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Analyzing critical success factors using blockchain based framework for intelligent transportation systems

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This study examines the incorporation of blockchain technology into Saudi Arabia's Intelligent Transportation Systems (ITS), concentrating on enhancing the bus permission procedure for religious mass gatherings in Makkah. The research illustrates how blockchain might improve the security and operational effectiveness of transportation management for major events. The research used a weighted significance methodology and Decision-Making Trial and Evaluation Laboratory (DEMATEL) analysis to identify the critical success factors (CSFs) influencing transportation at religious events. The research illustrates the strong interrelation of the CSFs, emphasizing the notable enhancement in transparency and efficiency in the approval and management processes using blockchain-based solutions. The research examines the impact of reformulated CSFs on the proposed blockchain-based transportation framework (BTF), emphasizing key domains such as people (P_1), technology (P_2), the environment (P_3), and organization (P_4). The findings indicate that blockchain-related CSFs exhibit the greatest influence, which is 21.62, while financial CSFs demonstrate the least influence of 0.25. This research significantly addresses current system limitations and stimulates wider blockchain usage inside Intelligent Transportation Systems by developing a thorough mathematical model. This paper presents a strategy framework for the successful management of large-scale transportation difficulties with blockchain technology, assuring optimum operations in organizational and environmental contexts.

KEYWORDS

blockchain technology, CSFs, mass event transportation, decentralized authority, security in transportation

1 Introduction

Large religious mass gatherings, such as those in Saudi Arabia, where millions of people converge quickly, demand efficient transportation management for their success. However, huge events face complex logistical challenges requiring efficient crowd movement. The current traffic management systems in Saudi Arabia must be improved to mitigate these

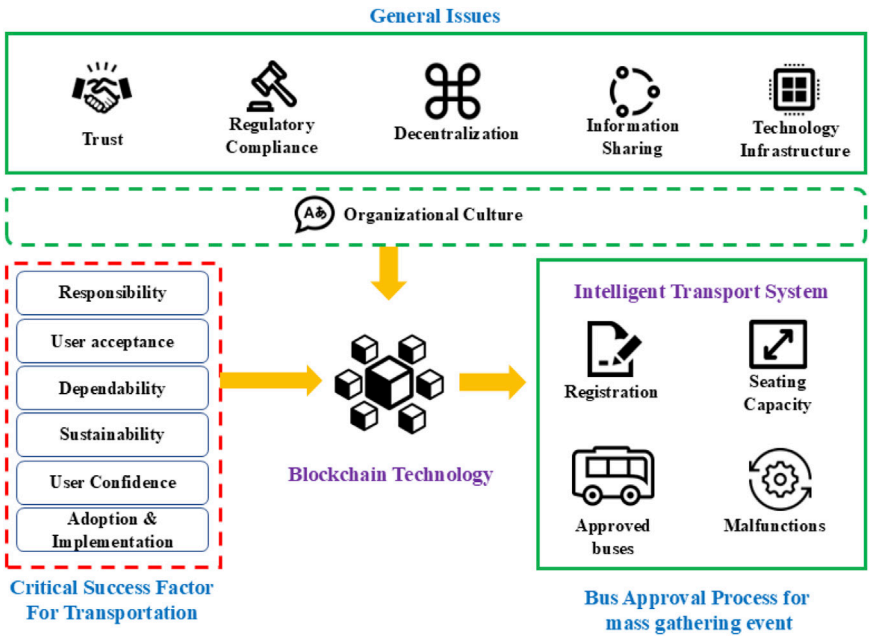

FIGURE 1
Implementing Blockchain Technology in Transportation management for major religious event approval critical success factors.

challenges, providing persistent bottlenecks, congestion control, and delay avoidance (Hassija et al., 2021). The congestion slows down the traffic flow and prevents access to emergency routes (Fernandez-Carames and Fraga-Lamas, 2018).

In addition, bus transportation must be efficient in order to move large numbers of passengers between ritual places. However, the registration, inspection, and validation processes in the bus approval process (BAP) continue to operate with limited automation. As a result, inefficiencies and unapproved practices negatively influence trust between service providers and regulatory authorities (Taherdoost, 2022). The researchers provide various solutions, such as emerging technologies, including blockchain, artificial intelligence (AI), and the Internet of Things (IoT) (Khanzada and Shah, 2016). However, they need drastic improvements to counter the available confronts for existing traffic systems (Oladimeji et al., 2023). Even more so, infrastructural limitations bound the effective management of religious mass gatherings (Badshah et al., 2024).

