildings through the verification of ecologically appropriate approaches and the ethical sourcing of resources by providing supply chain transparency (J. Yang et al. 2022). The encryption possibilities of blockchain could be utilized for responsible land and resource management that would help, in turn, to prevent illegal actions and support environmentally favorable techniques (Waqar, Othman, Shafiq, Altan, et al. 2023).

Water management, on the other hand, can be efficiently achieved by the usage of blockchain technology, which would enable the tracking of water use in real time and the implementing of conservation measures (Teisserenc and Sepasgozar 2021). The transparent and immutable ledger of blockchain technology gives the stakeholders real-time information about potential risks (Qian and Papadonikolaki 2021). More relevantly, smart contracts are automated so that the mitigating processes happen, reducing human errors and increasing the chances of timely responses to risks (R. Yang et al. 2020). Because Blockchain is capable of recording transactions in real time, it enables accurate and rapid analysis of emerging hazards, which in turn makes it possible to implement proactive risk management measures (Yoon and Pishdad-Bozorgi 2022). In addition, blockchain encourages cooperation among stakeholders, which makes it easier for groups to conduct risk assessments and make decisions based on accurate information (Waqar, Skrzypkowski, Almujibah, Zagórski, Khan, et al. 2023).

Concerning the improvement of data security, the cryptographic characteristics of blockchain prevent unauthorized access to sensitive risk-related information and prevent such information from being altered (Xu et al. 2023). Because of blockchain's decentralized design, there are less opportunities for a single point of failure to occur, which increases the

system's resilience to cyberattacks and other security flaws (San, Choy, and Fung 2019). Blockchain technology reduces the risk of fraudulent behavior to a minimum since it verifies the authenticity of both transactions and identities (Reference 13). Audits and compliance verification are made easier by the immutable record-keeping of risk assessments on blockchains (J. Hunhevicz, Dounas, and Hall 2022).

In summary, Table 2 presents the factors that have been identified. Based on current research, it appears that blockchain technology has the potential to transform high-rise buildings by offering numerous benefits related to data security, sustainability, structural integrity, and risk management. This is shown by the fact that technology already exists. To achieve the full transformational influence that blockchain technology may have in the construction sector, however, further study is required despite the promise that has been revealed. This research should investigate practical implementation issues and feasibility factors.

Table 2 Identification of factors through literature review.

Construct	Code	Description	References
Enhancing Structural Integrity	BC-ES1	The blockchain can trace and verify the origin as well as the quality of the materials used in building, guaranteeing that they are compliant with requirements.	(Mohammed et al. 2021; Wang et al. 2022)
	BC-ES2	Blockchain technology makes it easier to conduct structural audits and inspections, which in turn promotes transparency and the prompt discovery of problems.	(Kim, Lee, and Kim 2020; C. Z. Li et al. 2021)
	BC-ES3	Smart Contract Utilization to Guarantee Compliance When these criteria are broken, smart contracts monitor compliance with building codes and health and safety standards by notifying relevant parties.	(Chung and Caldas 2022; Sadeghi, Mahmoudi, and Deng 2022a)
	BC-ES4	Blockchain technology assures that important structural data will not be changed and will remain tamper-proof at all times.	(Akinradewo et al. 2021; Waqar, Othman, Shafiq, and Mansoor 2023)
Fostering Sustainability	BC-FS1	The tracking of carbon footprints by blockchain enables the identification of potential opportunities for sustainable process changes.	(Figueiredo et al. 2022; Waqar, Khan, Shafiq, Skrzypkowski, Zagórski, et al. 2023)
	BC-FS2	Blockchain technology enables supply chain transparency by confirming environmentally responsible business operations and ethical product sourcing.	(Hamma-adama, Salman, and Kouider 2021; Waqar, Qureshi, and Alaloul 2023)
	BC-FS3	Data relating to the management of land and resources may be encrypted using blockchain technology, which both deters illicit activity and encourages environmentally responsible behavior.	(Hamma-adama, Salman, and Kouider 2020; K. Kang

			et al. 2022)
	BC-FS4	The features of blockchain may be used for efficient water management in order to monitor consumption and guarantee that conservation initiatives are taken.	(Celik, Petri, and Barati 2023; Suliman Eissa Mohammed and Jamal Salem Alharthi 2022)
Managing Risk	BC-MR1	Blockchain technology offers a ledger that is both visible and unchangeable, making it possible for stakeholders to obtain data on potential hazards in real time.	(Elbashbishy, Ali, and El-adaway 2022; Sadeghi, Mahmoudi, and Deng 2022b)
	BC-MR2	The use of Smart Contracts in Risk Management Smart contracts automates risk mitigation measures based on established circumstances, so lowering the likelihood of human mistake and guaranteeing that timely answers are provided.	(Waqar, Hannan Qureshi, et al. 2024)(Waqar, Othman, Aiman, Khan, et al. 2023)
	BC-MR3	Blockchain records transactions in real time enables accurate and fast analysis of developing threats, which in turn enables proactive risk management techniques.	(Prakash and Ambekar 2020; Waqar, Othman, and González-Lezcano 2023)
	BC-MR4	Blockchain technology encourages cooperation among many stakeholders, which enables the conducting of group risk assessments and the making of group decisions.	(J. Kang 2022; H. Yang, Fan, and Liu 2022)
Data Security Enhancement	BC-DS1	Blockchain's cryptographic features protect sensitive information relating to risks from being accessed or altered inappropriately by unauthorized parties.	(Waqar, Othman, Aiman, Khan, et al. 2023)(Waqar, Othman, Aiman, Khan, et al. 2023)
	BC-DS2	The design of distributed ledgers minimizes the number of single points of failure and increases the system's resistance to cyberattacks and other security breaches.	(Sajjad et al. 2023; Waqar, Othman, and Skrzypkowski 2023; H. Yang, Fan, and Liu 2022)
	BC-DS3	Blockchain technology helps to reduce the likelihood of fraudulent activity by checking the legitimacy of both transactions and identities that take place on the network.	(Scott, Broyd, and Ma 2021; Shojaei 2019)
	BC-DS4	Blockchain technology keeps an immutable record of risk assessments, which makes it possible to conduct audits and verify compliance with regulations.	(Sadeghi, Mahmoudi, and Deng 2022b;

