Sustainable Futures 9 (2025) 100477

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Potential application areas and benefits of blockchain-enabled smart contracts adoption in infrastructure Public-private partnership (PPP) projects

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ARTICLE INFO

Keywords:
Blockchain technology
Smart contract
Long-term infrastructure
Public-private partnerships
PLS-SEM
Construction industry

ABSTRACT

The traditional, paper-centric infrastructure public-private partnership (PPP) contracts have experienced record numbers of failures and terminations due to contract compliance issues, lack of trust and transparency, and information distortions. While studies on the adoption of blockchain and smart contracts in PPP are still growing, a quantitative survey of global experts on the application areas and potential benefits of Blockchain-enabled smart contracts (BSC) in the context of PPP is lacking. This study comprehensively examined the potential application areas and benefits of BSC adoption in infrastructure PPP projects to understand their impact on the decision to digitalise PPP and ensure sustainable PPP project performance. The snowball sampling technique and questionnaire were used to gather data from experts across countries. Data analysis was done using means analysis, normalisation value, coefficient of variation, Kendall's coefficient of concordance, Kruskal-Wallis test and partial least square-structural equation modelling (PLS-SEM). The study found high awareness and knowledge of the potential benefits of smart contract adoption in infrastructure PPP projects. The leading benefits of BSC adoption in PPP are (1) decentralisation of payments and other transactions, (2) enhancing supply chain visibility and integration, (3) the autonomy in contract administration, (4) prevent misapplication of contractual provisions, and (5) enhances alternative dispute resolution (ADR). The PLS-SEM revealed that six of the eight hypothetical paths were significant. This study advocated for promoting the digitalisation of infrastructure PPP projects. It could serve as an essential resource to policymakers and industry professionals in their quest to improve PPP project performance and minimise failures.

1. Introduction

Public-private partnership (PPP) is significant in helping governments in both developed and developing countries meet their infrastructure gaps. It reduces the pressure on strained government budgets, scarce resources and know-how. Despite these benefits and the increasing usage of high-capital-intensive infrastructure, an appreciable number of PPP projects have suffered from poor schedules, budgets and quality performance problems [1,2], and cancellation, failures, termination and re-municipalisation are also commonplace in PPP projects in both developed and developing countries [3]. Reports revealed that the UK has many failed, cancelled or terminated PPP projects in Europe and that the losses to public funds amounted to over £27,902 million, a sum sufficient to build 1520 new secondary schools for 1975,00 pupils across the UK [4]. These feeble performances were attributed to the financial crisis and deficiencies in contract preparations (European Court of Auditors [[5], 2018]. Also, 7 completed projects out of the 12 EU cofinance PPP projects in Greece and Spain's transportation and information and communication technology sector experienced up to 52 months of delays and extra public funds of €1.5 billion [5]. Case study reports across 7 countries showed how PPP projects have failed and impacted communities negatively [6]. In another report, 1561 cases of re-municipalised projects were recorded between 2000 and 2022 in 56 countries of the world. Most of these cases happened in France, Germany, the UK, the United States and Spain, and in sectors such as healthcare, transportation, water, energy, and telecommunication [7]. The 35 failed water PPP projects investigated by Zhang and Tariq [8] were spread to 5 continents Europe, North America, South America, Asia and Africa. Similarly, the 35 failed transportation projects investigated by Soomro and Zhang [9] spread across the leading PPP markets of the

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https://doi.org/10.1016/j.sftr.2025.100477
Received 20 October 2024; Received in revised form 29 January 2025; Accepted 29 January 2025
Available online 30 January 2025

UK, North America, and Europe and the maturing PPP markets of Latin America, Asia, and Africa. Certain contractual factors cause these failures, cancellations, terminations, re-municipalisation, and associated losses.

Some of the leading reasons are deviance in contractual obligations, hardly established value for money, lack of accountability and transparency, poor commitment on the part of public sector partners, administrative crime and corruption, lack of trust, lack of accurate and updated records and systems, malpractice in partner selection, mismatch between inputs and quality of output/services and poor supervision and monitoring of PPP contract implementation [2,4,10,11]. These factors have contributed to the lack of trust in the system by potential private investors and development agencies. They are also responsible for limiting the broader diffusion of this procurement approach [12]. While the failure factors can occur at any phase of the PPP project infrastructure life cycle, most of the contractual performance issues happen during the implementation (construction and operational) phases, as evident in the literature [13]. Adopting information and communication technology can help strengthen and expand PPPs, helping them overcome their limitations and boundaries [14] at any stage of the projects and particularly at the implementation phases where the failures, cancellations and terminations occur most.

Blockchain technology and smart contracts have unique characteristics that make them suitable for mitigating a more significant proportion of the contractual challenges of PPP projects [15–17]. Tafuro et al. [12] state that blockchain can disrupt and transform PPP for sustainable development. Blockchain technology can improve transparency and traceability in the administration of PPP and increase collaboration and coordination among partners and within teams. Blockchain can mitigate data and information alteration along the lengthy chains of communications networks in PPP projects that could cause failures and possible public opposition in PPP project delivery [18]. Akaba et al. [15] found that blockchain adoption enabled citizen participants to audit and monitor public projects. Blockchain allows for a decentralisation of the business environment, strengthens harmony and consensus, and ensures holistic transparency and immutability of records. The transparency in data and immutability of records provided by blockchain technology and the contractual compliance automation are needed to sustain trust and ensure that parties in PPP work in harmony during the lengthy project duration. The automation brought by adopting Blockchain-smart contracts helps eliminate third parties inherent in the traditional PPP. Thus, smart contracts enabled by blockchain could aid the automation of functions and processes in the complex chain of relationships in PPP. Blockchain technologies have gained relevance in other sectors like banking, agriculture, education, tourism and hospitality, logistics and supply chain, intelligence community, and others [19]. Also, its adoption in the construction sector is still in its infancy. However, in recent times, blockchain and smart contract studies have attracted much of the attention of researchers and academics [20].

Subsequent sections cover a review of related studies on the subject-application areas, and potential benefits of blockchain-smart contract adoption in PPP projects, and the challenges of BSC adoption in PPP, research gap and relevance, the adopted methodology for the study, results, discussion, implications of the study, and conclusion.

2. Potential application areas and benefits of blockchain-enabled SC

2.1. Payment and financial administration

Blockchain and smart contracts have been advocated to prevent or curtail payment issues, as it is seen as a panacea for payment delays and non-payments in the construction sector [21]. Its application and benefits in payment and financial administration and management have contributed to the high traction this technology has gathered among researchers, academics, and industry practitioners in recent years. Interest in these novel digital technologies has been sporadic and has led to a good number of developed models and frameworks integrating blockchain and smart contracts technologies for payments and financial administration, as evident in [22–24].

In PPP projects, whether in the government-pay or user-pay model, payments for products and services rendered can be automated by adopting smart contracts once the prescribed quality conditions are met. Smart contracts can also ensure the smooth financial administration of subcontracts in long-term infrastructure projects. Hamledari and Fischer [25] reported that smart contracts enable decentralisation and disintermediate the execution of terms of contracts and payment administration. These guarantee the execution of contract terms and eradicate unanticipated consequences for the project stakeholders. Blockchain technology provides decentralised, safe, and automated financial management functions at different project stages [26]. The integration of blockchain with project bank accounts (PBA) has the potential to minimise payment delays and enhance trust in data [27]. The potential of blockchain and smart contracts to mitigate the prevalence of payment issues in the construction industry through payment security and the exchange of payment-related information can also be seen [24,28]. Brothwell [29] submitted that Blockchain-smart contracts foster automation of payments between public and private entities in PPP projects, which helps to minimise payment delays and administrative overheads. Based on this, hypothesis (H1) is formulated.

***H1:** 'Payments and financial administration' is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.2. Quality and safety management

Uniformity and transparency are absent in the management of quality information in the paper-based, centralised system of traditional contracts, and this is central to the poor-quality performance records of the construction sector. Adopting digital technologies such as blockchain and smart contracts can mitigate the shortcomings in the outdated traditional and manual paper-based quality management system. Studies have demonstrated that Smart contract enabled by blockchain is a leading industry 4.0 technology that has the potential to overcome the drawbacks of traditional quality management practices in PPP projects. Wu et al. [30] showed that adopting BSC cam improve quality management by providing credible and reliable records of quality data and allowing quality compliance checking automation. The "Product Organization Process" POPqualityChain framework developed by [31] can provide a tamper-proof record of non-conforming work and track it to the responsible party. This framework enabled the sharing of Quality information securely and consistently between the quality inspector and supervision engineers, thus providing an immutable and unaltered record of quality information. Blockchain-driven information platforms can improve traceability, transparency, and effectiveness for the quality management of ready-mixed concrete infrastructure projects [32]. Blockchain technology can provide automated asset compliance checking and immutable records of quality-related transactions in the construction industry [33]. Records provided by blockchain-smart contract platforms can help give stakeholders an early signal of potential safety issues and failures [34].

The role of smart, digital construction technologies in health and safety is well acknowledged. In recent times, researchers and academics' interest in technologies that can acquire, transmit, process, analyse, visualise, and automate safety data and information has consistently increased in the AEC industry [35]. Blockchain and smart contracts technologies are integrated to allow for on-site tower crane safety inspection, provide on-site safety inspection, and ensure the effectiveness of lifting equipment and machinery. These technologies automate tower crane safety inspection, provide transparent and tamper-proof safety inspection data and information, and trace defects to the responsible authority [30,36]. Smart contracts enhance inspection of installation components to ensure that vertical and horizontal movement accidents during materials lifting are minimised and/or avoided on project sites. Thus, potential cracks and failures in crane bolts, pins, and wire rope, among others, are properly inspected to avoid fatalities during operations [36]. Blockchain and smart contracts are incorporated in a smart construction setting to strengthen safety deviance detection, security, and reliability. Nyato et al. [35] reported that blockchain provides proactive safety management, allowing for zero loss and preservation of near-miss safety information. Xiong et al. [37] stressed the benefits of these technologies in the automatic detection of construction operatives without a safety helmet and other PPE. Hypothesis (H2) was formulated based on evidence from the reviewed literature, highlighting the potential of blockchain-smart contract implementation to improve project quality and safety management.

H2: *Quality and Safety management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.3. Supply chain management

Effective supply chain management is pivotal for smooth and successful project delivery in the construction industry. However, it is challenging to achieve problem-free supply chain management because of the many stakeholders involved in PPP projects, the complex and high volume of inter-connected activities, fragmented systems, and specialised professionals who are separated by space and time. These sometimes make stakeholders' relationships in project delivery confrontational [33]. Trust and transparency issues are also prominent, and accountability and acceptance of data become questionable [38]. The predominance of the centralised, manual paper-based technique in managing supply chain stakeholders makes it impracticable for deviances in products and materials compliance checking to be automated. Further, quality assurance verification, process control evaluation, and the responsible party's identification are challenging to do with the traditional manual approach. Blockchain-enabled Smart contract has the potential to overcome these shortcomings through their ability to provide decentralised, trustless, and automated functionalities where data on the progress made and other information are immutable and transparent. Smart contracts enable the integration of cash and product flows in the supply chain network [39]. Wang et al. [40] found that smart contracts enabled by blockchain improved the sharing of information, information traceability and project schedule control happened in real-time. Thus, product delivery delays and associated disputes are minimised or eliminated in the construction supply chain. Studies have observed that smart contracts application in the construction supply chain helps to facilitate collaboration and sustainability and ensure better information sharing among stakeholders to improve supply chain performance [41,42]. Blockchain implementation in the supply chain significantly improves accountability and dispute resolution, transparency and traceability, quality compliance, automation of transactions, and enhanced supplier verification and management in infrastructure projects. Based on these findings, Waqar et al. [43] concluded that blockchain adoption significantly impacts the efficiency and sustainability of the supply chain of infrastructure project development, leading to the formulation of hypothesis (H3).

H3: *Supply Chain Management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.4. Dispute resolution and management

Mahmudnia et al. [44] averred that smart contracts can potentially prevent and/or minimise these contractual-related claims and dispute factors in construction. It also facilitated dispute resolution and management, which is necessary for improved project performance. A blockchain-enabled smart contract allows for the automation of dispute management processes, thus providing a single tamper-proof source of truth for amicable claims management, dispute resolution, and management [44,45]. It lowers business overheads as it accelerates claims and disputes management and provides a conducive work atmosphere between contracting parties. David [46] posits that distributed ledger technology facilitates the timely resolution of contractual issues before they crystallise into disputes. This is done by reducing the magnitude of claims events, ensuring objectives administration of contracts, and automating payments. Blockchain and smart contract adoption have the potential to minimise dispute occurrence, speed up dispute resolution, and improve stakeholders' relationships and project performance, and these have been demonstrated in studies [47,48].