This research proposes a blockchain-enabled framework to improve scalability, security, and transparency in transportation management during religious mass gatherings, specifically addressing the annual event of Hajj. More specifically, it aims to investigate the bus approval processes unique to Hajj, which require a specialized regulatory framework encompassing stringent safety, timing, and logistical requirements due to the high-density conditions of the pilgrimage. Unlike general bus approvals, these processes involve complex oversight to meet the large-scale transport demands specific to Hajj. By examining the role of blockchain technology in optimizing transportation management for such large-scale religious gatherings, this study addresses a critical gap in the literature. It provides a framework to tackle congestion, security, and scalability challenges, ensuring its applicability for both current and future needs like increased scalability, enhanced real-time monitoring and adaptability to emerging technologies.

1.1 Motivations

The objectives of this study are to identify critical factors for successfully implementing a blockchain-based transportation system for major religious events, which involve numerous attendees and complex organizational needs to ensure smooth and efficient operation. The blockchain's secure, transparent, and decentralized features are leveraged to coordinate services and enhance service quality. In this framework, the features of blockchain such as decentralized and security have been explored and investigated to provide improve service quality.

These religious mass gatherings rely on transportation management, and integrating proposed blockchain technology for the BAP is critical, as shown in Figure 1. User confidence is increased by regulatory compliance, which implies that the blockchain-based transportation system satisfies safety and legal requirements. Blockchain operations require a robust IT infrastructure to be dependable and efficient, adoption and engagement are driven by increasing user acceptance. These components work together to create an organizational culture that encourages all users and helps the transportation system for major religious events run smoothly.

By incorporating blockchain into the bus approval system, passenger experience will be enhanced, and it will also enable government authorities to ensure that transport operators adhere to compliance and regulations (Khanzada et al., 2023). The entire

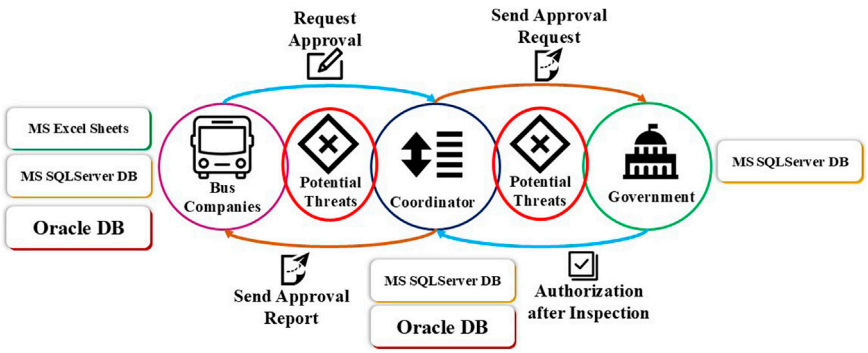

FIGURE 2
Current Bus Approval Process (Khanzada et al., 2023).

framework operates autonomously, with each entity connected in a decentralized manner, improving the efficiency of transportation management during religious events.

1.2 Problem statement for bus approval system (BAS)

The Bus Approval System (BAS) for large religious mass gathering in Saudi Arabia is challenged by critical problems with data security, stakeholder trust, inefficient approval process, strict time deadlines, and security vulnerabilities (Taherdoost, 2022; Zheng et al., 2021; Rabbani et al., 2024). To resolve these problems, blockchain integration is necessary to improve its scalability, security, and transparency.

The current BAS implies several entities, which comprises bus companies, governmental institutions, and the coordinator, all operating in an environment filled with threats like competition, non-compliance, less trust and lack of information. There are several security risks associated with the exchange of bus data between three different stakeholders, each utilized a separate database management system as shown in Figure 2. This fragmentation can cause an increase in the time taken in the approval process, leading towards costly and time-consuming problems in the approval process. This work aims to identify and evaluate CSFs, to establish the relations between these stakeholders, and to rectify and mitigate the challenges that hinder a systematic bus approval process, ensuring conformity to legal provisions.