			Sajjad et al. 2023)
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4. Methodology

In this section the research approach utilized to achieve the intended output of the study has been explained. Following this, the research methodology of this work, the following three main parts that each address an essential element that affects blockchain technology implementation: first, the literature review, which allowed drawing from several industries their critical success factors, challenges, and best practices, thus becoming the basis for the study's hypotheses and research strategy. Second, the identified factors were further validated using a quantitative approach, where a constructed questionnaire was sent to the stakeholders of blockchain implementation. The responses to the survey are subjected to thorough statistical analysis, including regression and correlation analysis, to check on the relevance and impact of the identified factors. Finally, an exhaustive SEM technique was applied in developing an overall measurement model by investigating interrelationships among critical components and their cumulative influence on the success of blockchain deployment. Goodness-of-fit and actual data alignment from the SEM analysis will lead to well-supported conclusions about the key factors affecting the successful adoption of blockchain technology.

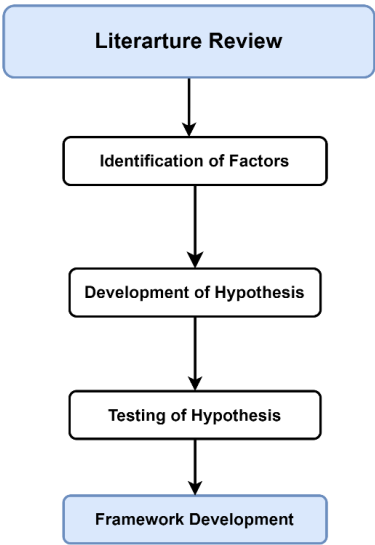


Figure 2 Flow chart of the study.

4.1 Questionnaire Development (Hypothesis)

A quantitative study is employed to find out the role that blockchain technology plays in high-rise buildings for structural integrity, sustainability, and risk reduction. This information was obtained from a survey among high-rise building construction project stakeholders. A total of 245 questionnaires were sent out via email to involve professionals,

architects, engineers, contractors, and others, with a few other surveys done through direct distribution to the professionals in the construction industry within the local sector. In the Likert form of five points, the questionnaire sought responses where the respondents' expressed views in line with the statements on using blockchain technology in high-rise buildings (Sajjad et al. 2023). Out of the 245 questionnaires sent, 164 received reliable responses for analysis, giving a rate of 66.9%. The sample size is large enough to be useful for quantitative analysis. It is in accordance with the practices of other studies carried out that an appropriate insight comes from samples of 100–200 respondents with statistical significance. The responses collected from the survey are analyzed using statistical tools. Descriptive statistics have been immensely helpful in ascertaining an overview of the perceptions and judgments, while inferential statistics such as t-tests and analysis of variance have been helpful in the understanding of the relationship between variables and finalizing the results. This research work, therefore, intends to add valuable insights into the potential impacts that blockchain technology may have on high-rise projects through sound quantitative analysis of 164 valid responses collected from the stakeholders within the high-rise construction sector. The email survey, coupled with manual distribution, enabled broad exposure and a representative sample to detail benefits and problems arising from integrating blockchain into the construction sector.

4.2 Testing of Hypothesis

4.2.1 Measurement Model

A Partial Least Squares Structural Equation Modelling (PLS-SEM) approach test was conducted in the context of high-rise buildings and the impact generated by blockchain technology using the SmartPLS 4 software. This exam was designed to assess the connections between latent components. PLS-SEM works well for exploratory research with low participant numbers because of its small sample size; it involved just 164 valid responses. Convergent validity was assessed by the reliability of the measurement model and validity. Internal consistency and reliability of the latent constructs were evaluated by computing composite reliability (CR) and Cronbach's alpha values. The reliability of a construct is good if both the CR value and Cronbach's alpha are more significant than 0.6 (Waqar, Othman, Falqi, Almujiab, et al. 2023). Furthermore, the Average Variance Extracted (AVE) was calculated to estimate validity between the constructs. The AVE values should be greater than 0.5 for convergent validity to be acceptable. True Equation of Convergent Validity:

$$CR = \sum (\lambda^2) / (\sum (\lambda^2) + \sum (\epsilon))$$

$$\text{Cronbach's alpha} = (\text{Number of items} / (\text{Number of items} - 1)) * (1 - (\sum (\epsilon) / \sum (\lambda^2)))$$

$$AVE = \sum (\lambda^2) / (\sum (\lambda^2) + \sum (\epsilon))$$

The discriminant validity test was based on how distinctive the constructs are from different concepts. The present study deployed the Fornell-Larcker criterion, which relates the square root of the AVE with the correlations between the constructs. Discriminant validity is said to be achieved where the square root of the AVE for each construct is more significant than its correlations with other constructs.

$$\sqrt{AVE} > \text{Correlation between Constructs}$$

This study ensured that the model's measurement model is valid and reliable by assessing the convergent and discriminant validity of latent components using the PLS-SEM test through SmartPLS 4. The test outcomes ensure conclusions drawn with more credence from data evaluation and further uphold the validity and accuracy of the research findings.