The effectiveness of blockchain and smart contracts in dispute management was shown by [49], who developed a framework based on blockchain and smart contracts that recorded a 90 % success rate in contract execution and the provision of 100 % accurate project status information. These attributes helped reduce conflicts to the barest minimum among the stakeholders. Besides the contractual factors, adopting blockchain and smart contracts can minimise the human and external factors responsible for conflicts and disputes in the construction industry [45]. The dispute management process is data-intensive and, thus, requires proper and verifiable information and documentation management. Blockchain and smart contracts provide accurate data and traceable proof essential for speedy dispute resolution and/or prevention in infrastructure delivery [50]. Therefore, dispute resolution and management represent an area where blockchain-smart contract applications can significantly impact infrastructure project delivery. Hence, the formulation of hypothesis (H4)

H4: *Dispute resolution and management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.5. Information and data management

Smart contracts and blockchain implementation in the built environment provide a decentralised, secured, and reliable platform for efficient project information and data management. It also minimises the tedious and laborious documentation and human errors involved in the traditional paper-based project information management system [51,52]. Blockchain-enabled Smart contract helps to enhance communication and document sharing and provide instant data security, which makes tracking of changes easy and fast, and accurate information analysis can be made for payment purposes [31,53,54]. BSC improves the security of document management systems' security, data integrity and irreversibility [55]. Managing site information (text data, image data, time series data, etc.) is better with blockchain-smart contract platform [56].

In PPP projects, blockchain and smart contracts have the potential to reduce information asymmetry and enhance project governance for improved project management and supervision of projects by the Government [18]. Adopting these technologies in infrastructure projects such as airports and bridges could improve the quality of information during the lengthy project duration. Data and information are stored and managed and are available during project operation, and this helps the operating companies to optimise changes. Blockchain technologies provide a data structure that is resistant to unauthorised manipulations and, thus, gives verifiable information to critical stakeholders to make key decisions that affect both the private and public entities in PPP projects. Therefore, blockchain plays a significant role in building stakeholders' confidence and trust by archiving and providing reliable and tamper-proof information for the parties in PPP [57]. Based on this, hypothesis (H5) is formulated.

H5: *Information and data management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.6. Procurement management

Bid shopping and bid peddling are central issues that affect the price-centred nature of the procurement processes in the construction industry [58]. Although not illegal, bid shopping and peddling are unethical practices that result in projects failing to meet quality, time, and cost baselines. The advent of blockchain and smart contracts and their application in construction have shown the potential to mitigate these unethical and unwholesome procurement practices in the built environment [59]. This application area is still emerging, and evidence from the literature has shown significant practical and scientific potential in ensuring transparency in the management of procurement [60]. Blockchain can be integrated with BIM to minimise relationship bias in contract awards [61]. These technologies introduce a fair playing field for all bidders, which helps improve the trust and transparency in the procurement process, as every transaction is automated, stored and can be traced for auditing [59,60]. The role of Blockchain-enabled smart contracts improves procurement management was also reported by [62]. Infrastructure PPP projects may contain several subcontracts and rely on a strong collaborative agreement among the stakeholders. Therefore, appropriate partner selection, agreement formation and contract execution in PPP can positively be impacted by adopting blockchain and smart contracts [63], as tendering and procurement frauds are eliminated in the complex PPP model. The blockchain-smart contract helps improve the procurement process's efficiency for better project performance. It automates market analysis, bid evaluation and subcontractor selection. Procurement data can be traced and analysed to detect anomalies and favouritism in procurement management in PPP projects [64,12]. These led to the formulation of hypothesis (H6).

H6: *Procurement management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.7. Energy and environmental management

A large quantity of waste and pollutants are produced in construction, impacting the environment and contributing to climate change, affecting workers' health and adjoining properties. The traditional system of pollutant collection for compliance assessment is subject to manipulation with no traceability [56]. Blockchain and smart contracts enable tracking social and environmental information across the complex supply chain of construction projects, ensuring compliance with environmental laws [65]. Zhong et al. [56] developed a blockchain and smart contracts framework that showed the potential to automatically monitor the level of pollutants produced on construction sites and evaluate their environmental impacts. In addition, blockchain-enabled smart contract technology can help monitor and control the level of energy consumption and emissions on construction sites [66].

Wongthongtham et al. [67] state that although peer-to-peer energy trading is still in its infancy, blockchain technology is one of the modern technologies with fundamental energy trading and distribution potential. The direct exchange of excess energy (e.g., electricity) between two or more particles in an energy distribution grid is peer-to-peer (P2P) trading. Blockchain provides a secure platform for energy trading against participants' misconduct, fraud, and criminal violations. It offers a transparent store of energy transaction data in a decentralised network for easy monitoring and tracking of assets. [68]. The smart contract components allow for the automation of buying and selling of energy based on the dynamics of demand and supply. The blockchain-smart contract is an attractive solution for energy distribution companies. The study by Xu et al. [69] shows that blockchain adoption has the potential to mitigate carbon data manipulation, ensure transparency and provide a reliable tracking of carbon footprint data. Infrastructure PPP projects are usually massive with huge carbon footprint and energy requirements. Adopting blockchain smart contracts will help improve energy trading and carbon footprint data management and the sustainability of the built environment [70,69]. Hypothesis (H7) was formulated based on the foregoing information.

H7: *'Energy and Environmental management' is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

2.8. Project management and contractual administration

Blockchain application in Contract administration is among the four key potential application areas reported by [71]. This technology can perform these functions owing to its features, such as immutability, security, transparency, and traceability. There is consensus among researchers that blockchain adoption enhances contract management, particularly in mitigating payment-related issues, document management, stakeholders' management, contract delay and claim management [45]. Blockchain-enabled smart contracts can potentially transform project management functions and the administration of construction contracts [72], and operation and maintenance-based contracts. Blockchain-smart contracts improve transparency in stakeholder communication because of their accessibility to information and data immutability across the many stakeholders involved in contracts and chains of operations and functions [53]. These technological innovations have also been demonstrated to bolster efficiency in communication and decision-making for project smooth management and administration [73]. PPP projects are megaprojects with substantial capital investments and multi-stakeholders whose relationships must be properly coordinated and managed. These make the administration and governance of PPP contracts complex, which require the unique functionalities of the blockchain and smart contracts for better performance and to curb the high number of failures that have affected infrastructure PPP projects in recent decades. The adoption of BSC in PPP will help reduce the misapplication of contractual provisions because of the automation of enforcing contractual terms. It will also aid the management of project resources and enhance trust and transparency in PPPs. Therefore, smart PPP project management and contract administration are possible with blockchain-enabled smart contracts [12]. Thus, the formulation of hypothesis (H8)

H8: *'Project management and contractual administration' is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects.*

Table 1 summarises the selected potential application areas and benefits of Blockchain-enabled Smart contracts in Infrastructure PPP projects.

3. The challenges of blockchain- Smart contract adoption

While the barriers of blockchain and smart contracts are outside the scope of this present study, they are worth mentioning so that stakeholders are aware and guided in their implementation decisions. This section presents a brief discussion of the limitations posed by blockchain scalability and legal and regulatory framework and the possible mitigation strategies. PPP projects are usually complex and involve many stakeholders and multiple subcontracts. This could present some challenges due to blockchain scalability challenges. The scalability issues of blockchain can lead to serious transactions throughput, latency, and performance issues. However, there has been a recent development in blockchain scalability advancement. 'Sharding' is one of the blockchain scaling options that involves splitting blockchain networks into smaller data sets (called shards) for ease of management [75]. Each shard has its smart contract, which helps improve transaction throughput to accommodate the large stakeholders and volume of transactions in PPP projects. The complex hierarchical governance structure of infrastructure projects could conflict with the decentralised networks and the

Table 1
Summary of Potential application areas and benefits of blockchain-smart contracts.

Code	Application areas and benefits of smart contracts	Source(s)
A	**Payment and financial administration**	
PF1	Decentralisation of payments and other transactions	Das et al. [74]; Ahmadisheykhsarmast and Sonmez [22]; Elghaish et al. [23]; Hamledari and Fischer [25]; Elghaish et al. [26]; Sonmez et al. [28]
PF2	Automating and processing payments and transactions	Das et al. [74]; Ahmadisheykhsarmast and Sonmez [22]; Elghaish et al. [23]; Hamledari and Fischer [25]; Elghaish et al. [26]; Sonmez et al. [28].
PF3	Security and guarantee of payments to beneficiaries	Das et al. [74]; Ahmadisheykhsarmast and Sonmez [22]; Elghaish et al. [23]; Hamledari and Fischer [25]; Elghaish et al. [26]; Sonmez et al. [28]
PF4	Auto-execution of project bank accounts (PBAs)	Scott et al. [27]; Das et al. [74]
B	**supply chain management**	
SC1	enhancing supply chain visibility and integration	Hamledari and Fischer [39]; Yoon & Pishdad-Bozorgi [42]
SC2	automation of operation and maintenance activities (processes)	Wang et al. [40]; Yoon & Pishdad-Bozorgi [42]
SC3	Allows for tracking and verification of assets, components, products and materials	Wang et al. [40]; Yoon & Pishdad-Bozorgi [42]
C	**project management and Contractual administration**	
PC1	The autonomy in contract administration	Msawil et al. [72]; Celik et al. [71]; Zeberga et al. [45]; Tafuro et al. [12]
PC2	prevent misapplication of contractual provisions	Tafuro et al. [12]; Celik et al. [71]
PC3	Better project resources management	Tafuro et al. [12]; Celik et al. [71]
PC4	Enhance trust and transparency among PPP core stakeholders	Yang et al. [53]; Tafuro et al. [12]; Celik et al. [71]
PC5	Increasing the reliability and transparency of decision-making processes on PPP projects	Lee et al. [73]; Tafuro et al. [12]; Celik et al. [71]
D	**Dispute resolution and management**	
DR1	Enhances alternative dispute resolution (ADR) by providing a single source of truth for stakeholders in PPP projects	Mahmudnia et al. [44]; Zeberga et al. [45]
DR2	provides accumulative risk/reward values for performance evaluations of projects/parties	Mahmudnia et al. [44]; Wahab et al. [49]
DR3	Tracking, managing and minimising claims and disputes associated with payments, documentation, and supply chain, among other	Mahmudnia et al. [44]; Wang et al. [40]; Saygili et al. [48]; Zeberga et al. [45]
E	**Data and Information management**	
DM1	improve interoperability in data exchange	Anthony (2024); Du et al. [18]; Zhang et al. [56]; Ciotta et al. [52];
DM2	Provides immutable, auditable and cryptographic data for better collaboration of parties across the project life cycle	Baxter [57]; Erri Pradeep et al. [55]; Du et al. [18]; Das et al. (2022); Yang et al., [53]; Sheng et al. [31]
DM3	promote collaboration and information sharing among stakeholders	Yoon and Pishdad-Bozorgi [42]; Du et al. [18]; Ciotta et al. [52]; Yang et al. [53]; Sheng et al. [31]
DM4	Improve open communications and transparency in data management	Du et al. [18]; Ciotta et al. [52]; Yang et al. [53]; Sheng et al. [31]
F	**Quality and safety management**	
QS1	improve materials and services inspection and specifications compliance checking	Sheng et al. [31]; Wu et al. [30]; van Groesen and Pauwels [33]; Wu et al. [36]
QS2	Automation of project quality and safety inspections	Sheng et al. [31]; Wu et al. [30]; van Groesen and Pauwels [33]; Wu et al. [36]; Xiong et al. [37]
QS3	Provide on-site safety inspection and ensure the effectiveness of lifting equipment and machinery.	Wu et al. [30]; Wu et al. [36]; Xiong et al. [37]
QS4	Provide trustworthy quality and safety inspection records to relevant stakeholders.	Sheng et al. [31]; Wu et al. [30]; van Groesen and Pauwels [33]; Wu et al. [36]
QS5	Gives the stakeholders a warning sign of potential failures and hazards	Wu et al. [30]; Wu et al. [36]; Eze et al. [34]; Xion et al. [37].
H	**Procurement management**	
PM1	Improve contractors/ subcontractors' selection.	Scott et al. [62]; Lumineau et al. [63]; [59];
PM2	enhance trust and transparency in the procurement of projects	Pishdad-Bozorgi and Yoon [59]; Scott et al. [62]; Trautmann and Lasch [60]
PM3	Governing and automating contracts and operations agreement	Scott et al. [62]; Pishdad-Bozorgi and Yoon [59]; Trautmann and Lasch [60]
J	**Energy and Environmental management**	
EE1	Supply trustworthy environmental data.	Filhol [65]; Shu et al. [66]; Zhong et al. [56]; Perera et al. (2020);
EE2	automatically monitor the level of project pollutant emissions	Shu et al. [66]; Zhong et al. [56]; Perera et al. (2020)
EE3	Enhance sustainability promotion	Shu et al. [66]; Zhong et al. [56];
EE4	Energy trading and/or transfer	Wongthongtham et al. [67]; Shu et al. [66]; [68]

environment of blockchain technology. With the appropriate legal framework and shared desire for transparency and accountability, the hierarchical governance structure of the infrastructure projects could be redesigned with a focus on disintermediation to reap the importance of automation and trustless transactions of the blockchain-enabled smart contracts.

Integrating blockchain technology with existing legal frameworks of the PPP could also present some limitations. In a geographical context, there could be some weakness in the legal framework for PPP implementation in infrastructure projects [11]. The lack of applicable legal and regulatory policies on blockchain and smart contracts has remained a significant barrier to the drive to adopt the technologies in the construction industry [76]. At present, there is no defined law governing smart contract adoption [77], and the absence of widespread recognition of these technologies in different regions makes enforceability a difficult task [78,76]. There is an absence of legal clearness with blockchain technology, which further makes the enforceability of smart contract enforcement a complicated issue [79]. Ameyaw et al. [16] recommended a blockchain-smart contract mandate by nations to give legal backing and overcome the lack of uniformity in legal and regulatory frameworks to ensure industrywide adoption. Therefore, government policies and regulations regarding blockchain adoption put in place to ensure smooth adoption in PPP projects.