The high traffic of participants is another transport management consideration in the current BAS. Delays, overcrowding, and a lack of accountability are the challenges to effective management due to inadequate structures and systems (Wahab et al., 2018). Integrating blockchain technology will mitigate these challenges by improving the level of transparency, accuracy of data input and process efficiently managing the expectations of stakeholders in order to solve needs is crucial while seeking to build trust with various stakeholders (Farrukh et al., 2022). The work in Nasser et al. (2019), presented that through improving data precision and speeding up decision-making, CSFs based blockchain integration to BAS can facilitate the transportation administration for this mass gathering event.

1.3 Contributions to the research work

The following are the contributions of the proposed work carried out within the current research;

i. Complexity Analysis: Analyze and examine the existing bus approval system used during religious events and demonstrated how blockchain technology can improve it.
ii. Mathematical Model: To support the current proposal about the implementation of blockchain and to clarify its work, the mathematical description is developed.
iii. Transportation Framework Methodology: A new bus approval framework is proposed and intended to deal with existing problems in the existing transportation system.
iv. Systematic Strengthening: Developed a plan of action to implement CSFs designed to improve the efficacy of transportation control system.

These contributions altogether will help in improving the approach of integration and management of transportation systems during religious occasions by using blockchain solutions.

2 Literature review

The following review explores blockchain technology as a transforming industry by exploring its use in improving BAS.

2.1 Blockchain technology

Table 1 summarizes existing research on blockchain applications in different areas. Each study makes unique contributions and employs unique methodologies (Basahel et al., 2021). studied the management of mass events and focus on the role of digital solutions, yet their analysis needs to be more balanced towards some technologies, leaving the bigger picture unexplored. As (Mandourah and Yamin, 2022) confirm, this point is similar to an examination of efficient technology management technologies, there is a limitation in the diversity of the technological view. Additionally (Binsawad and Albahar, 2022), and (Owaidah et al.,

TABLE 1 Existing works on Blockchain Technology.

Ref.	Services	Contributions	Methodology	Limitations
Basahel et al. (2021), Mandourah and Yamin (2022)	Mass events and gatherings	Analyzes technologies for efficient management, emphasizing digital solutions	AI, Blockchain	Bias towards specific technologies need for more diverse perspectives
Binsawad and Albahar (2022), Owaidah et al. (2023)	Attendees of large events	Examines digitalization's role in enhancing experience and safety	Digitalization, Stratification, Blockchain	Facility challenges in Makkah still need to be fully addressed
Aina et al. (2023), Jabbar et al. (2022)	Transportation systems for mass events	Uses simulation to study transportation efficiency	ExtendSim, Transport Modules	Simplifications in simulation may not fully capture real-world variables
Farshidi et al. (2020), Ćirić et al. (2019)	Comparative Study of Blockchain	Explores Blockchain's application in transport management	Blockchain, Transport Management	Limits due to model study assumptions and practical applications
Bijalwan et al. (2024)	Blockchain in event management	Discusses Blockchain's potential in improving logistics and security	Blockchain technology	Limitations in Blockchain adoption in specific contexts
Our Paper (BTF)	Transportation for religious mass gathering	It focuses on enhancing transportation and introducing novel success factors	Qualitative and quantitative methods	Acknowledges the need for further field advancements and real-world applications

TABLE 2 Existing work on CSFs.