4.2.2 Structural Model

A structural model analysis was done in this study by using SmartPLS 4 software to verify the hypotheses and explore the relationships between latent constructs in high-rise building projects where blockchain technology has been incorporated. This entailed bootstrap resampling with 5000 subsamples to enable a reliable parameter to estimate, from which the standard errors, t-statistics, and p-values for each of the path coefficients of the structural model could be calculated in testing the significance of these relationships. The sample mean was the average results of the bootstrap samples, and standard deviation was the dispersion of the estimates. The t-statistics are developed based on the ratio of parameter estimates to their standard errors, while p-values are drawn from the t-distribution. More insight into the magnitude and direction of the relationship between the latent components is derived from the correlation tests; the results indicate a significant relationship between blockchain adoption and structural integrity, sustainability, and risk management in high-rise projects. This comprehensive analysis, using PLS-SEM, bootstrap, and empirical correlation tests, has substantiated the proposed model and further advanced the understanding of blockchain's impact on high-rise buildings, offering solid and dependable insights to academicians and professionals in the construction industry.

4.2.3 Predictive Relevance

To test the model's predictability of high-rise building outcomes from blockchain adoption relationships with the notions supporting sustainability, reducing risks, and increasing structural integrity, a Q2 Predictive Relevance test was carried out (Waqar, Othman, Shafiq, Deifalla, et al. 2023). The test aimed to establish how good a prediction the model makes of high-rise building results. To carry out this analysis, the dataset must be divided into a training dataset and a testing dataset—the training dataset is used to estimate the model's parameters. Then, the parameters assessed were used in calibrating the structural connections. Goodness-of-fit metrics like R-squared and Q-squared values checked the correspondence of the model with the training dataset. The expected accuracy of the model was tested against the testing dataset. To check the prediction accuracy of the model, the following prediction errors were computed: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE). Low values of these variables demonstrate good predictive relevance, which justifies that the model predicts the outcomes accurately in cases of high-rise building construction.

5. Results and Analysis

5.1 Demographic Details

The demographic information of the people who participated in the survey reveals that it included a broad and knowledgeable group of people. When it comes to the level of education that the respondents have, the vast majority of them, which accounts for 29% of

Nanotechnology Perceptions Vol. 20 No.5 (2024)

the total, have a Bachelor's degree (Waqar, Othman, Skrzypkowski, and Ghumman 2023). A remarkable 43 percent of the respondents have a master's degree, while 24 percent reported having completed some other kind of educational program. A far lower percentage, 4%, said that they had a PhD in their field. In terms of the age distribution of the participants, the greatest section of those who took the survey falls within the age range of 31 to 35 years, making up 31% of the total respondents. The age range of 26 to 30 years accounted for 30% of the total participants, while the age range of 36 to 40 years accounted for 20% of the total participants. Surprisingly, respondents older than 40 years made up just 1% of the entire population in the survey.

The respondents who participated in the poll came from a wide range of professional backgrounds and were all at various points in their careers. The highest proportion of respondents (29%) said that they have experience ranging from 11 to 15 years in their respective industries. Close behind them, 24% of them have between 16 and 20 years of experience, while 21% of them have between 5 and 10 years of experience. 19% of the respondents had experience ranging from 0 to 5 years, while only 7% could claim to have over 20 years of experience. Those who had experience ranging from 0 to 20 years made up the smallest number. According to the poll results, 43% of those who participated were civil engineers. The participants who were architects consisted of 21%, and 17% were project managers. In addition, 9% were safety managers, while those who worked in other occupations made up 10%. In general, the demographic data describe a broad population sample. The sample involves respondents from multiple levels of education, years of experience, and professional backgrounds. In this regard, diverse opinions from individuals at different levels of expertise and competence working in the high-rise construction industry improve the validity and generalizability of the research findings.

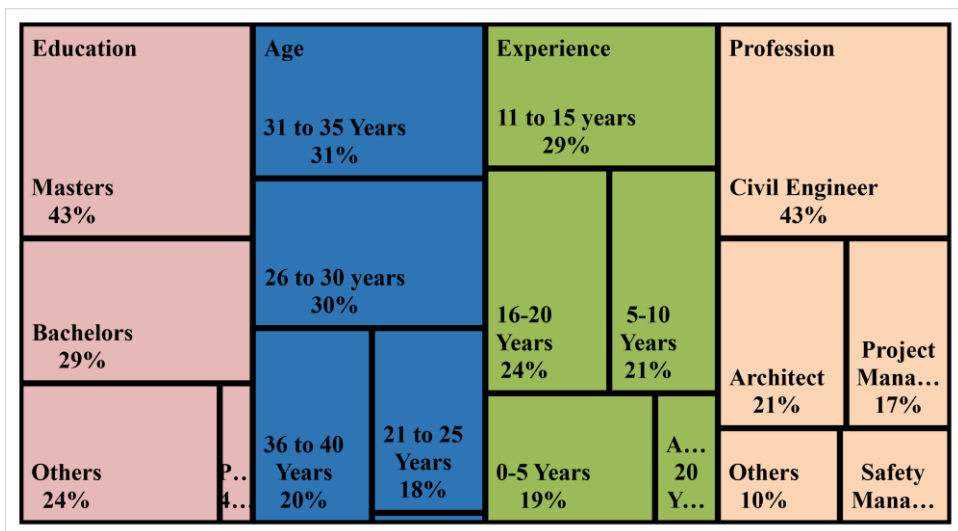


Figure 3 Demographic details of respondents.