Agapiou [78] identified some legal implications of smart contract adoption that stakeholders should consider. They are (1) The validity of the smart contract, (2) parties must have contractual capacity, (3) choice of applicable law when parties are in a different jurisdiction, (4) disputes resolution for disputes in smart contract execution, (5) data privacy and security, and (6) compliance to relevant laws and regulations. For public projects like the infrastructure PPP projects, a hybrid blockchain could be adopted against the public blockchain that does not have a level of restriction. This is to avoid cyber security issues associated with technologies that run on networks. Furthermore, a clear agreement and data protection laws should guide partners' actions [80].

4. Research gap and relevance

Literature showed increased efforts by researchers and academics to proffer digital technology-based solutions to the myriads of contractual problems challenging the traditional, centralised infrastructure PPP project delivery system. Most of these studies are centred on BIM applications in PPP projects [1,81,82]. Blockchain technology has unique functionalities and capabilities that make it superior to other digital technologies in managing and administrating contracts, particularly for the long duration of the PPP projects. Recent developments and improvements in blockchain scalability capabilities [83] make it suitable for PPP projects. However, studies on Blockchain adoption in PPP contracts are still a growing area of interest, as evident in the few existing studies. For instance, in Nigeria, Abodei et al. [84] focused on the impact of blockchain technology on collaboration and involvement of the public in the planning and delivering of public infrastructure projects. Blockchain-based e-procurement to improve trust and transparency in the procurement of public infrastructure projects in Nigeria. [15]. These studies adopted a qualitative approach. Nel [14] adopted a qualitative approach to investigating risk allocation in ICT PPP projects. Blockchain can enhance the design of a crowdfunding-based PPP financing model for port city projects in Indonesia [85]. This study adopted desk study, benchmarking, and life cycle costing approaches. Blockchain-enabled Tokenisation to attract private investment (resourcesbera, innovation, and expertise) in infrastructure projects [17,86]. While Lyudmila et al. [17] adopted an interdisciplinary scientific approach, Tian et al. [86] adopted a conceptual approach. Tafuro et al. [12] adopted a problem-focused approach, proposed a conceptual framework that linked Blockchain and PPP and concluded that blockchain can transform and/or disrupt PPP innovatively but lacks empirical validation from real-world experiences. Blockchain can improve financial control efficiency and effectiveness in transportation infrastructure [87]. A framework was developed to aid government agencies in issuing "transportation infrastructure tokens" for sustainable funding and recovery of investment in transportation infrastructure in the USA. Du et al. [18] adopted a design science approach to assess blockchain adoption to improve data and information quality and reduce information asymmetry for better project management and supervision of PPP projects by the government.

While the contributions of these studies to literature should not be disregarded, a detailed assessment of the potential benefits and applications of blockchain-smart contracts in PPP is needed. While there have been enormous discussions on the theoretical potentials of BSC in the construction industry, a quantitative, survey-based assessment of its benefits and application areas in the context of PPP requires more attention, particularly in long-term infrastructure projects. Moreover, none of the cited works leveraged experts' inputs from across countries. Tafuro et al. [12] averred that PPP-integrated blockchain-smart contract projects are still a nascent development domain requiring more research. With this knowledge, this study comprehensively assesses the different areas of application and benefits of the adoption of blockchain-enabled smart contracts (BSC) in PPP projects. This study also fills the methodological gap (i.e., survey). This study adopted a questionnaire survey approach and partial least square-structural equation modelling (PLS-SEM) to analyse the perception of global experts on BSC adoption in PPP. This approach has not been used in previous PPP-integrated blockchain studies. Thus, its utilisation in this study would provide a solid and sustainable foundation to underpin the need for further discourse on PPP project digitalisation and the diffusion of the applications of blockchain and smart contracts in the built environment. The study also opens the doorway for the digitalisation of PPP projects using other industry 4.0 technologies for delivering civil and heavy engineering infrastructure projects for more extensive societal benefits beyond the construction sector.

This study gives a detailed assessment of the views of experts from across countries on the potential benefits and application areas of smart contracts adoption on infrastructure PPP projects. Infrastructure drives economic development, poverty reduction, inequality reduction, employment creation, and environmental sustainability, which are key to meeting sustainable development goals [88]. The report shows that 50 % of partnership projects fail at the global level. In the UK alone, most failed projects are PPP projects. The high failure has enormous financial, social, and environmental implications for the government and the public [89]. Failure of PPP could lead to delays, costly renegotiation, financial burden on tax players and the government, and economic instability. The Social Impact of failed PPP includes job losses, increased poverty and inequality, loss of trust in governments, social unrest and abandoned sites that could become a den for criminals. Fraud and lack of transparency in project impact assessment can lead to environmental issues in water projects and reduced water quality and aquatic life [90]. PPP projects are complex and high-risk investments and can negatively impact millions of lives and livelihoods and an entire economy when they fail. The high rate of failure of PPP projects and the consequences of their failure to the public were important considerations to focus on PPP projects in this study.

5. Research methods and approach

5.1. Variables identification and data collection

The variables used to develop the study questionnaire were obtained through a thorough review of PPP and technology adoption studies. A total of 31 benefits of blockchain-enabled smart contract were identified and categorised into 8 broad potential areas of application in PPP projects. Questionnaire was selected for this study because it allows for uniformity and provides a structured format for collecting unbiased data, making systematic analysis and comparison of results easier [91]. Furthermore, the questionnaire provides the most suitable time-efficient and economical means of gathering data from large audiences separated by space and time [92] compared to other methods of gathering data. In addition, the use of a questionnaire in this study aligns with the study's objectives of gathering data from global experts to (1) determine the leading benefits and application areas of smart contracts adoption in PPP projects and (2) identify application areas that could significantly impact the decision to adoption smart contracts in the delivery infrastructure PPP projects. The questionnaire used in this study was developed using the JISC Online survey, which offers electronic means to collect data remotely [93]. The questionnaire had two parts: (i) gathered data on the respondents' background information, which served to determine the quality of data from other sections, and (ii) Part 2 of the questionnaire garnered data on the application and potential benefits of smart contracts adoption in PPP projects. The participants were asked to rate the variables based on their experience and knowledge of the extent to which they agree or disagree with the applications and benefits of Smart contracts in PPP projects. This was based on a 5-point Likert scale (where 5 = strongly agree and 1=strongly disagree).

The targeted participants were PPP experts, blockchain experts, construction experts, built environment academics and researchers, and other allied professionals. Key sample recruitment criteria are knowledge and experience of PPP projects and /or blockchain technology and smart contracts. Nevertheless, blockchain-smart contracts are still new, and their actual use in the built environment is in its infancy. General knowledge of fourth-industrial digital technologies in construction was equally considered when recruiting survey participants. Furthermore, to ensure quality data collection and unbiased responses, the respondents must have at least 3 years of work experience in the construction industry and in PPP projects. These criteria were boldly written on the questionnaire so that unqualified participants would not participate. The absence of a population sample frame of experts who met these sample recruitment criteria and from which a firm sample size can be calculated informed the use of the snowball sampling approach in this study. The snowball sampling technique is respondent-driven as it depends on referrals from one respondent to another [94]. It can contribute equally to a higher survey response rate [95].

Data collection started by sharing the survey link with experts within the researchers' cycle, peers, and others identified from a preliminary survey who served as the initial set of respondents. The survey link was shared with these potential respondents via their email addresses, WhatsApp and other social media handles. Potential response bias due to the snowball sampling approach was mitigated by first defining the sample selection criteria (characteristics). Secondly, the respondent pool was widened through network variety. The initial respondents were asked to consider contacts within their cycle and outside the work network (i.e., acquaintances outside the same work or industry). This was done to improve respondents' diversity and response robustness and reliability. Lastly, the researchers would analyse the respondents' demographic characteristics at intervals during the sampling. Further recruitment/invite is sent to under-underrepresented segments; this iterative process ensured a balanced distribution of survey participants [96].

The reasonableness and completeness of the questions contained in the questionnaire were established via a pilot survey carried out among 6 industry experts and 6 academics who are knowledgeable and experienced in the subject of this study [97]. Pilot testing helps enhance the research outcome's accuracy and acceptability [98]. Following the feedback from the pilot test, typos were corrected, some variables were rephrased, and the questionnaire was restructured before the final sampling. The industry experts have an average of 15 years of industry experience and occupy managerial positions in various organisations/countries. The academics were lecturers/researchers with previous industry experiences/knowledge of this research subject, and the least ranked among them were senior lecturers. The pilot survey is not meant for hypothesis testing and, as such, does not require a larger sample size [99]. When there is no sampling frame to calculate a firm sample size, Julius [100] recommended a sample size of 12 for a pilot trial. Oke et al. [101] pilot-tested 12 industry experts and confirmed that their inputs improved the 'quality and validity' of the study questionnaire. Therefore, the 12 experts who participated in the pilot survey were adequate as the pilot did not confirm the study hypotheses but tested the questions' reasonableness and completeness and aided the primary survey.

5.2. Data screening and analysis methods

After 16 weeks of sampling, 101 responses were received. Of these, 4 were screened out because of incomplete and poor responses. This leaves 97 valid and usable responses, which formed the basis for the analysis carried out in this study. The 97 responses were deemed satisfactory for the various analyses since they were higher than the central limit theorem minimum sample size of 30 [102]. Furthermore, survey research on emerging digital technologies in construction has yielded small responses. This was confirmed by Ameyaw et al. [103], who submitted that obtaining a low response rate for online surveys of built environment experts on emerging technologies (e.g., blockchain and smart contracts) is possible. Nulty [104] states that online surveys yield a lower response rate than paper-based surveys. Aghimien et al. [105], via an online survey of construction experts, obtained 70 usable responses. Ameyaw et al. [16,103] obtained 61 responses, but only 41 were valid and used for analysis. Based on the foregoing, the 97 responses are valid. The technologies assessed in this study are new. Therefore, not many built environment experts have knowledge of the technologies. Also, the number of PPP-experienced built environment experts is limited. These factors may have contributed to the number of responses received in this study.

The gathered data were then subjected to normality and reliability evaluations. The normality test was carried out using the Shapiro-Wilk test, and the results showed that the data were non-parametric as a p-value of 0.000 (i.e., less than 0.05) was obtained. A Cronbach's alpha coefficient (α) of 0.938 was obtained from the Cronbach's alpha test, and this indicates that the research instrument has remarkably high reliability and the data is of decent quality. Frequencies and percentages were used to analyse the respondent's background information. Mean score ($\overline{X}$) was used to rank the assessed variables in order of their relative weights. The mean scale for determining the level of significance/importance of the potential areas and benefits of smart contracts adoption in PPP projects are $\leq$1.50=very low significance/importance; 1.51–2.50 = low significance/importance; 2.51–3.50 = neutral; 3.51–4.50 = high importance/ significance; and $\geq$4.51 = very high importance/significance [103]. In addition, the mean normalisation value was used to determine the criticality of the variables. The cut-off mark for critical is NV $\geq$ 0.50 as in [106]. The NV was calculated using the formula below.

$$\text{Normalised value (NV)} = \frac{\textit{Mean value of variable} - \textit{Minimum mean value of variables}}{\textit{Maximum mean value of variables} - \textit{Minimum mean value of variables}} \quad (1)$$

The Coefficient of variation (CoV) was used to measure the degree of variance in the respondents' subjective judgement in the rating of the variables [107], which was meant to determine the level of agreement among the research participants. The scale for interpreting the CoV values was obtained from [108], and they are: 0< CoV $\leq$ 0.5 = "good degree of agreement", 0.5< CoV $\leq$ 0.8 ="less than satisfactory agreement", and CoV > 0.8 = "poor degree of agreement". Kendall's Coefficient of concordance (Kendall's W) and Chi-square (X^2) values were also used to establish the level of agreement in the respondents' ranking of the variables. The higher the Kendall's value, the better the agreement level among the respondents. However, where the assessed variables are more than seven, the X^2 should be used [109]. Furthermore, since the participants are from different countries and with different professional and experienced levels, the Kruskal-Wallis H test (K-W) was applied to determine the level of agreement among the respondents' views at a 95 % confidence level [110].

Confirmatory Factor Analysis (CFA) and Partial Least Square Structural Equation Modelling (PLS-SEM): The SmartPLS 4 was used to execute the CFA to ascertain further the reliability and validity of 8 constructs covering the applications areas and benefits of smart contracts. The significance of the application areas and benefits of smart contracts in enhancing the performance of infrastructure PPP projects were determined using the PLS-SEM. The PLS-SEM performs better than other multivariate methods (e.g., multiple regression, factor analysis, and path analysis), in analysing the relationships between latent constructs [111]. The model was evaluated using PLS-SEM, which was achieved on SmartPLS software developed by [112].

The sample size of 97 made PLS-SEM the most suitable tool to adopt since it is not rigid to small sample size like the co-variance-based SEM. PLS application can be helpful for researchers who want to test complex models' relationships with a constraint in sample size [113]. This study met two principal statistical conditions that guarantee sample size adequacy for statistical analysis before PLS-SEM was used. (i) The central limit theorem prescribed a minimum sample size of 30. The sample size of this study is 97. Thus, the central limit theorem is satisfied. (ii) The sample size should not fall below 10 times the number of the maximum relationships that a latent construct can form with other unobserved constructs [114,115]. This study has 9 latent constructs. The maximum number of relationships a latent construct can form between itself and others is eight. Therefore, the sample size should not be <80 (10 times 8). The sample for this study is 97, thus fulfilling the second requirement.