Ref.	Services	Contributions	Methodology	Limitations
Basahel et al. (2021), Bugami (2022)	Large religious events traffic	Addresses traffic congestion using AI and communication technology	AI, ML, CSFs	Real-time data simulation and the intricacies of Hajj pose challenges
Binsawad and Albahar (2022), Bugami (2022)	Transportation System	Focuses on knowledge gaps related to CSFs in Blockchain-based (ITS)	CSFs, Blockchain technology	Need for additional research on CSFs, potential implementation issues
Aina et al. (2023)	Saudi Arabia's Sustainability	Provides a comprehensive overview of Saudi Arabia's sustainable development	Blockchain technology, IoT, ML, Digital Infrastructure	Complexity of sustainable development, technology adoption challenges
Kayikci et al. (2022)	Supply Chain	Pinpoints CSFs for Blockchain-based circular supply chains (CSCs)	CSFs, Blockchain technology, FCM-FBWM	Nascent stage of Blockchain adoption in the supply chain, lack of real-world examples
Kouhizadeh et al. (2021)	Intelligent Transportation	Studies the role of AI and Blockchain in enhancing long-term travel experiences in the MENA region	IMRAD, Hall's frameworks, PRISMA guidelines	AI and Blockchain can significantly improve cultural and environmental sustainability
Kayikci et al. (2022)	Saudi Arabia's Sustainability	Provides a comprehensive overview of Saudi Arabia's sustainable development	Blockchain technology, IoT, ML, Digital Infrastructure	Complexity of sustainable development, technology adoption challenges
Our Paper (BTF)	Large religious events transportation	Introduces innovative solutions using Blockchain	Blockchain Technology, CSFs	Simulating real-time data and handling transportation complexities pose challenges; integrating AI methods might introduce additional hurdles

2023) are both interested in digitalizing the attendee experience at large events, but neither one of them properly addresses the logistical problems that exist in certain environments, Similar to (Bijalwan et al., 2024), this limitation is mentioned in Agi (2022), discussing the use of blockchain for enhancing logistics and security in event management while highlighting the barriers to adoption in some settings.

Moreover (Aina et al., 2023), and (Jabbar et al., 2022) also simulate transportation efficiency in mass events transportations. But both studies admit the simplifications that support their findings, which are not sufficient to address real-world complexities. Furthermore, the model studies of Farshidi et al. (2020) are limited by the assumptions contained within their model study, it is needed to deploy the Blockchain system based on the CSFs in order to enhance the efficiency of the legacy systems. The current research in this study concentrates familiarizing new success factors with the combination of qualitative and quantitative methods.

2.2 CSFs for Implementing Blockchain Technology

CSFs across various services, particularly for transportation systems have been exploited by various researchers to address blockchain based solutions highlighting sustainability efforts. Various methodologies from artificial intelligence (AI), machine learning (ML), and blockchain technology are highlighted in recurrent studies, which tackle raised challenges inside large-scale transportation operations. Table 2 provides an overview of existing

TABLE 3 Blockchain technology selection overview.

Blockchain	Description	Association with BTF
Bitcoin (Jabbar et al., 2022)	Launched in 2009, the first and most famous cryptocurrency. It runs on a decentralized network developed by Satoshi Nakamoto	Offers a decentralized, public and secure ledger system, its not a suitable solution for the fast transaction speeds that BTF requires
Hyperledger (Zheng et al., 2021)	Open-source project backed by IBM and the Linux Foundation. Focuses on cross-industry Blockchain technologies. Supported by various sectors since 2015	Excellent for BTF's regulatory requirements and permissioned access, it allows for inter-organizational sharing while providing data protection
EOSIO (EOS) (Kouhizadeh et al., 2021)	Accommodates both public and private applications. Tailored for business needs with secure, fast, and role-based security features	Suitable if deployed as a private network. It meets BTF's needs for fast, scalable transactions and customizable access
IOTA (Taherdoost, 2022; Kayikci et al., 2022)	It features a unique "tangle" transaction method that is distinct from traditional Blockchain structures like Bitcoin and Ethereum	Because of its scalable and lightweight architecture, which facilitates safe and effective transactions in a private setting, it is conditionally appropriate
Other Blockchains (Taherdoost, 2022; Geng et al., 2024)	Alternatives include Ethereum, TRON, SmartChain, Stellar, and Polygon. Each Blockchain has distinct characteristics affecting implementation	varies depending on the blockchain; BTF may not be compatible with public blockchains like Ethereum, but permissioned solutions within this category may be able to meet its scalability and privacy requirements

research on CSFs-based blockchain systems in the transportation domain, comparing these studies with the proposed BTF. For instance (Basahel et al., 2021; Bugami, 2022), and (Bugami, 2022) focus on traffic congestion management, while (Bijalwan et al., 2024) explores travel experience in the Middle East and North Africa (MENA) region. This comparison of services, contributions, methodologies, and limitations offers a foundation for reformulating CSFs within the transportation system, supporting the development of a blockchain framework to address current challenges effectively.