5.2 Measurement Model Development

The results of convergent validity testing for each of the concepts being studied are

presented in Table 3. The extent to which the parts of a concept are related to one another and the extent to which collectively they actually represent the underlying construct are two dimensions that are assessed by convergent validity (J. Yang et al. 2022). To determining whether or not each item exhibited convergent validity, numerous measures, such as loadings, the Variance Inflation Factor (VIF), Composite Reliability (CR), and Average Variance Extracted (AVE), were taken into consideration shown in Figure 4.

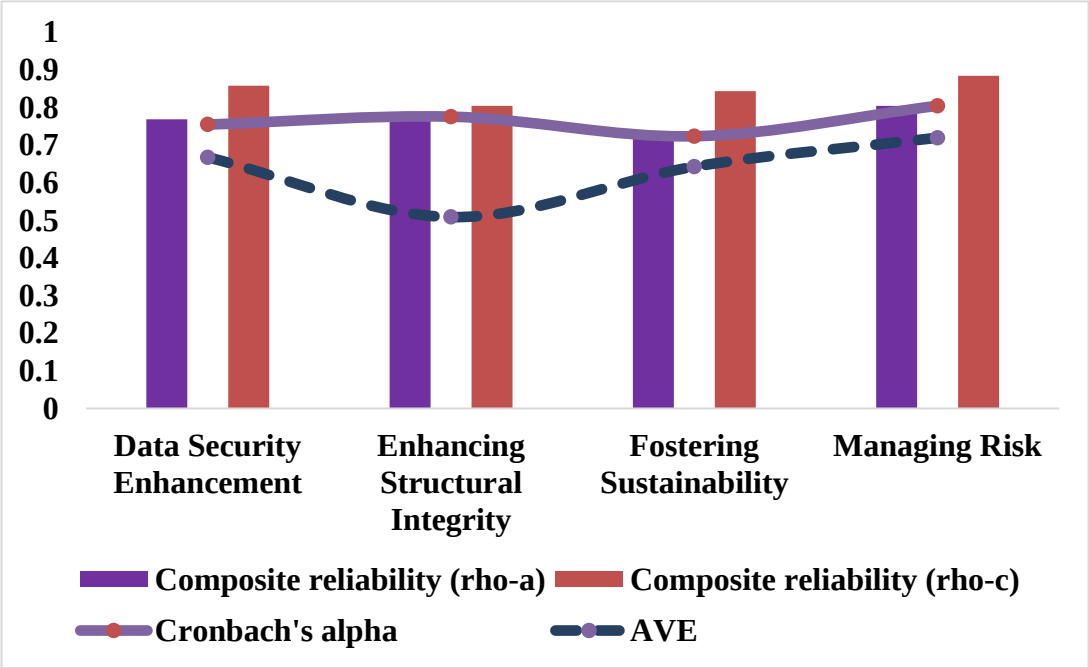


Figure 4 Cronbach alpha, composite reliability and average variance extracted identification.

When it came to the concept of "Enhancing Structural Integrity," all of the items presented evidence of satisfactory convergent validity. BC-ES1 had a considerable loading of 0.746, which indicated a significant association with the construct. In addition, BC-ES2, BC-ES3, and BC-ES4 exhibited substantial loadings of 0.768, 0.612, and 0.718, respectively. All the VIF values fell below the cutoff value of 5, indicating that there were no problems with multicollinearity. The CR values were all higher than 0.7, which indicates that the construct has a high level of internal consistency. Additionally, the AVE value of 0.509 was higher than the suggested criterion of 0.5, which indicates that the items capture more than 50% of the variation in the construct (Hamma-adama, Salman, and Kouider 2021; M. S. Kiu, Chia, and Wong 2022).

Due to a lack of adequate convergent validity, the BC-FS1 construct pertaining to the "Fostering Sustainability" construct was removed. On the other hand, BC-FS2, BC-FS3, and BC-FS4 all revealed significant loadings with values of 0.840, 0.791, and 0.774, respectively. This suggests that these factors have substantial associations with the construct (San, Choy, and Fung 2019; Shojaei 2019). All the VIF values were within a proper range, and the CR values were all higher than 0.7; thus, they indicate satisfactory levels of internal consistency (Waqar, Othman, et al. 2024). The AVE value was 0.643, higher than the

suggested threshold; hence, the remaining items in this construct had acceptable convergent validity. For the "Managing Risk" construct, BC-MR1 had a high loading of 0.867, indicating a strong association with the construct. Both BC-MR2 and BC-MR3 showed high loadings of 0.837 and 0.840, respectively. BC-MR4 was discarded as it failed to show enough convergent validity. Every VIF score was less than 2, indicating no problems with multicollinearity. All the CR values were found to be >0.8 , which is suggestive of a good level of internal consistency of the instrument. AVE value of 0.72 was also found to be greater than the cutoff value, substantiating that the convergent validity is good (Khan et al. 2023). The three-factor loadings towards the "Data Security Improvement" construct are: BC-DS1. All values indicate that all three items possess sound relationships with the construct. However, BC-DS3 was dropped as the convergent validity was not strong enough. Every VIF score was less than 2; therefore, multicollinearity was not a problem. (Waqar, Othman, Shafiq, Altan, et al. 2023). The CR values were all more than 0.7, which indicates that the items had a good level of internal consistency. Additionally, the AVE value of 0.668 was greater than the required threshold, which confirms that the remaining questions have a sufficient level of convergent validity.