Moreover, evidence from studies that used PLS-SEM on small sample sizes abounds. Adeleke et al. [116] applied PLS-SEM to 40 responses to explore organisational factors influencing construction risk management. The measurement items exhibited satisfactory validity and reliability. Darko et al. [117] applied PLS-SEM to data from 43 samples to study green building adoption in developing countries. Maria et al. [118] used 36 responses to investigate the "readiness to face industry 4.0″. Belay et al. [119] used a sample size of 96 to assess the key drivers of BIM adoption to improve infrastructure projects in Ethiopia. Adabre and Chan [120] utilised 47 responses to assess the barriers to sustainable housing development in developing countries. Aghimien et al. [105] applied PLS-SEM on 70 responses to unearth the factors hindering sustainable construction in developing countries. Adabre et al. [114] used 47 responses to model the relationship between policies and goals for sustainable housing in developing countries. Kukah et al. [121] applied PLS-SEM on a sample size of 48 to determine the interrelationships among risks associated with PPP power projects. The assessed items in these cited studies showed acceptable validity and reliability and yielded significant results.

Finally, the participants' consent was sought and obtained prior to their participation in the study. The flow chart (Fig. 1) below summarises the entire research process.

6. Results

6.1. Respondents' demographical information

Table 2 details the respondents' demographic information. The

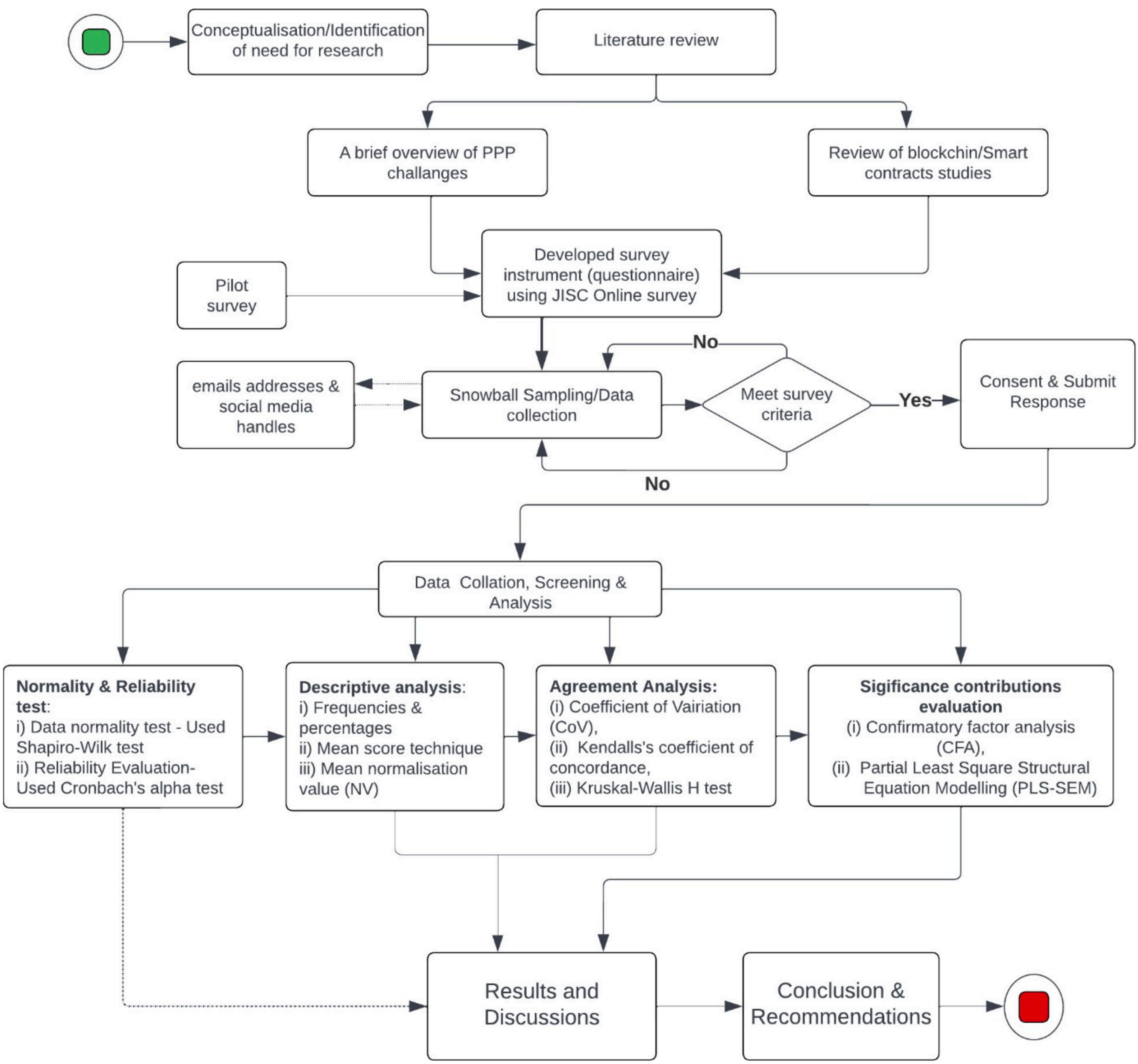

Fig. 1. Study methodological flow chart.

Table 2
Respondents background information.

Categories		Frequency	Per cent
Country of practice/work			
Africa	(Ghana, South Africa, Kenya, Nigeria)	9	9.28
Asia	(China, Hong Kong, Malaysia)	12	12.37
Europe	(UK, Republic of Ireland, Turkey, Sweden)	36	37.11
North America	(USA, Canada)	12	12.37
South America	Nil	0	0.00
Oceania	(Australia, New Zealand)	9	9.28
Global	Participants with work experience covering multiple countries/regions (i.e., >2)	19	19.59
Total		**97**	**100.00**
Respondents Job title			
Contract Administrator / Quantity surveyor		24	24.74
Commercial, contract/programme manager		21	21.65
Technology consultant		13	13.40
PPP analyst/consultant		16	16.49
Academic/researcher		18	18.56
Other:	Blockchain architects/specialist (2) Smart contract administrator (1) Supply chain consultant (1) Concession consultant (1)	5	5.15
Total		**97**	**100.00**
Years of industry/professional experiences			
3–5years		5	5.15
6–10years		19	19.59
11–19years		30	30.93
20+ years		43	44.33
Total		**97**	**100.00**
Organisational type			
Government / Procuring authority (e.g., public utility provider)		16	16.49
Project Company		15	15.46
Consulting organisation		24	24.74
University/research institution		18	18.56
Multilateral organisation		24	24.74
Other	Nil	0	0.00
Total		**97**	**100.00**
professional membership			
CIOB		19	19.59
RICS		25	25.77
PMP		10	10.31
ASCE		12	12.37
RICS & CIOB		6	6.19
PMP & RICS		2	2.06
RICS & ASCE		4	4.12
ICE & RICS		2	2.06
ASCE & PMP		7	7.22
Other[a] (IQSK, NIQS, COREN, GhIS, ASAQS, AIQS)		10	10.31
Total		**97**	**100.00**
Years of involvement in PPP practice and/or research			
3–5years		17	17.53
6–10years		35	36.08
11–19years		27	27.84
20+ years		18	18.56
Total		**97**	**100.00**

[a] Institute of Quantity Surveyors of Kenya (IQSK), Nigerian Institute of Quantity Surveyors (NIQS), Ghana Institution of Surveyors (GhIS), Council for the Regulation of Engineering in Nigeria (COREN), Association of South African Quantity Surveyors (ASAQS), and Australian Institute of Quantity Surveyors (AIQS).

distribution of the respondents by country/region of practice shows that 37.11 % work in Europe, and 19.59 % have experience in two or more countries of the world. 12.37 % have each worked in countries of Asia and North America. The participants who work in Oceania and the African continents constitute 9.28 % each. This global distribution of the expert participants would improve the credibility and generalisation of this study.

Analysis of the job titles of the respondents showed that 24.74 % of them work as contract administrators/quantity surveyors, 21.65 % of them work as commercial, contract/programme managers, 18.56 % are academic/researchers, 16.49 % are PPP analysts/consultants, 13.40 % are technology consultants. Other participants (blockchain architects/specialists, smart contract administrators, supply chain consultants, and concession consultants) constitute 5.15 % of the respondents. These show a diverse mix of experts from different sectors of the economy, which will aid the robustness and credibility of the responses.

Regarding years of industry/professional experience, a greater proportion (44.33 %) have spent 20+ years in practice/professional experience. The next are those respondents with 11–19 years of professional or industry experience, constituting 30.93 % of the respondents. Participants with 6–10 years of industry/professional experience are 19.59 %, and those with 3–5 years of industry/professional experience are 5.15 %. These show that the respondents possess appreciable years of experience to contribute meaningfully to this study.

The analysis of the organisational types of the respondents showed that a good number of the experts work with consulting and multilateral organisations, as they constitute 24.74 % of each of these organisations. Participants from university/research institutions make up 18.56 % of the respondents, while those from the government / procuring authority (e.g., public utility provider) are 16.49 %, and those from project companies are 15.46 %. These show that the participants came from diverse organisational backgrounds that covered both industry and academics, as well as multilateral organisations that strongly support PPP, technology innovation, and the sustainability of the global economy.

The respondents' professional membership status shows that 25.77 % are members of RICS, 19.59 % are members of the CIOB, 12.37 % are ASCE members, and 10.31 % are project management professionals (PMP). 21.65 % of the survey participants have at least two professional qualifications, and other professional qualifications constitute 10.31 % of the respondents. This result shows that the respondents are professionally qualified to contribute to the subject of this study.

The analysis of the respondents' years of involvement in PPP practice and/or research showed that 36.08 % of the respondents have 6–10 years of experience in PPP practices/research, 27.84 % have 11–19years of involvement in PPP practice/research, 18.56 % and 17.53 % have 20+years and 3–5years involvement in PPP practices and /or research respectively.

6.2. *Level of awareness and knowledge of blockchain-smart contract application in infrastructure PPP projects*

The analysis of the overall response on the level of awareness and knowledge of blockchain-smart contract applications in infrastructure PPP projects shows that it is high as the mean of the responses is 3.84, which fell within the range of 3.51–4.50 for high importance/significance. The breakdown revealed that 35.05 % of the participants indicated a 'very high' level of awareness and knowledge of the potential roles of Blockchain-enabled smart contracts (BSC) applications in PPP projects. 27.84 % indicate that the awareness and knowledge are 'high', and 24.74 % have a 'moderate' level of awareness and knowledge of the application of BSC in infrastructure PPP projects. The experts who indicated 'low' and 'very low' levels of awareness and knowledge represent 10.31 % and 2.06 % of the participants, respectively (Fig. 2). This shows that built environment experts are aware and possess a good knowledge of the potential benefits of smart contract adoption in PPP projects on infrastructure provision and development in the global economy.

6.3. *Mean ranking of the potential application areas and benefits of smart contract in adoption in PPP projects*

Table 3 and Fig. 3 show that smart contract adoption has significant potential to transform and bring important benefits in delivering infrastructure PPP projects. This is premised on the mean score of the assessed variables, which fell within the range (3.51–4.50 = high importance/significance). Fourteen of the variables had a critical NV ≥ 0.5, and these variables with their corresponding mean are: Decentralisation of payments and other transactions ($\overline{X}$ = 4.49; NV = 1.000), enhancing supply chain visibility and integration ($\overline{X}$ = 4.43; NV = 1.000), the autonomy in contract administration ($\overline{X}$ = 4.35; NV = 1.000), prevent misapplication of contractual provisions ($\overline{X}$ = 4.35; NV = 1.000), enhances alternative dispute resolution (ADR) by providing single source of truth for stakeholder in PPP projects ($\overline{X}$ = 4.38; NV = 1.000), improve interoperability in data exchange ($\overline{X}$ = 4.42; NV = 1.000), improve materials and services inspection and specifications compliance checking ($\overline{X}$ = 4.25; NV = 1.000), improve contractors/subcontractors' selection ($\overline{X}$ = 4.19; NV = 1.000), supply trustworthy environmental data ($\overline{X}$ = 4.39; NV = 1.000), increasing the reliability and transparency of decision-making processes on PPP projects ($\overline{X}$ = 4.27; NV = 0.767), better project resources management ($\overline{X}$ = 4.25; NV = 0.700), provide on-site safety inspection and effectiveness of lifting equipment and machinery ($\overline{X}$ = 4.16; NV = 0.571), governing and automating contracts and operations agreement ($\overline{X}$ = 4.08; NV = 0.524), and enhance sustainability promotion ($\overline{X}$ = 4.29; NV = 0.500). The standard error of the mean (S.EM) of the assessed variables ranged between 0.063 and 0.091, which indicates negligible divergence between the population mean, and the sample mean. The variables' standard deviation (SD) ranged between 0.612 and 0.886, indicating a marginal dispersion of responses around the mean and the absence of outliers.