Further (Binsawad and Albahar, 2022), and (Bugami, 2022) focus to fill knowledge gaps related to CSFs and (Kayikci et al., 2022) discuss the complexity of sustainable development. All these conclude to blockchain solution based on optimally reformulated CSFs, will enhance the efficiency and trustworthiness of the implemented system. It is therefore, needed to deploy an optimally formulated CSFs based blockchain solution to mitigate the highlighted issues encountered by the mass level transportation system. This research presents CSFs based innovative solutions for large religious event transportation using Blockchain technology. It is worthy to note that the key CSFs improve making operations smoother during these events.

Investigating CSFs for the adoption of blockchain technology in transportation control, targeting bus approval during large-scale religious gathering is being worked out in our model. It aims to improve transportation efficiency and effectiveness in blockchain based transportation systems. We also provide an overview of the blockchain based systems overview in Table 3.

3 Methodology

This research develops a comprehensive framework called BTF to mitigate the highlighted issues raised in Section 1. BTF is based on the determination of the CSFs. This study used a mixed-methods approach, analyzing articles from 2010 to 2024 and collecting primary data through questionnaires with government representatives, transportation managers, and IT specialists. This approach ensures a thorough analysis of blockchain implementation in transportation management.

The first process is the design phase, which involves a comprehensive bibliographic review. The design incorporates feedback from multiple sources, such as government departments, transport organizations, and the coordinator. The second phase of the framework deals with the identification of technology by evaluating various blockchain systems, investigating accommodation capacity for various numbers of users, the level of security, and their integration.

The suggested blockchain-based architecture for the BAS is depicted in Figure 3, highlighting its main architectural advantages that improve stakeholder synchronization, data security, and transparency. By incorporating permissioned blockchain protocols, enhancing transparency via real-time data sharing, and preserving synchronization across all involved organizations, the framework ensures secure data transfers.

The framework also includes a comprehensive assessment of the CSFs that are derived and vital for the effective implementation of the BTF. During pilot implementation stages, surveys and feedback loops are created to capture information that is utilized to improve and adapt the framework. The iterative solutions guarantee that the BTF is adaptive to stakeholder considerations and technological advances. These technological improvements enable the system to process more transactions through the volume capacity without necessarily reducing efficiency and security rates.

The integration of new CSFs based rules ensures that the framework complies with data privacy laws in various regions while, at the same time, strengthening stakeholder confidence in the system. The next section discussed the data collection during the implementation of the proposed model BTF.

The process of identifying CSFs and their subsequent validation requires a holistic and complex approach. Existing CSFs recouped from literature delve inadequate implementation, lack competency, and are comprising deficiency to be part of successful BAS implementation. We have integrated secondary analysis of publications with primary data obtained from interviews with government officials, transportation managers, and IT professionals, so assuring a thorough examination of blockchain deployment in transportation management.

Our proposed methodology eliminates these shortcomings and provides new categorization of CSFs into four key dimensions: These are people (P_1), technology (P_2), environment (P_3) and