The bulk of the items within every concept have adequate correlations to their respective constructs, according to the convergent validity study's results, which supports the measuring model's validity (Sajjad et al. 2023; Teisserenc and Sepasgozar 2021). This was found after looking at all of the outcomes of the analysis. The results provide credence to the validity of the dependability and precision of the measurement model, which in turn helps to strengthen the credibility of the study outcomes and conclusions.

Table 3 Convergent validity to test the items.

Construct	Code	Loadings	VIF	CA	CR	AVE
Enhancing Structural Integrity	BC-ES1	0.746	2.067	0.776	0.805	0.509
	BC-ES2	0.768	1.919			
	BC-ES3	0.612	1.855			
	BC-ES4	0.718	2.374			
Fostering Sustainability	BC-FS1	Deleted	1.930	0.724	0.844	0.643
	BC-FS2	0.840	2.157			
	BC-FS3	0.791	2.137			
	BC-FS4	0.774	1.580			
Managing Risk	BC-MR1	0.867	1.274	0.805	0.885	0.72
	BC-MR2	0.837	1.551			
	BC-MR3	0.840	1.970			
	BC-MR4	Deleted	2.370			
Data Security Enhancement	BC-DS1	0.837	1.896	0.755	0.858	0.668
	BC-DS2	0.781	1.238			
	BC-DS3	Deleted	2.133			
	BC-DS4	0.834	1.837			

HTMT Table 4 shows results achieved from the Heterotrait-Monotrait (HTMT) analysis. This method studies the discriminant validity of the factors analyzed in this research. "Discrimination validity" is the ability of constructs to measure plenty of concepts in a way not significantly related to their very own measurement. The square roots of the average variance extracted values of the corresponding construct are shown in the diagonal elements of the table. The values display the percentage of variance in each construct that its elements

Nanotechnology Perceptions Vol. 20 No.5 (2024)

can explain. The off-diagonal elements give the HTMT values, which are the direct correlations among constructs. However, from the findings, every diagonal element is greater than its corresponding value on the HTMT. This means the constructs are discriminant. That is to say, the correlation between each construct and itself is more robust, which is given by the diagonal elements, compared with the correlation between each construct and the other constructions, which is provided by the off-diagonal elements. While the AVE value of the "Data Security Enhancement" construct was more excellent at 0.755, its HTMT value with "Enhancing Structural Integrity" was 0.567. This is so because, as opposed to reinforcing structural integrity, "Data Security Enhancement" refers to the practice of enhancing data security. Similarly, $\sqrt{\text{AVE}}$ is more significant for "Fostering Sustainability" at 0.643, but the HTMT value by comparing "Fostering Sustainability" to "Enhancing Structural Integrity" was at 0.54. Results show that all components express satisfactory discriminant validity since the HTMT values concerning each construct remain underneath the square root of AVE. Results of the HTMT test show that there is discriminant validity in the constructs employed in this study. This means that these constructs measure different ideas and are not substantially related. This helps to assure the precision and reliability of the measurement model but also validates the results of the study and the soundness of the conclusions drawn from the research.

Table 4 HTMT analysis to find discriminant validity.

Constructs	Data Security Enhancement	Enhancing Structural Integrity	Fostering Sustainability	Managing Risk
Data Security Enhancement				
Enhancing Structural Integrity	0.567			
Fostering Sustainability	0.54	0.882		
Managing Risk	0.561	0.51	0.46	

This step involves the Fornell-Larcker analysis to check the discriminant validity of constructs in a structural equation model as shown in Table 5. Discriminant validity is confirmed where the square root of the Average Variance Extracted (AVE) of any of the constructs on its respective diagonal exceeds the inter-construct correlations on the off-diagonal elements. In this table, the square root of the AVE values are 0.818, 0.713, 0.802, and 0.848 for Data Security Enhancement, Enhancing Structural Integrity, Fostering Sustainability, and Managing Risk, respectively. Each of these values is higher than any of the correlations between the constructs, which range from 0.258 to 0.445. So therefore, the results depict that discriminant validity is achieved in that each of the constructs is different and not highly correlated to the others. In turn, therefore, it effectively measures diverse aspects of the phenomena under study.

Table 5 Fornell Lacker analysis to find discriminant validity.

Constructs	Data Security Enhancement	Enhancing Structural Integrity	Fostering Sustainability	Managing Risk
Data Security Enhancement	0.818			
Enhancing Structural Integrity	0.418	0.713		
Fostering Sustainability	0.41	0.293	0.802	
Managing Risk	0.445	0.258	0.359	0.848

The following data presents the result obtained from testing for discriminant validity of the constructs through the Cross-Loading Criterion—Table 6. A construct possesses discriminant validity if most items on the construct load on that construct and the loadings on that build are higher than those on any other build. Table 2 presents the loadings of each item on its construct and the loadings of the same item on other constructs in the Cross-Loading Criterion analysis. Because it suggests that the primary association of an item is with that structure itself, the rule states that the highest loading of each item should be on its construct.