6.4. *Agreement analysis*

The results of the CoV in Table 3 revealed a 'good degree of agreement' among the respondents regarding the assessed variables. The maximum and minimum CoV values are 0.223 and 0.145, respectively, while the average CoV of 0.184 was obtained. These falls within the 0< CoV ≤ 0.5 = "good degree of agreement". Kruskal-Wallis H test revealed that the participants' views converged in 27(87.10 %) of the assessed variables, thus indicating non-significant differences as these

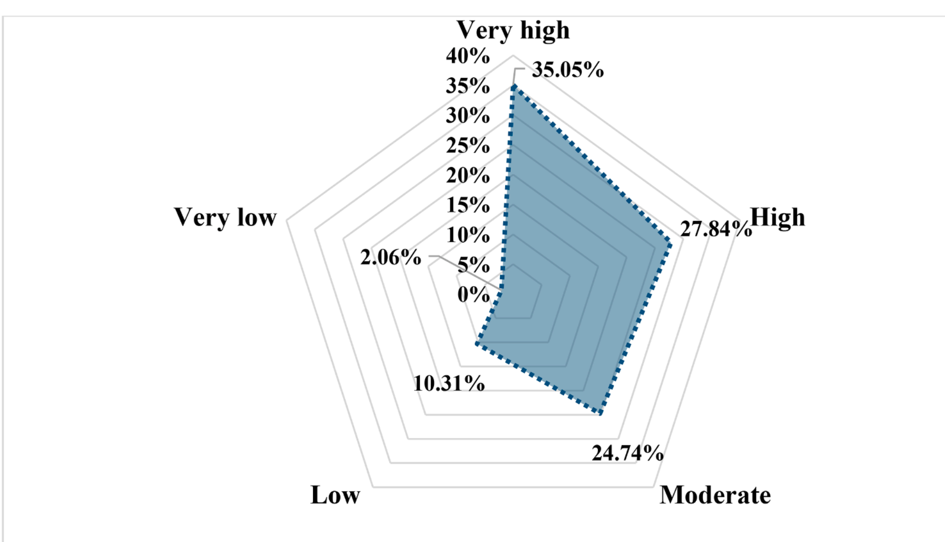

Fig. 2. Level of awareness and knowledge of BSC application in PPP projects.

Table 3
Ranking of the Roles of Smart contracts in automation of PPP operations agreements and processes.

Code	Variables	$\overline{X}$	S.EM	SD	NV	CR	OR	Kruskal-Wallis		CoV	
								X^2	Sig.	Values	Decision
A	**Payment and financial administration**	**4.31**									
PF1	Decentralisation of payments and other transactions	4.49	0.084	0.824	1.000**	1st	1st	4.871	0.432	0.192	GDA
PF2	Automating and processing payments and transactions	4.27	0.081	0.791	0.276	3rd	12th	5.395	0.37	0.193	GDA
PF3	Security and guarantee of payments to beneficiaries	4.27	0.075	0.736	0.276	2nd	11th	10.637	0.059	0.174	GDA
PF4	Auto-execution of project bank accounts (PBAs)	4.19	0.078	0.762	0.000	4th	19th	6.769	0.238	0.183	GDA
B	**Supply chain management**	**4.34**									
SC1	enhancing supply chain visibility and integration	4.43	0.073	0.709	1.000**	1st	2nd	6.3	0.278	0.191	GDA
SC2	automation of operation and maintenance activities (processes)	4.28	0.071	0.694	0.000	3rd	10th	9.109	0.105	0.163	GDA
SC3	Allows for tracking and verification of assets, components, products and materials	4.31	0.075	0.730	0.143	2nd	8th	9.276	0.099	0.164	GDA
C	**Project management and Contractual administration**	**4.25**									
PC1	The autonomy in contract administration	4.35	0.083	0.809	1.000**	2nd	7th	2.302	0.806	0.169	GDA
PC2	prevent misapplication of contractual provisions	4.35	0.065	0.632	1.000**	1st	6th	7.729	0.172	0.188	GDA
PC3	Better project resources management	4.25	0.083	0.812	0.700**	4th	15th	4.559	0.472	0.148	GDA
PC4	Enhance trust and transparency among PPP core stakeholders	4.03	0.087	0.844	0.000	5th	29th	9.104	0.105	0.2	GDA
PC5	Increasing the reliability and transparency of decision-making processes on PPP projects	4.27	0.077	0.750	0.767**	3rd	11th	2.819	0.728	0.214	GDA
D	**Dispute resolution and management**	**4.23**									
DR1	Enhances alternative dispute resolution (ADR) by providing a single source of truth for stakeholders in PPP projects	4.38	0.077	0.746	1.000**	1st	5th	4.519	0.477	0.18	GDA
DR2	provides accumulative risk/reward values for performance evaluations of projects/parties	4.12	0.065	0.634	0.000	3rd	25th	6.985	0.222	0.169	GDA
DR3	Tracking, managing and minimising claims and disputes associated with payments, documentation, and supply chain, among other	4.18	0.087	0.850	0.240	2nd	21st	2.188	0.823	0.154	GDA
E	**Data and Information management**	**4.25**									
DM1	improve interoperability in data exchange	4.42	0.077	0.752	1.000**	1st	3rd	2.798	0.731	0.204	GDA
DM2	Provides immutable, auditable and cryptographic data for better collaboration of parties across the project life cycle	4.18	0.083	0.812	0.207	3rd	21st	4.273	0.511	0.179	GDA
DM3	promote collaboration and information sharing among stakeholders	4.26	0.077	0.747	0.483	2nd	14th	6.684	0.245	0.196	GDA
DM4	Improve open communications and transparency in data management	4.12	0.091	0.886	0.000	4th	25th	4.604	0.466	0.183	GDA
F	**Quality and safety management**	**4.14**									
QS1	improve materials and services inspection and specifications compliance checking	4.25	0.076	0.743	1.000**	1st	15th	3.196	0.67	0.223	GDA
QS2	Automation of project quality and safety inspections	4.03	0.085	0.831	0.000	5th	29th	11.769	0.038*	0.173	GDA
QS3	Provide on-site safety inspection and effectiveness of lifting equipment and machinery	4.16	0.078	0.762	0.571**	2nd	23rd	2.354	0.798	0.212	GDA
QS4	Provide trustworthy quality and safety inspection records to relevant stakeholders	4.11	0.073	0.713	0.338	4th	27th	8.808	0.117	0.184	GDA
QS5	Gives the stakeholders a warning sign of potential failures and hazards	4.14	0.087	0.846	0.476	3rd	24th	17.101	0.004*	0.18	GDA
H	**Procurement management**	**4.08**									
PM1	Improve contractors/subcontractors' selection	4.19	0.084	0.816	1.000**	1st	19th	8.634	0.125	0.206	GDA
PM2	enhance trust and transparency in the procurement of projects	3.97	0.078	0.764	0.000	3rd	31st	5.005	0.415	0.196	GDA
PM3	Governing and automating contracts and operations agreement	4.08	0.079	0.767	0.524**	2nd	28th	3.04	0.694	0.193	GDA
J	**Energy and Environmental management**	**4.27**									
EE1	Supply trustworthy environmental data	4.39	0.072	0.704	1.000**	1st	4th	3.864	0.569	0.195	GDA
EE2	automatically monitor the level of project pollutant emissions	4.20	0.063	0.612	0.000	4th	18th	11.215	0.047*	0.166	GDA
EE3	Enhance sustainability promotion	4.29	0.082	0.797	0.500**	2nd	9th	23.249	0.000*	0.145	GDA
EE4	Energy trading and/or transfer	4.21	0.079	0.770	0.056	3rd	17th	10.325	0.067	0.185	GDA
	N	97									
	Kendall's W[a]	0.04									
	Calculated Chi-Square (X^2) value	115.59									
	Critical Chi-Square (X^2) value from Table	43.773									
	df	30									
	Asymp. Sig.	0.000									

* p-value < 0.05; SD= Standard deviation.
** NV=Normalisation value is critical; CR=Component rank; OR= Overall rank, X2 = Chi-Square, GDA = Good degree of agreement.

items have p-values≥0.05. A significant statistical difference was observed in 4(12.9 %) of the assessed variables. Overall, the results in Table 4 indicate convergence and non-significant statistical differences in the study across the experts. This shows a high level of agreement among the study participants regarding the potential application areas and benefits of BSC applications in PPP projects. The Kendall's W is another valuable tool for assessing agreements among respondents. This test was conducted to confirm the outcome of the overall Kruskal-Wallis test. With a critical chi-square (X^2) of 43.773, which is less than the calculated chi-square (X^2) of 115.591, it was concluded that there is a strong agreement among the raters of the variables and a consensus on the significance and potential benefits of blockchain and smart contract application in PPP projects delivery. Using the chi-square values from Kendall's test to explain and interpret agreement and relatedness in rating observed variables is common [122].

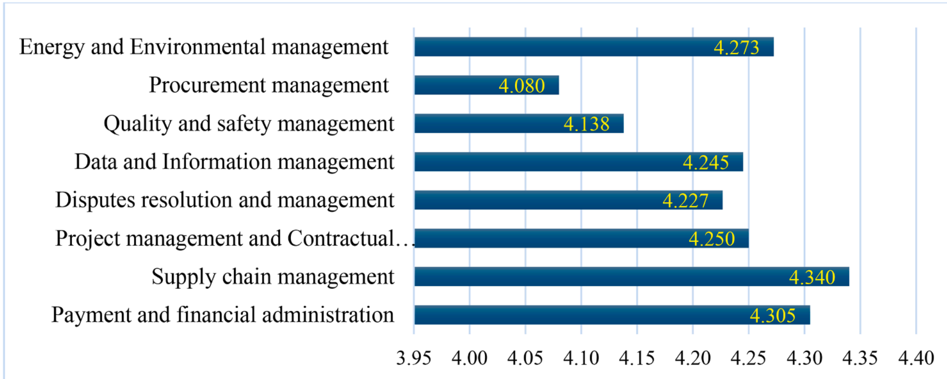

Fig. 3. Blockchain potential application areas in PPP.

Table 4
Overall Kruskal-Wallis H test for respondents' agreement.

Variables evaluated	Continental distribution	N	Mean Rank	K-W	df	P-value
Potential application areas and benefits of BSC application in PPP projects	Africa	9	33.06	5.067	5	0.408
	Asia	12	40.58			
	Europe	36	51.65			
	North America	12	51.79			
	Oceania	9	51.39			
	Global	19	53.95			
	Total	**97**				

6.5. *PLS-SEM of the application areas and benefits of blockchain-enabled smart contracts adoption in PPP projects*

The evaluation of the model is a two-stage process: the first is for measurement models, and the other is for structural models.

6.5.1. *Measurement models*

The measurements model is the most important test and a key component of the SEM. This is because it helps to establish the underlying relationship between the measured (observed) items and the latent (unobserved) constructs. Convergent and discriminant validity are central to determining the validity of the measurement model [123]. Convergent validity is a key measure for model measurement validation in SEM, and it measures the convergence of the latent constructs by assessing the different items (indicators) [124]. An indication that the multiple variables (indicators) capture a similar core concept is

Table 5
Summary of internal consistency and convergent validity.

Construct	Item code	Initial iteration				Final iteration				
		Loading	α	ρC	AVE	Loading	α	ρC	AVE	VIF
Payment and financial administration		0.827	0.824	0.884	0.655		0.824	0.883	0.654	1.832
	PF1					0.816				
	PF2	0.794				0.809				1.652
	PF3	0.843				0.845				1.676
	PF4	0.771				0.764				1.596
Supply chain management	SC1	0.819	0.723	0.842	0.640	0.801	0.723	0.842	0.640	1.445
	SC2	0.743				0.748				1.408
	SC3	0.836				0.848				1.697
Project management and Contractual administration	PC1	0.777	0.819	0.873	0.581	0.763	0.819	0.873	0.579	1.712
	PC2	0.719				0.717				1.574
	PC3	0.824				0.821				1.974
	PC4	0.737				0.730				1.594
	PC5	0.748				0.770				1.667
Dispute resolution and management	DR1	0.789	0.589	0.783	0.550	0.832	0.594	0.831	0.711	1.217
	DR2	0.617				–				–
	DR3	0.805				0.854				1.217
Data and Information management	DM1	0.810	0.797	0.868	0.623	0.800	0.779	0.872	0.694	1.556
	DM2	0.829				0.884				1.979
	DM3	0.729				–				–
	DM4	0.784				0.813				1.582
Quality and safety management	QS1	0.707	0.782	0.852	0.538	0.713	0.789	0.861	0.609	1.695
	QS2	0.755				0.758				1.708
	QS3	0.798				0.828				2.277
	QS4	0.614				–				–
	QS5	0.778				0.818				1.739
Procurement management	PM1	0.838	0.740	0.853	0.660	0.831	0.74	0.853	0.66	1.616
	PM2	0.851				0.856				1.732
	PM3	0.744				0.746				1.308
Energy and Environmental management	EE1	0.477	0.652	0.791	0.495	–	0.684	0.825	0.612	–
	EE2	0.788				0.808				1.323
	EE3	0.757				0.772				1.305
	EE4	0.747				0.766				1.371

indicated when a high convergent validity is obtained. The convergent validity uses the result of (1) indicator reliability, (2) Cronbach's alpha (α), (3) composite reliability (ρC) and (4) the average variance explained (AVE) for measurement model validation [125].