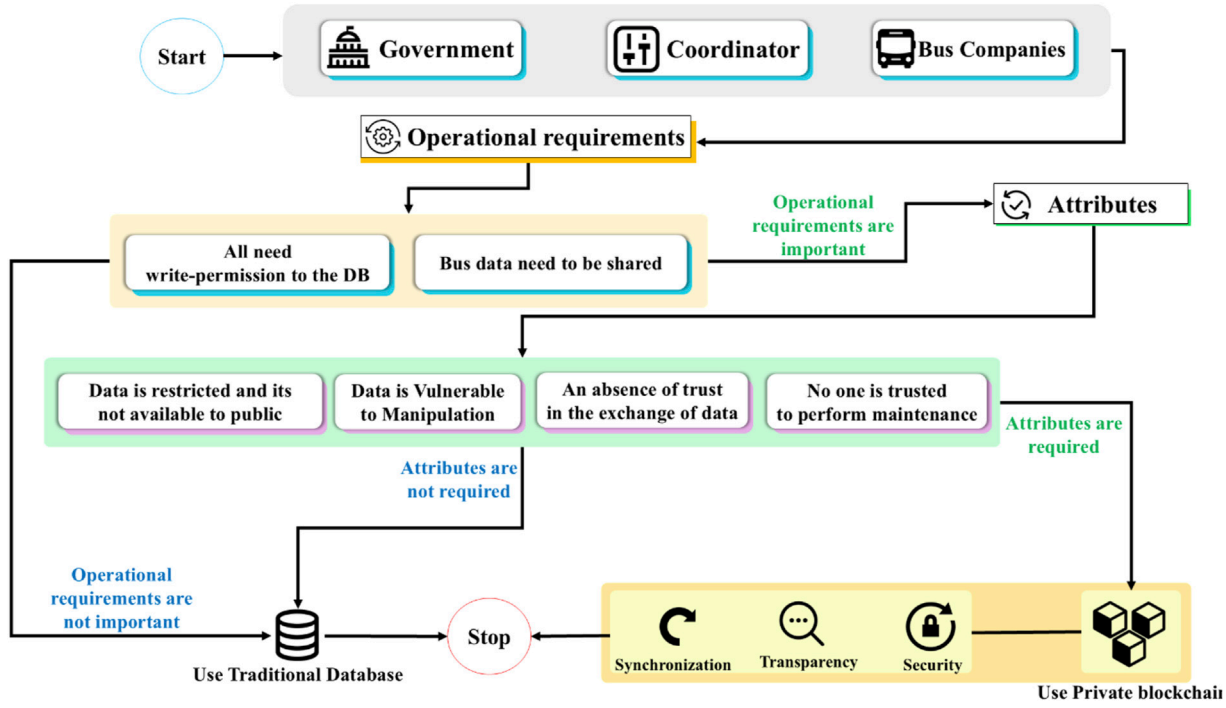

FIGURE 3
Decision-making framework for selecting either a private blockchain or traditional database for BAS.

TABLE 4 Comparative analysis of dimension derivation and methodological contributions in blockchain-based BAS.

Dimension	CSFs	Derivation	Literature Context	Our Contribution
People (P_1)	User acceptance, training requirements, behavioral adjustment	Ensuring stakeholders are prepared and willing to adopt the new system	(Aina et al., 2023) and (Basahel et al., 2021) emphasized user acceptance and training in implementing digital solutions	This plan outlines training and behavioral modification for the stakeholders in large-scale religious events with specific user engagement and training information
Technology (P_2)	Scalability, interoperability, cybersecurity	Focusing on technical robustness to handle large volumes of transactions, integrate with existing systems, and provide a secure environment	(Nasser et al., 2019) and (Huang et al., 2018) highlighted the role of scalability and security in blockchain adoption	Describes technological approaches and possible solutions, including layer-two technologies and other consensus algorithms when needed for higher transaction throughput or better security
Environment (P_3)	Regulatory policies, economic conditions, societal norms	Considering external factors like regulatory compliance, economic feasibility, and societal acceptance	(Bugami, 2022) and (Kayikci et al., 2022) discussed the impact of regulatory and economic factors on blockchain implementation	Offers comprehensive regulatory compliance examination and economic viability recommendations for the country, focusing on appropriate regulatory structures and the economic environment of Saudi Arabia
Organization (P_4)	Organizational readiness, strategic alignment, resource allocation	Focusing on internal capabilities to adopt and integrate blockchain technology, including alignment with strategic goals and availability of necessary resources	(Farshidi et al., 2020) and (Ćirić et al., 2019) stressed the importance of organizational readiness and strategic alignment in technology deployment	Provides specific steps for considering organizational readiness and linking blockchain implementation to portfolio priorities, which is useful for optimizing resource investments

organization (P_4) factors. In addition, each dimension has sub-categories, the details of derivation and contributions are shown in Table 4 which also presents comparison of newly derived CSFs, with prior research. The newly derived CSFs fill the identified gaps and provide an optimal solution to improve BAS.

Based on their crucial importance to the effective deployment of blockchain-based transportation frameworks, we chose the four dimensions—people (P_1), technology (P_2), environment (P_3), and organization (P_4)—as well as their associated sub-categories were acknowledged and refined with assessments from interviews with transportation managers, IT professionals, and a comprehensive analysis of deployment strategies. In order to ensure alignment with the unique problems of the BAS, these aspects were selected following a thorough assessment of the existing literature and primary data analysis.