As can be seen, most of the items satisfy the Cross-Loading Criterion in the sense that their loadings on their construct are higher than their loadings on other constructions. In this respect, for instance, the construct "Data Security Enhancement" is mainly loaded with 0.837, but the component BC-DS1 is loaded relatively poorly with other constructions. Analogously, on the build "Enhancing Structural Integrity," item BC-ES1 has the highest loading of 0.746, while the loadings on the remaining structures are lower.

It is important to keep in mind that when the largest loadings are far larger than the cross-loadings, discriminant validity is often preserved. While these may suggest that constructs share some variance, one must remember that such overlaps are bound to be present. Furthermore, considering the nature of the context and the items involved, it is likely that such stray cases of cross-loading will not compromise the overall validity of the measurement model.

However, the results of the Cross-Loading Criterion analysis provide evidence supporting the discriminant validity between the constructs. This is evident because most items had higher loadings on their constructs than on others.

Table 6 Cross loading criterion of discriminant validity.

Variables	Data Security Enhancement	Enhancing Structural Integrity	Fostering Sustainability	Managing Risk
BC-DS1	0.837	0.452	0.417	0.428
BC-DS2	0.781	0.268	0.283	0.308
BC-DS4	0.834	0.274	0.283	0.339
BC-ES1	0.299	0.746	0.254	0.284
BC-ES2	0.32	0.768	0.291	0.297
BC-ES3	0.266	0.612	0.212	0.254
BC-ES4	0.304	0.718	0.284	0.329
BC-FS2	0.304	0.218	0.84	0.329
BC-FS3	0.273	0.432	0.791	0.193
BC-FS4	0.405	0.481	0.774	0.325
BC-MR1	0.435	0.596	0.322	0.867
BC-MR2	0.398	0.587	0.337	0.837
BC-MR3	0.299	0.246	0.254	0.84

5.3 Structural Model Development

Figure 5 represents the PLS-SEM model. In this model, the relationship existing between the latent constructs that are under analysis is reflected. The figure depicts the path loadings, which explain the strength and direction of constructs' relationships, with their corresponding p-values that identify the statistical significance of a path. These loadings may be considered to express the strength and direction of the relationships between the constructs. Path

loadings in a PLS-SEM model relate to standardized regression weights associated with the paths among the components. When the path loadings are positive, the connection between the constructs is indicated to be positive, and when the route loadings are negative, the relationship is shown to be negative. The strength of the association increases proportionately with the absolute magnitude of the route loading.

The amount of statistical significance may be determined based on the p-values that are linked with each route loading (Shojaei 2019; Yoon and Pishdad-Bozorgi 2022). If the p-value is lower than the significance threshold, which is often fixed at 0.05 but may vary from study to study, this indicates that the link is statistically significant, which means that it is unlikely to have been the result of random chance.

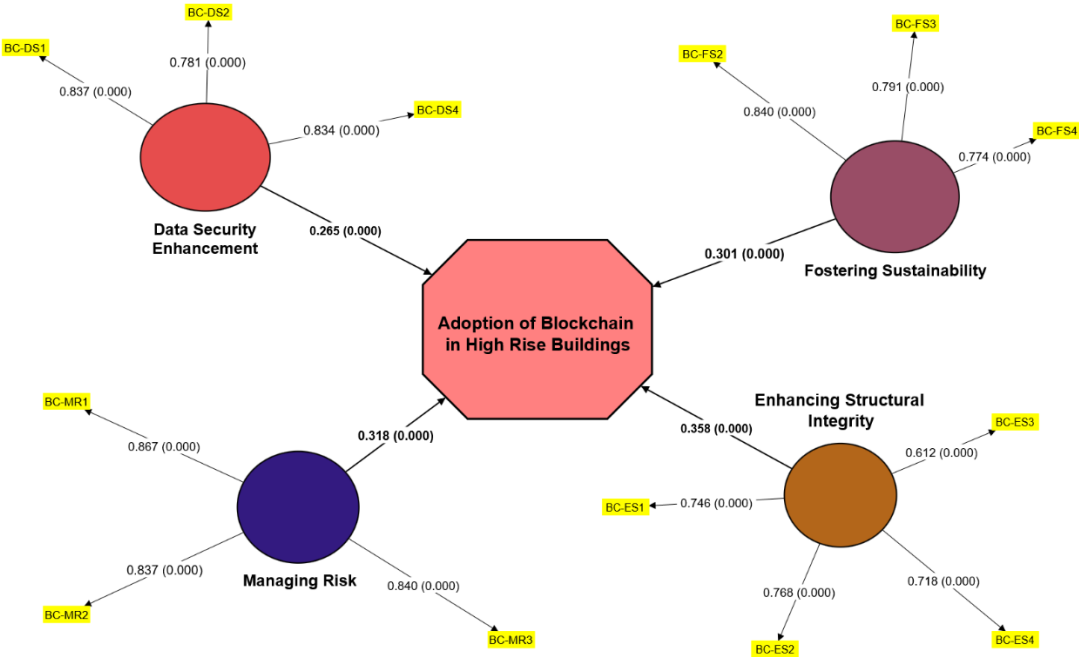


Figure 5 PLS SEM model indicating path loadings with P-values.