The indicator reliability was achieved using the indicators' outer loadings (factor loadings) under each construct. The indicators with outer loading of ≥0.70 are considered highly satisfactory [126]. While those with outer loadings of 0.50 are acceptable, variables with <0.50 should be discarded [127,128]. Hulland [124] contends that an outer loading of 0.40 should be acceptable. However, it was suggested by Henseler et al. [129] that items with loadings between 0.40 and 0.70 should be carefully reviewed prior to elimination. If the elimination of the indicator increases composite reliability, then they should be retained. For this study, a 0.70 cut-off was used and guided by suggestions from Henseler et al. [129] on indicator elimination. The initial PLS-SEM algorithm was run, and some items were systematically removed iteratively because they did not meet the cut-off point of 0.7 for items loading. The effects of item removal on the validity and reliability of the model were carefully examined before they were removed. If such deletion does not increase the magnitude of the AVE and other measures, the item will not be removed from the measurement model [124]. Table 5 shows that the factor loadings of the remaining indicators me the cut-off point of ≥ 0.70.

The cut-off points for α, ρC and AVE are 0.70,0.70 and 0.50, respectively [130,124]. Hair et al. [131] state that where the α or ρC is < 0.70, the construct should be considered reliable if the AVE is ≥0.50. The final iteration shows that the α values obtained ranged between 0.594 and 0.878, while the (ρC) values ranged between 0.825 and 0.902. Thus, confirming the internal consistency and reliability of the constructs. The AVE values are well above the threshold of 0.50 for each of the constructs, an indication of meeting acceptable level. Based on this, the convergent validity of the constructs was established. This further showed that the AVE satisfactorily explained over 50 % of the variance observed in the measured items. The 'final iteration' part of Table 5 is the reliability of the measurement model.

The variance inflation factor (VIF) was used to ascertain the indicators' multicollinearity. Kock [132] recommended a VIF value of below 3.3 as the acceptable threshold. Based on the VIF values obtained for the measured items (Table 5) and the constructs (Table 6), the data do not have common method bias, thus, confirming the absence of multicollinearity issues.

The discriminant validity of the measurement model was evaluated using three criteria, and they are (i) Fornell-Larcker criterion, (ii) cross-loadings, and (iii) Heterotrait-monotrait ratio (HTMT) of correlations, were used to assess the discriminant validity of the latent constructs. The discriminant validity confirms how well the instrument effectively measured unique and separate concepts.

Table 6
Summary Convergent reliability evaluation for latent constructs.

Constructs	Cronbach's alpha (α)	Composite reliability (ρC)	AVE	VIF
Payment & Financial Administration	0.824	0.883	0.654	2.017
Supply chain Management	0.723	0.842	0.640	1.963
Project Management & Contract Administration	0.819	0.873	0.579	2.022
Dispute Resolution & Management	0.594	0.831	0.711	2.082
Data & Information Management	0.779	0.872	0.694	2.441
Quality & Safety Management	0.789	0.861	0.609	2.701
Procurement Management	0.74	0.853	0.660	1.744
Energy & Environment Management	0.684	0.825	0.612	1.505

The heterotrait-monotrait (HTMT) ratio of correlations method is the most recent method of examining discriminant validity in SEM [133]. The efficacy of this method lies in the tighter and stricter means of establishing discriminant validity issues. Henseler et al. [134] averred that the performance of the HTMT techniques is better compared to Fornell-Larcker and cross-loading criteria in determining discriminant validity. The HTMT measures the empirical difference between latent variables (LVs) to evaluate discriminant validity [135]. The HTMT values for all the constructs should be below the 0.90 recommended threshold, and based on the results in Table 7, the discriminant validity was established and this followed [134,136].

The Cornell-Larcker criterion is meant to examine the correlations between constructs. It considers and ensures that the square root of AVE for each construct is larger than the corresponding correlation coefficient [137]. Higher AVEs over the correlations imply that the constructs are distinct and do not measure the same fundamental concepts. Thus, further reinforcing the validity of the measurement model. The AVE results in Table 7 align with the Fornell-larker criterion, thus confirming the requirements for discriminant validity.

The cross-loadings criterion holds that indicators' loadings should be higher under their own construct compared to their loadings under other constructs in the study. A critical examination of the cross-loading of the items (Table 8) revealed no cross-loading problems in the measurement items, as they had the highest loading under their own constructs. Thus, there are no discriminant validity issues.

6.5.2. *Structural model*

Having confirmed the measurement model's reliability and convergent validity criteria, sets the base for the structural model assessment. The boostrapping analysis was used to evaluate the structure of the model.

6.5.3. *Path analysis*

Bootstrapping is the most widely used non-parametric approach that utilises a resampling technique to establish the robustness and significance of path coefficients in SEM [138,139]. The bootstrap was executed with 5000 subsamples as advised by [140] and a confidence interval of 95 %. The analysis gave the path coefficient/original sample (β), the sample mean (M), the standard deviation (SD), the T-statistics, the confidence interval (CI) and p-values which were used to determine the significance of the path coefficient. The bootstrapping aids the testing of the research hypotheses. The results in Table 10 and Fig. 4 show that two of the eight relationships defining the study's hypotheses were non-significant. This is based on the p-value, which is greater than 0.05, and the existence of zero between the upper confidence interval (UCI) and the lower confidence interval (LCI). Besides, the T values for these relationships are lower than 1.96, which further supports the non-statistically significant relationship outcome for the hypotheses (H4 & H6). The results also showed that six path relationships are significant roles blockchain-enabled smart contracts could play in Infrastructure PPP project delivery. The p-values are below 0.05 significance level, the T – T-statistics are greater than 1.96, and there is no zero between the UCI and the LCI. Notably, the application of blockchain-enabled smart contracts adoption in infrastructure PPP projects would make the strongest contribution to PPP projects' data and information management (β=0.488; T = 9.718; p-values=0.000). This justifies the critical role of blockchain and smart contracts in managing the mass volume of data and information in a large-scale project procured through the PPP procurement route. Similar statistically significant relationships with blockchain-smart contract application in PPP projects were obtained with regards to payment and financial administration (β=0.249; T = 6.572; p-values=0.000), Supply chain management (β=0.147; T = 4.809; p-values=0.000), project management and contractual administration (β=0.113; T = 4.666; p-values=0.000), Quality and safety management (β=0.179; T = 4.399; p-values=0.000), and energy and

Table 7
Heterotrait-monotrait ratio (HTMT) of correlations & Fornell-Larcker criterion.

	Data & Information Management	Dispute resolution and management	Energy and Environmental management	Payment and financial administration	Procurement management	Project management and Contractual administration	Quality and safety management	Supply chain management
Heterotrait-monotrait ratio (HTMT) of correlations								
Data & Information Management								
Dispute resolution and management	0.879							
Energy and Environmental management	0.633	0.519						
Payment and financial administration	0.717	0.779	0.408					
Procurement management	0.756	0.619	0.614	0.641				
Project management and Contractual administration	0.697	0.797	0.480	0.696	0.558			
Quality and safety management	0.853	0.898	0.672	0.721	0.715	0.736		
Supply chain management	0.654	0.879	0.504	0.684	0.443	0.730	0.706	
Fornell-Larcker criterion								
Data & Information Management	0.833							
Dispute resolution and management	0.596	0.843						
Energy and Environmental management	0.471	0.337	0.782					
Payment and financial administration	0.574	0.539	0.309	0.809				
Procurement management	0.577	0.409	0.443	0.499	0.812			
Project management and Contractual administration	0.563	0.557	0.374	0.574	0.437	0.761		
Quality and safety management	0.688	0.612	0.525	0.597	0.559	0.596	0.781	
Supply chain management	0.508	0.598	0.369	0.542	0.344	0.587	0.545	0.800

environmental management (β=0.056; $T = 2.112$; p-values=0.035).

The confidence values for the 6 statistically significant constructs/relationships indicate that the developed model can provide a good prediction of smart contract adoption in PPP projects. This can also improve the model's generalisability and the study's findings. The non-significant relationships (H4 & H6) do not mean poor model predictability; they could indicate that more implementations could reveal the actual model effects on smart contract adoption in PPP projects.

6.5.4. Model fits indexes

The Coefficient of determination (R^2) measures the contribution of the exogenous variable to the endogenous variable within a model. It is also regarded as 'in-sample predictive capability' and should be interpreted within the context of the study [141,142]. The R^2 value ranges from 0 to 1, and the closer it is to 1, the higher the explanatory power of the independent variables on the dependent variables. The R^2 value of this study is 0.971 (Table 9), and this is well above the threshold of 0.26 [127] and 0.75 [135] for a substantial R^2 value. Within the context of the PPP study, Kukah et al. [121] considered R^2 of ≥ 0.10 as high. Based on these, the R^2 for this study is considered high. This implies that the constructs and their variables have the potential to cause a significantly high (97.1 %) interest in the implementation of smart contracts in PPP projects by the stakeholders. Thus, the model has strong predictive accuracy and model quality [131]. The effect size (f^2) measures the relative contribution of the constructs on R^2. To support the statistical significance of the f^2 values, Cohen [143] categorised f^2 values into; $\geq$0.02=weak, $\geq$0.15-moderate and $\geq$0.35=large. Table 9 showed that the constructs with the smallest (f^2=0.003) and highest (f^2=3.405) impact on R^2 are 'procurement management' and 'data & information management', respectively.

The Q^2 is the model's predictive power. While positive values indicate significant predictive power, negative values indicate the absence of predictive powers [142]. Furthermore, in the PLS-SEM model, Q^2 values for moderate and substantial predictive powers are >0.25 and 0.50, respectively [141]. For this study, the model's predictive power (Q^2) is 0.968, and this is > 0.50 for substantial predictive relevance. Thus, the model's predictive power is very strong. Moreover, the approximate model fit of the hypothesised model revealed that it is acceptable. In addition, the standardised root mean square residual (SRMR) is 0.10, which falls within the acceptable threshold for a good model fit of 0 to 1 [144].

6.5.5. CVPAT (Cross-validated predictive ability test)

The cross-validated predictive ability test (CVPAT) is the most current extension that permits researchers to determine and substantiate the predictive capabilities of the proposed SEM model [145,146], and

Table 8
Cross-loadings.

Variables	Data & Information Management	Dispute resolution and management	Energy and Environmental management	Payment and financial administration	Procurement management	Project management and Contractual administration	Quality and safety management	Supply chain management
DM1	**0.800**	0.564	0.288	0.490	0.439	0.455	0.579	0.428
DM2	**0.884**	0.505	0.433	0.512	0.492	0.493	0.505	0.440
DM4	**0.813**	0.425	0.452	0.433	0.509	0.458	0.641	0.402
DR1	0.479	**0.832**	0.253	0.475	0.360	0.486	0.532	0.510
DR3	0.525	**0.854**	0.314	0.435	0.331	0.455	0.501	0.499
EE2	0.433	0.300	**0.808**	0.280	0.377	0.312	0.432	0.367
EE3	0.371	0.284	**0.772**	0.202	0.308	0.278	0.430	0.246
EE4	0.286	0.197	**0.766**	0.240	0.354	0.287	0.362	0.239
PC1	0.366	0.489	0.294	0.383	0.285	**0.763**	0.529	0.443
PC2	0.389	0.306	0.221	0.471	0.273	**0.717**	0.339	0.429
PC3	0.411	0.406	0.238	0.486	0.454	**0.821**	0.517	0.421
PC4	0.444	0.458	0.165	0.437	0.288	**0.730**	0.383	0.398
PC5	0.507	0.454	0.453	0.412	0.345	**0.770**	0.484	0.524
PF1	0.454	0.520	0.316	**0.816**	0.396	0.406	0.491	0.478
PF2	0.491	0.327	0.282	**0.809**	0.400	0.514	0.471	0.506
PF3	0.445	0.473	0.203	**0.845**	0.451	0.498	0.518	0.472
PF4	0.467	0.440	0.197	**0.764**	0.366	0.426	0.452	0.277
PM1	0.451	0.325	0.420	0.434	**0.831**	0.425	0.546	0.259
PM2	0.569	0.352	0.434	0.340	**0.856**	0.252	0.451	0.276
PM3	0.377	0.320	0.212	0.449	**0.746**	0.393	0.356	0.306
QS1	0.390	0.521	0.230	0.383	0.371	0.479	**0.713**	0.462
QS2	0.587	0.539	0.435	0.601	0.385	0.482	**0.758**	0.438
QS3	0.452	0.452	0.300	0.388	0.411	0.442	**0.828**	0.363
QS5	0.651	0.408	0.589	0.447	0.552	0.459	**0.818**	0.438
SC1	0.410	0.543	0.323	0.424	0.200	0.476	0.516	**0.801**
SC2	0.279	0.276	0.219	0.377	0.167	0.319	0.323	**0.748**
SC3	0.493	0.566	0.329	0.487	0.409	0.571	0.453	**0.848**

Table 10
Summary of path coefficient (bootstrapping analysis) and Significant level.

Hypothetical paths	β	M	SD	T	p-values	CI		Remark
						LCI (2.5 %)	UCI (97.5 %)	
H1 - Payment and financial administration -> SC Role in Infrastructure PPP	0.249	0.245	0.038	6.572	0.000*	0.168	0.317	Supported
H2 - Quality and safety management -> SC Role in Infrastructure PPP	0.179	0.185	0.041	4.399	0.000*	0.109	0.270	Supported
H3 - Supply chain management -> SC Role in Infrastructure PPP	0.147	0.147	0.031	4.809	0.000*	0.087	0.206	Supported
H4 - Disputes resolution and management -> SC Role in Infrastructure PPP	−0.050	−0.04	0.028	1.631	0.103	−0.100	0.014	Not Supported
H5 - Data & Information Management -> SC Role in Infrastructure PPP	0.488	0.492	0.05	9.718	0.000*	0.405	0.607	Supported
H6 - Procurement management -> SC Role in Infrastructure PPP	0.013	0.011	0.027	0.483	0.629	−0.040	0.066	Not Supported
H7 - Energy and Environmental management -> SC Role in Infrastructure PPP	0.056	0.056	0.026	2.112	0.040*	0.005	0.107	Supported
H8 - Project management and Contractual administration -> SC Role in Infrastructure PPP	0.113	0.114	0.024	4.666	0.000*	0.065	0.160	Supported

* p-value (<0.05) =statistically significant; β=path coefficient; *M*= sample mean; SD = Standard deviation; *T* = *t*- statistics; CI=confidence interval.

therefore, it is essential when reporting PLS-SEM results [130]. The CVPAT is critical to test if the researcher's proposed model can perform better than a naïve baseline, which is a principal predictive legitimacy component [147]. The outcome of the PLSpredict [148] and the CVPAT for comparison overall introduced by [145] show that the model meets the evaluation standard. For a model to be predictively valid, the average loss of the model must be significant and lower than the naïve indicator averages. If the model fails this predictive validity criterion, it should be discarded, as submitted by [149]. The model is invalid and should be discarded. Therefore, with an average loss difference of −0.320, $t = 3.163$ and p-value of 0.002, the model is confirmed to have sufficient and higher predictive ability and, thus, validated (Table 11). The use of CVPAT for establishing the predictive validity in this study follows [80,136].

7. Discussion

The study revealed a growing interest in improving the performance of PPP projects using transformative technologies like blockchain and smart contracts [18]. This is evidenced in the results of the level of awareness and knowledge of blockchain-smart contract application in infrastructure PPP projects, which showed a significantly high level of awareness and a good knowledge of the potential benefits of smart contract adoption in PPP projects would have on infrastructure provision and development in the global economy, by the participants. This finding aligns with the high level of awareness and knowledge of digital innovation in the construction industry, which is known to be triggered by the need to improve efficiency, productivity, and safety [103,16,80]

The mean normalisation analysis revealed that the leading benefits of the adoption of blockchain-enabled smart contracts in PPP are Decentralisation of payments and other transactions, enhancing supply chain visibility and integration, autonomy in contract administration, prevent misapplication of contractual provisions, and Enhances alternative dispute resolution (ADR) by providing single source of truth for stakeholder in PPP projects, improve interoperability in data exchange, improve materials and services inspection and specifications compliance checking, improve contractors/subcontractors' selection and Supply trustworthy environmental data. These cut across each investigated

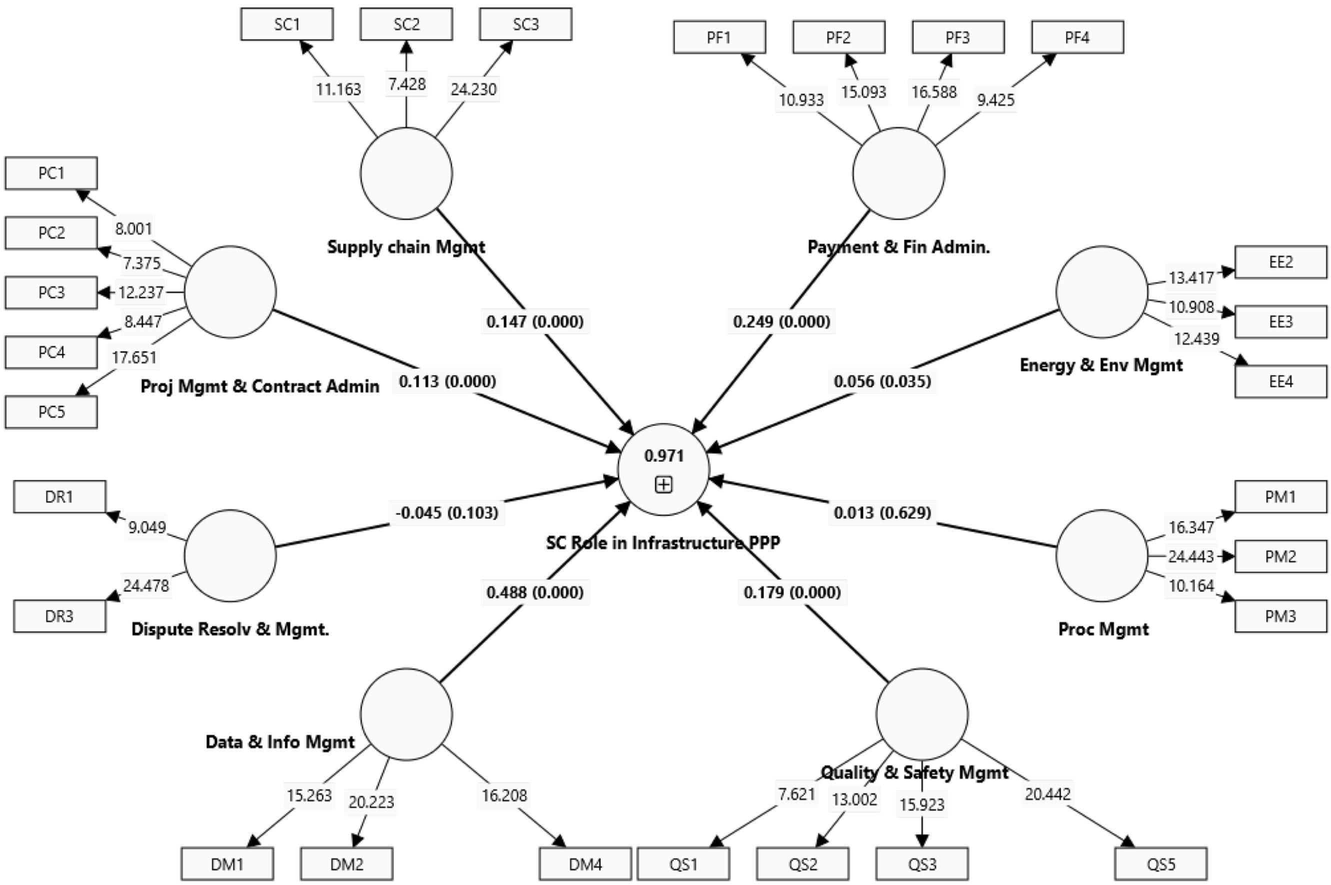

Fig. 4. Bootstrapping showing path coefficient/P-values (inner model) and t-values (outer model).

Table 9
F2 and R2 for (Effect of LV on DV).

Constructs	f^2	f^2 effect size	R^2	R^2 adjusted
Data & Information Management	3.405	Large	0.971	0.968
Dispute resolution and management	0.034	low		
Energy and Environmental management	0.072	low		
Payment and financial administration	1.073	Large		
Procurement management	0.003	low		
Project management and Contractual administration	0.221	medium		
Quality and safety management	0.415	Large		
Supply chain management	0.385	Large		

Table 11
Cross-Validated Predictive Ability Test (CVPAT).

	PLS loss	Indicator average (IA) loss	Average loss difference	t-value	p-value
SC Role in Infrastructure PPP	0.344	0.664	−0.320	3.163	0.002
Overall	0.344	0.664	−0.320	3.163	0.002

application area of smart contracts in PPP projects. This implies that the contractual issues that make it difficult for payment from the end-users or government to be automated are eliminated with smart contracts, and this is what construction management researchers have advocated in the construction industry [21,23,25]. Blockchain-smart contracts automate payments and other transactions once the target level of services rendered or product quality meets the contractual provisions prescribed [74]. The private sector is guaranteed to recoup its investments in PPP, and the public sector is confident that the people will feel the governance dividend, which will bring little or no opposition from the public. This is because payment and financial administration problems are persistent issues in the traditional, paper-based contracting system, which lead to costly time wastes because of the centralised nature of the system [25]. Therefore, 'payment and financial administration' is the leading and significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects**.** The participants acknowledged this view as (H1) was supported.

Managing the complex networks of activities and stakeholders involved in delivering mega projects undertaken under the PPP arrangement is challenging. This is because maintaining a smooth and conflict-free relationship for the entire contractual duration of PPP projects is impossible because of the high potential of fraud and transparency issues occasioned by the lack of accountability and poor data records in the centralised, traditional system [38]. One benefit of adopting blockchain-smart contracts in PPP projects is improving supply chain visibility and integration. Transparency and accountability in the supply chain of such complex projects delivered through PPP arrangements are critical to successfully delivering partnership projects. A smart contract allows for information sharing and traceability, and project schedules are controlled in real-time [40,42]. Cash and product flows can be integrated into a supply chain network using a blockchain-smart contract system [39], aiding transparency and accountability. Supply Chain Management is among the leading and significant application areas of blockchain-enabled smart contracts adoption in infrastructure PPP projects. This is supported by the participant's views, as evident in the bootstrapping analysis result for the hypothetical path (H3). This could also be why studies on blockchain and smart contract adoption in supply chain management are among the leading focus areas of construction management researchers.

Blockchain-enabled smart contracts allow for autonomy in contract administration and prevent misapplication of contractual provisions. These benefits are among the leading contributions of this technology to ensuring effective project management and contractual administration [34]. These benefits of Smart contracts are possible due to the immutability, security, transparency, and traceability the technology brings to project management and administration [53,45]. Blockchain adoption bolsters efficiency in communication and decision-making for healthy management and administration of projects. PPP projects involve huge capital, many stakeholders, and many subcontracts, which require proper coordination and collaboration to manage. Blockchain-smart contract adoption can permit the effective management and administration of these complex networks of stakeholders and the volume of transactions and data generated. The digitalisation of PPP projects using smart contracts can mitigate the high failure rates and performance issues of PPP projects and bring about efficiency and progress in infrastructure provision by governments. This is supported by the significant relationship obtained for hypothesis (H8).

Data and information capturing, storage, process and sharing efficiency are central to ensuring the successful realisation of PPP projects. The integrity and credibility of information and data shared between the public and private sector partners are key to maintaining healthy long-term relationships in PPP. Data accuracy, transparency and reliability among collaborating teams help improve project information and communications management [55,31]. blockchain and smart contract adoption improve collaboration and information sharing, foster integration and interoperating in data transfer, and these help to reduce fragmentation in project and stakeholder management [51,42]. This study showed that Data and Information management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects (H5), and this corroborates the submission of [57,18].

Quality and safety are among the two leading parameters for adjudging a project successful. The construction industry is known for poor quality and safety performances, and this is because of the dominance of the outdated, traditional paper-based project delivery approach, among other issues. Most quality and safety issues emanate from materials, labour, and failure to comply with specifications and guidelines. This study found that a leading benefit of blockchain-smart contract adoption in PPP projects is improved materials and services inspection and specifications compliance checking. This is because of how critical materials, supervision and adherence to project specifications are to project quality and safety management. This finding supports the report of [30] [33] [36]. Blockchain and smart contracts are integrated into smart PPP projects to strengthen quality and safety performance for improved project management. Therefore, 'quality and Safety management' is one of the significant application areas of blockchain-enabled smart contracts adoption in infrastructure PPP projects (H2).

Because of their magnitude and complexities, long-term infrastructure PPP projects generate enormous amounts of waste and pollution and consume a large amount of energy that is detrimental to humans, plants, animals, and the environment. This study found that smart contracts supply trustworthy environmental data that the government and its agencies can utilise to monitor and control the activities of the private sector parties regarding the level of waste and dangerous emissions released to the environment from a project [56]. Blockchain also produces trusted and reliable data on the energy consumption level [66] and accurate records of surplus energy to enable companies to make decisions regarding energy trading and distribution (Wongthongtham et al. [67]. The findings also support the hypothesis that energy and environmental management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects (H7). Blockchain-enabled smart contracts adoption has the potential to significantly support efforts at minimising the environmental, social, and economic impacts of extensive infrastructure PPP projects, thus supporting sustainable development and societal growth.

This study revealed that Smart contracts provide a single source of truth for PPP project stakeholders, which helps to enhance alternatives despite resolution and management. This is in line with the submissions of [44,45]. This transformative technology plays a critical role in eliminating or minimising waste of time and cost associated with unverifiable claims, especially in infrastructure projects with complex activity networks and too many stakeholders. Blockchain provides immutable records of claims events, which can be traced to the responsible party, and thus, issues are resolved speedily before they develope into disputes [46,40]. Even though studies have reported a positive association between blockchain adoption and dispute resolution and management [48,49], this study found a non-statistically significant relationship in the role of blockchain-smart contract application in dispute resolution and management in PPP projects (i.e., H4 is unsupported). This could be because of the maturity level of blockchain technology and the adoption level, which is still in its infancy. Furthermore, the number of studies that have explored blockchain's potential for dispute resolution and management in the construction industry is still limited.

Regarding the procurement management application area, the blockchain-smart contract can potentially mitigate unethical practices in selecting and procuring contractors/subcontractors [60]. Bid shopping and bid peddling are unethical but not illegal, and they are common in contractors' selection [58]. These practices negatively impact project quality, time, cost, and safety performances. This study revealed that blockchain adoption in PPP projects has a leading benefit in improving contractors'/subcontractors' selection. This is in line with the findings of ([59]; and [63]). However, hypothesis H6, which states that Procurement management is a significant application area of blockchain-enabled smart contracts adoption in infrastructure PPP projects, was not supported. Aside from the maturity level of the technology, the number of studies on blockchain adoption for procurement management is limited.