The findings of testing the hypothesis via bootstrapping are shown in Table 7, which can be found here. The table below contains the hypotheses, their associated relationships, the values of the original sample (O), the values of the sample mean (M), the values of the standard deviation (STDEV), the t-statistics, and the p-values. In all the hypotheses, the relation between constructs has been established, and a bootstrapping analysis has been done to find out whether these relations are significant or not. The fact that the values for the sample mean (M) and the values for the original sample (O) are very similar means a lot about how consistent and reliable the findings. The t-statistics express the magnitude of the association about the variability in the data. In contrast, the p-values show the probability of finding the link due to random chance. The p-values of all the hypotheses are very small (0) and are indicated by the symbol "." These, therefore, suggest that the connections are highly significant. In other words, the bootstrapping analysis confirms the statistical significance of correlations between constructs, hence even further supporting the assumptions of the study.

The obtained results further enforce the conclusions derived from this research and substantiate the influence that the use of blockchain technology has on bettering structural integrity, encouraging sustainability, reducing risks, and promoting data security in high-rise building projects. It further extends previous research work done on the benefits of applying blockchain technology in improving structural integrity, sustainable encouragement, risk reduction, and data security promotion for high-rise buildings.

Table 7. Testing of hypothesis through bootstrapping analysis.

Hypothesis	Relation	(O)	(M)	(STDEV)	T stat	P value	Results
H1	Data Security Enhancement -> Adoption of Blockchain in High Rise Buildings	0.265	0.265	0.013	20.92	0	✓
H2	Enhancing Structural Integrity -> Adoption of Blockchain in High Rise Buildings	0.358	0.357	0.013	27.998	0	✓
H3	Fostering Sustainability -> Adoption of Blockchain in High Rise Buildings	0.301	0.3	0.011	26.346	0	✓
H4	Managing Risk -> Adoption of Blockchain in High Rise Buildings	0.318	0.317	0.011	28.509	0	✓

The PLS-SEM model, with the route loadings and T-values, can be illustrated in Figure 6. The link of that pathway shows the relationship between the constructs, whether positively or negatively linked. T-values give the associated statistical significance or otherwise. The image represents a condensed and clear visual illustration of the most significant associations obtained between the latent components of the investigation.

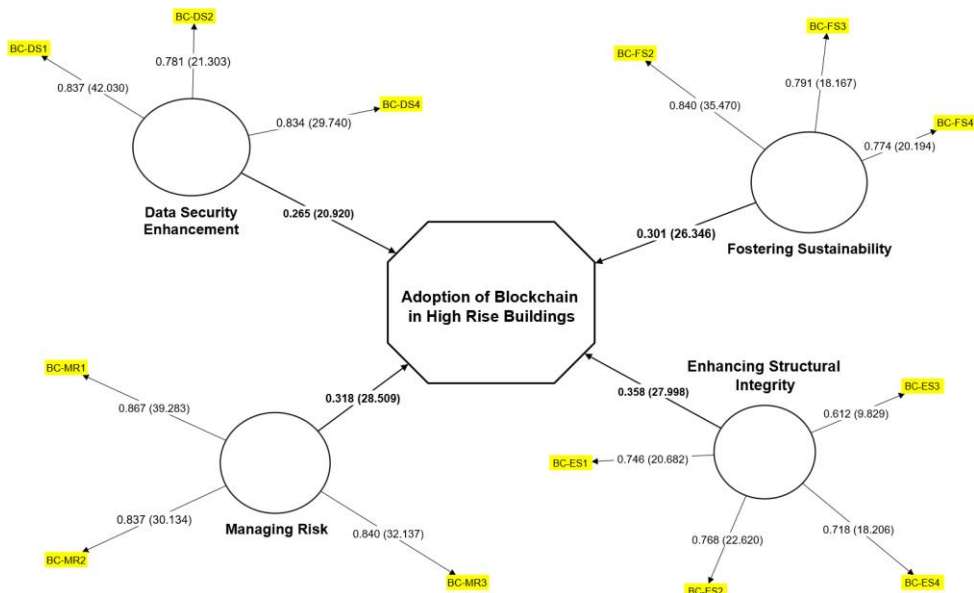


Figure 5 PLS SEM model indicating path loadings with T-values.

5.4 Predictive Relevance

Q² measures the quality of the model in predicting the endogenous constructs. In this study, *Nanotechnology Perceptions* Vol. 20 No.5 (2024)

the formula to be applied to compute the value for the Stone-Geisser Q^2 is as follows: $Q^2 = 1 - (SSO/SSE)$, where SSO = Sum of squares of the observations and SSE = Sum of squares of the prediction errors. It is found that the value of Q^2 is 0.304, i.e., SSO 3726.000 and SSE 2594.074 therefore since the value of Q^2 lies greater than zero, this indicates the model has a satisfactory level of predictive relevance and hence could effectively predict the adoption of blockchain technology in high-rise buildings. If the Q^2 of a given term is greater than 0, then it indicates that the model predicts well and reliably represents a substantive amount of variance in blockchain adoption.

Table 8 Predictive significance of the research.

Predictive relevance analysis of model	SSO	SSE	$Q^2 (=1- SSO/SSE)$
Adoption of Blockchain in High Rise Buildings	3726.000	2594.074	0.304

6. Discussion

This study aimed to explore how blockchain technology can be used to improve tall building projects' structural integrity, sustainability, and hazard management. In this regard, the present research conducted detailed data analysis with the help of a method known as Partial Least Square Structural Equation Modelling (PLS-SEM). Table 7 shows the path loadings, standard deviations, t-statistics, and p-values of the research findings for each hypothesis. The table can be found below. In general, the PLS-SEM model delivered an adequate level of prediction through the predictive relevance analysis, and the model provided a reasonable fit to the data, explaining around 30.4% of the variance in the adoption of blockchain technology in high-rise buildings. This means that it could predict, to some level of accuracy, the implications of the application of blockchain technology on high-rise construction (Waqar, Skrzypkowski, Almujiabah, Zagórski, Khan, et al. 2023; Yoon and Pishdad-Bozorgi 2022).

The hypothesis (H1) tested the relationship between an increase in the use of blockchain technology and enhanced data security in high-rise buildings. The computed test result yielded route loading 0.265 at $p < 0.001$, indicating statistical significance. This implies that the use of blockchain technology does enhance data security and leads to increased acceptance of tall structures. This shows the significance of data security and, hence, the current trend in using blockchain technology.

The second hypothesis (H2) has considered testing the impact of improved structural integrity on the use of blockchain technology in high-rise structures. The effect is significantly higher than the hypothesized 0.358 (T-statistic = 27.998, $p < 0.001$). In this regard, the following justifies how the adoption of blockchain technology alone could improve the structural integrity of high-rise building projects, therefore showing a direct link to an increase in structural integrity because of the use of blockchain technology (Hamma-adama, Salman, and Kouider 2020; J. Yang et al. 2022).

The third hypothesis (H3): sustainability promotion and blockchain technology uptake in high-rise buildings, were subjects. The two were evaluated for an association, and it was found that the route loading was 0.301 (t-statistic = 26.346, $p < 0.001$), such that a significantly positive relationship does exist. This conclusion reveals that implementing

blockchain technology may play a role in developing sustainability practices in high-rise buildings, promoting environmentally responsible behavior, and increasing transparency in the management of supply chains (M. S. Kiu, Chia, and Wong 2022; Shojaei 2019).

Hypothesis four (H4) tested the influence between risk management and using blockchain technology in high-rise buildings. The fact that the route loading of 0.318 was statistically significant (T-statistic=28.509, p-value<0.001) denotes the positive influence expected in adopting blockchain technology in a high-rise building attributable to risk management to be achieved through the use of blockchain technology (J. Hunhevicz, Dounas, and Hall 2022; Xu et al. 2023). This indicates that the implementation of blockchain technology may make proactive risk management tactics more feasible, hence improving decision-making and cooperation among stakeholders.

The solid findings for all the hypotheses point toward the fact that using blockchain technology may be beneficial for high-rise building projects. From these results, blockchain technology can improve data security, structural integrity, sustainability practices, and risk management; hence, the construction sector could greatly benefit from the technology (Waqar, Othman, Shafiq, Altan, et al. 2023; R. Yang et al. 2020).

All in all, the research adds accurate information to the benefit of using blockchain technology in high-rise buildings and improves the knowledge base. This evidence explains the possibility that blockchain technology will find broad use in transforming the construction sector into more technologically integrated and better-run higher-rise buildings. Readers should thus accept the limitation due to various reasons, such as the scope and depth of the data collected in this study. Recommendations for further research on factors that may influence the acceptance and long-term use of blockchain technology in high-rise construction projects are highly endorsed.

7. Conclusion

The study focused on finding the advantages high-rise construction projects would derive in using blockchain technology, hence improving structural integrity, encouraging sustainability, and reducing risks. From the extensive PLS-SEM analysis, significant positive associations were noted between the adoption of blockchain and the studied components. The study results are such that blockchain technology should be positively influential in raising the standards of data security, sustainability, structural integrity, and hazard management in high-rise buildings. Moreover, the predictive relevance analysis of the model showed only a moderate degree of its predictive power, which means it is possible to reveal how blockchain technology will change high-rise buildings with a certain level of precision. The use of this technology will promise more in terms of data security, the maintenance of integrity, and information accuracy during the course of a project. More importantly, the use of blockchain technology will give the said structures more security and thus provide a good promise for the development of more reliable high-rise buildings. There is also an increasing emphasis on sustaining development in high-rise construction, and blockchain technology has the potential to help improve transparency in supply chains in supporting pro-environmental behaviors that are very useful in the implementation of sustainable

development goals. Furthermore, this research also unveiled the potential application of blockchain technology within proactive risk management. The implementation of blockchain technology can assist in decreasing risks and optimizing procedures for improved decision-making. This is possible since the implication of blockchain technology encourages collaboration by stakeholders, allowing the real-time analysis of emerging hazards. However, it is essential to note that this study does have a few limitations. Caution in generalizing the results of this study to other professional sectors or locations must be exercised because it was undertaken under a specific context. Also, the study is focused on only a few categories of building types, thereby implying that other factors might come into play as determinants of blockchain technology diffusion in high-rise buildings. In summary, the results of this study will further enhance the growing body of knowledge pertinent to potential benefits of blockchain technology when used in high-rise construction projects. The findings support the idea that the possible application of blockchain technology should modify the building sector toward more secure, ecological, and better-managed high-rise construction. To foster innovation and positive changes in the construction industry, the paper suggests a broader acceptance and deployment of blockchain technology. As further study is conducted, an examination of the potential challenges, viability, and long-term effects of using blockchain technology in high-rise construction projects will provide valuable insights for the advancement and integration of this revolutionary technology. In the realm of high-rise construction, using blockchain technology to its full potential would surely lead to a more promising and resilient future.

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