8. Framework of the impacts of BSC adoption on PPP projects

Previous literature highlighted the high encryption and secured platform, contracts compliance automation and enforcement, tamper-proof and immutability of platforms, consensus algorithm, and decentralised and reliable attributes of the blockchain-enabled smart contracts (BSC) as the leading points of attraction to their adoption in PPP projects [15,18,84–86].

These characteristics of the blockchain-smart contract are essential in driving their functionalities and applications in PPP projects. Furthermore, stakeholders' knowledge of the potential benefits and application areas of BSC in infrastructure project delivery could trigger higher interest in their adoption and implementation in PPP projects.

Drawing from literature evidence and the results of this study, Fig. 5 was developed. It indicates the important and unique characteristics of BSC that make it suitable for mitigating the problems of the traditional, paper-based PPP approach. These characteristics are evident in the various application areas and associated benefits, as well as the overall impacts on PPP projects, society, and the environment.

9. Implications of the study

9.1. Theoretical implications

This study adopted known approaches within the context of PPP. Even though the questionnaire is not new, this study offers a fresh perception of the potential of blockchain and smart contracts in improving PPP projects. The data gathered from surveys, and the series of analyses provide vital and measurable support for the idea that smart

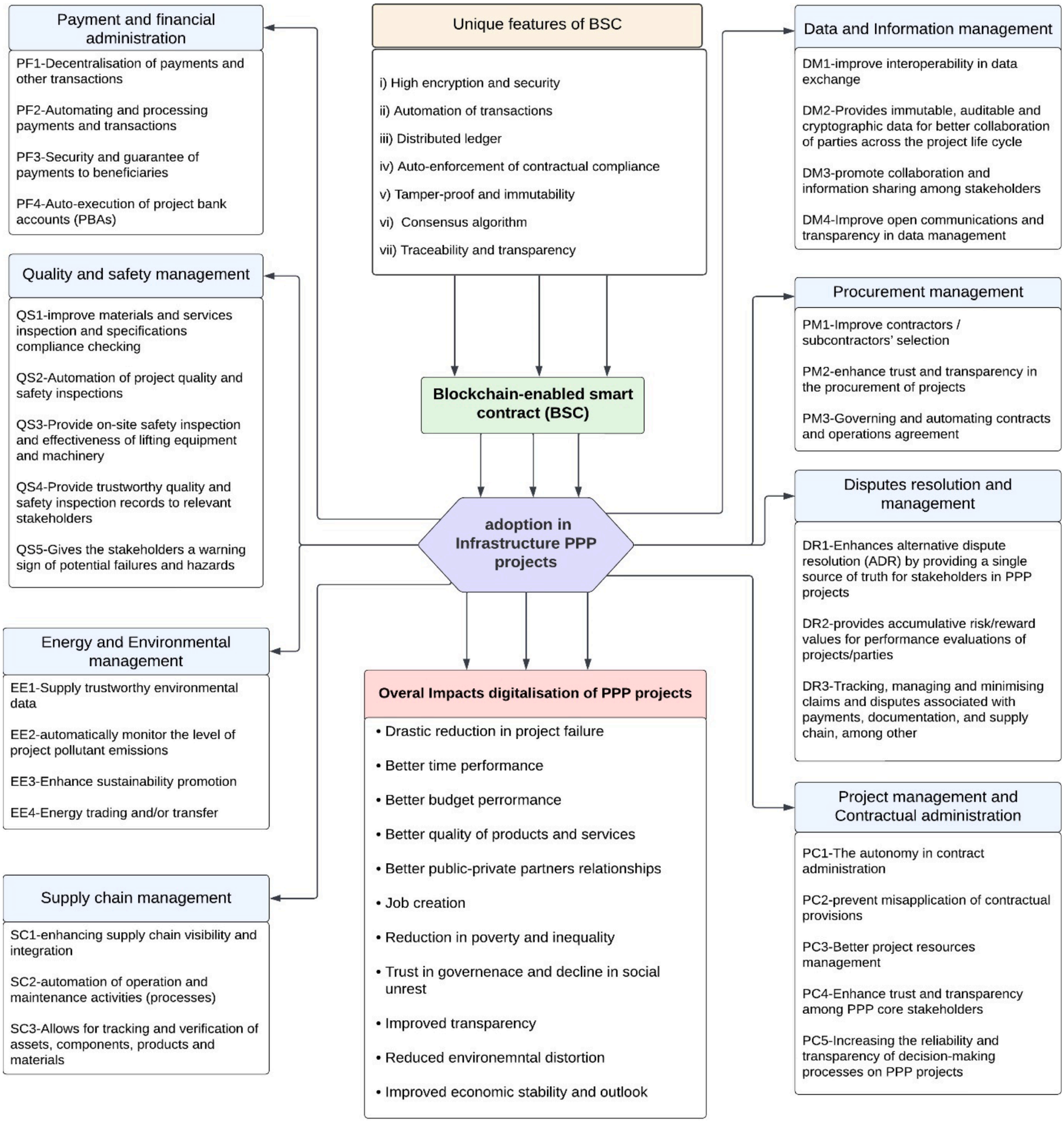

Fig. 5. Framework of the impacts of BSC adoption in PPP projects.

contracts can influence better PPP project management. Theoretically, this study adds to the growing pool of knowledge by using proven techniques and methodology to showcase the diverse potentials and benefits of the transformative impact of blockchain technology and smart contracts in the built environment, particularly in managing and administering capital-intensive projects. Blockchain application in PPP is novel, and it is beginning to get the attention of researchers and academics. Thus, this study provides a further background for future, related studies.

9.2. Practical implications

This study has valuable implications for the private and public sector partners in PPP projects and the public for which the projects are intended. For the private sector party (contractors, professionals, and other stakeholders), the study's outcome could motivate the adoption of blockchain-smart contracts in the implementation of PPP contracts, as it will help consolidate production of efficiencies in the delivery projects of a long-term nature. This will impact the level of trust and confidence reposed on their competence by the public sector and the public. This is because these transformative innovation technologies would help mitigate issues related to payment and the administration of finances associated with supply chain, data and information, quality and safety, and energy and environmental protection and management. Even though application areas such as "dispute resolution and management" and "procurement management" showed a non-significant relationship with smart contract adoption in PPP, with time and as the technology matures, increased claims and disputable events and issues with procurement would be mitigated. Thus, stronger private-public partnership relationships are needed for better and more sustainable project performance.

First, the key issues surrounding information asymmetry, trust, and transparency in dealing with the private sector partner whose focus is profit, are eliminated for the public sector. This is because information upon which decisions to negotiate or re-negotiate would be available unaltered. This puts the public sector agency in a knowledge position to engage with the private sector experts. In addition, the actual level of services rendered and/or quality of products will be known from the inputs of the public, who will also be represented in blockchain networks. Thus, the government knows precisely what to pay for, especially in the 'government pay' PPP arrangement. Secondly, there will be fewer disputes because of the level of transparency and the high level of traceability and auditability of performance and records. A healthy relationship with the private sector partner means less waste of public funds and the availability of scarce resources for investment in other critical sectors of the nation's economy.

The public is carried along as they can see and access undiluted data and information. This will mean fewer protests and opposition against government leaders and the disruption of the projects. Thus, the government can focus on and continue to deliver on its promises of national building and progress. Another practical implication to the public is that payments for services rendered are matched with the level of services rendered or the quality of the products offered, which is particularly important in the 'user pay' PPP arrangement.

Finally, the parties to PPP projects should take these practical steps before deciding to adopt blockchain-enabled smart contracts in PPPs. The steps are undertaking a thorough assessment of the cost-benefits of the technology investment, proper planning of technology implementation considering long-term implications, then acquisition of the technology and management.

9.3. *Market implications*

This study can open new opportunities in the construction industry because the benefits and importance of innovative technologies open a new window of opportunity and market for broader public participation. Innovative technology diffusion can be guaranteed when their benefits and capabilities are known. More stakeholders will be interested in adopting such technology because they know its usefulness. Blockchain and smart contracts are novel and critical drivers of innovation and sustainability. Since the sustainability market of the built environment is still largely under-tapped and unsaturated, this study can trigger the creation of a new market or expand the existing one on blockchain and other digital technology adoption for the sustainability of the construction industry. Further, the study will serve as valuable material to the advocates and enthusiasts of blockchain technology, especially blockchain architects and smart contract designers, contract managers, project managers and legal experts interested in offering their professional services to PPP project parties and construction clients.

10. Conclusion

This study assessed the potential application areas and benefits of blockchain-enabled smart contract adoption in long-term infrastructure PPP projects. Using the snowball sampling technique, a well-structured questionnaire was adopted to gather relevant data from international, qualified experts. Following a series of descriptive and inferential statistical tests carried out on the gathered data, critical findings were made, upon which this conclusion is based.

The study concludes that PPP stakeholders have a significantly high level of awareness and knowledge regarding the potential benefits of smart contract adoption in infrastructure PPP projects. It was also found that blockchain-enabled smart contract adoption in PPP projects has the potential to significantly transform and lead to sustainable performance of long-term PPP projects. The various agreement analyses echoed this carried out on the gathered data. Mean normalisation revealed that the leading benefits of the adoption of blockchain-enabled smart contracts in PPP are (1) Decentralisation of payments and other transactions, (2) enhancing supply chain visibility and integration, (3)the autonomy in contract administration, (4) prevent misapplication of contractual provisions, (5) Enhances alternative dispute resolution (ADR) by providing a single source of truth for stakeholder in PPP projects, (6) improve interoperability in data exchange, (7) improve materials and services inspection and specifications compliance checking, (8) improve contractors/subcontractors' selection and (9) Supply trustworthy environmental data.

Findings from the PLS-SEM showed that data and information management, payment and financial administration, Supply chain management, project management and contractual administration, Quality and safety management, and energy and environmental management were the significant application areas of blockchain-enabled smart contracts in infrastructure PPP projects. PPP projects are usually long-term, and lots of data and information are generated in each project life cycle. Blockchain-enabled smart contract adoption will ensure that the records of all transactions are kept, can be traced, and these records are immutable, thus making them reliable and acceptable. In a complex multi-party relationship network obtained in PPP projects, deploying smart contracts can build trust and transparency and maintain good working relationships throughout the project's lifecycle. Such a good working relationship impacts better project performance and avoidance of failures and terminations. The public and the private sector parties should take advantage of this transformative technology to ensure the continuous delivery of government dividends to citizens and sustainable infrastructure provisions.

The performance of PPP projects on other investigated potential application areas of smart contract in PPP, such as payment and financial administration, Supply chain management, project management and contractual administration, Quality and safety management, Energy and environmental management, Procurement management, and Disputes resolution and management; are dependent on accuracy and reliability of data and information. It follows the information and data attributes of the blockchain technology anchor that integration and management of PPP projects and stakeholders. PPP stakeholders should take advantage of the multi-faceted application of blockchain technology and adopt it in the delivery of infrastructure projects to guarantee better payments and financial management, safeguard project supply chain management, and enhance project management and contractual administration. Improve PPP project's quality and safety performance records, improve contracts procurement and dispute management, and manage the energy consumption and environmental impact of PPP projects.

Limitations and future research direction

While this study draws from the views of international participants, it still has some limitations that should guide the generalisation of the findings. First, although reliable results were obtained, the small sample size is a limitation. The blockchain-smart contract is still at the embryonic stage regarding technology maturity and adoption in the building and infrastructure sector, so getting a large pool of experts with experience in adoption in PPP projects was difficult. However, the small sample size was able to provide vital and dependable results. Secondly, the analysis did not consider the different sectors of infrastructure PPP projects (e.g., education, transportation, electricity). This followed previous comparable studies and, thus, calls for future studies to consider sector-specific differences. Thirdly, the study leveraged international experts from the construction industry, multilateral organisations, and the information and communication technology sector. The results obtained herein might vary if country-specific studies are embarked upon due to differences in culture, social, political, and legal environments. Fourthly, this study focused on only eight potential application areas of blockchain and smart contracts in PPP projects; this gives room for future studies to consider other application areas and benefits of this technology, particularly as they impact the performance of large-scale infrastructure project delivery. Fifth, even though measures were taken to limit experts' response bias, it could have impacted the outcome of this study, as the study is limited to the participants' knowledge and experiences and whatever bias is held by the expert participants. Therefore, complex decision multi-decision-making techniques, such as AHP (Analytic Hierarchical Process) and ANP (Analytic Network Process), should be used in future studies. Finally, the data collection approach utilised, which is cross-sectional at a single point in time, means that a longitudinal approach could be utilised in future studies. Furthermore, other analytical methods, such as Copula Bayesian Networks, could be adopted to augment PLS-SEM results. The use of a longitudinal approach could increase the sample size and the direction of the relationship obtained on hypothetical paths (H4) and (H6).

CRediT authorship contribution statement

Emmanuel Chidiebere Eze: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ernest Effah Ameyaw:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that there is no conflict of interest in this study.

Acknowledgement

This work is part of an ongoing PhD studentship under RDF at Northumbria University, Newcastle, UK.

Data availability

Data will be made available on request.

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