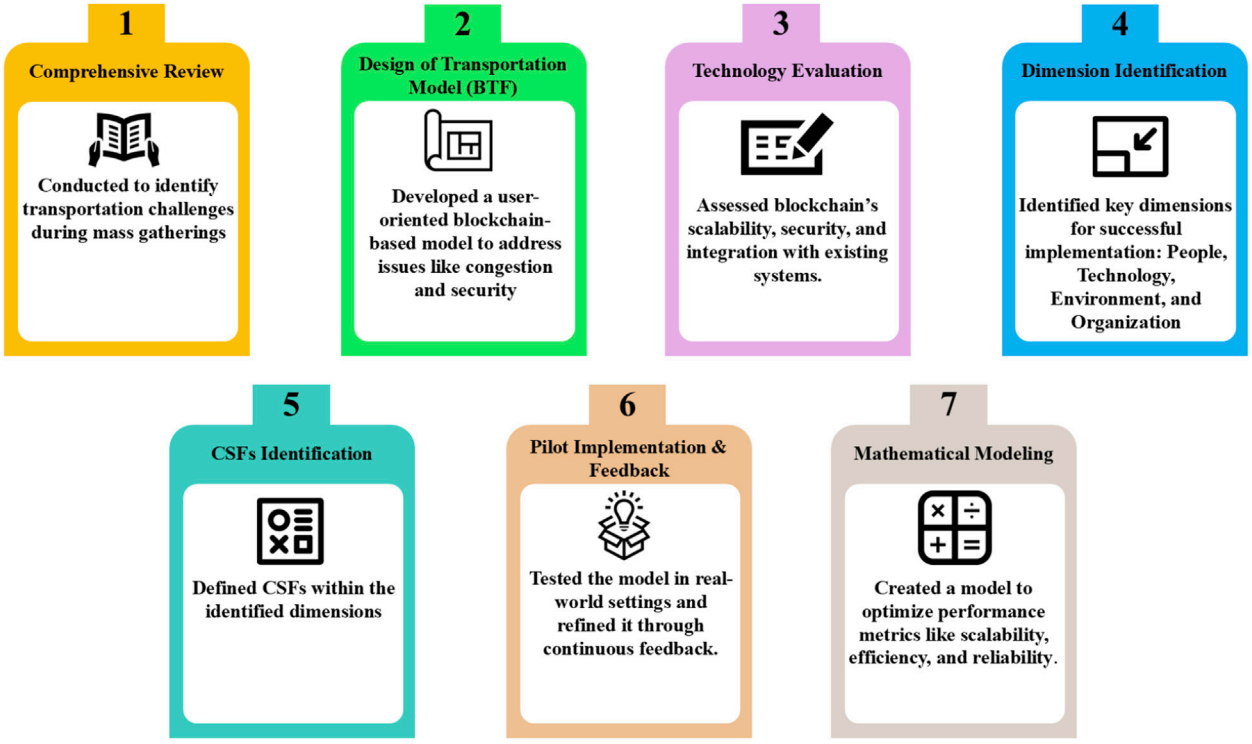

FIGURE 4
Step-by-Step Methodology for Blockchain-Based Transportation Framework (BTF).

Each dimension represents an important aspect of system functionality: people manage user adoption and behavior variables, organizations focus on strategy alignment and resource allocation, technology signifies scalability and security, and the environment dimension takes social and regulatory issues into account.

Each dimension's sub-categories were developed to capture the specific needs required to address the BAS, as confirmed by comparison with literature studies and feedback from transportation managers, IT professionals' response. With this methodical approach, a robust framework that is adapted to the particular requirements for religious mass gatherings is presented.

Our framework substantiates these CSFs through comprehensive research and practical utilization, providing a solid foundation for the application of blockchain technology (Naikwadi et al., 2021; Zhang, 2022). Based on these CSFs, we build a solid foundation for the implementation of blockchain-based transportation systems that may provide solutions to defeat the challenges associated with managing transportation during large religious events. Figure 4 illustrates a step-by-step methodology for the formulated BTF. The mathematical model for our developed framework is discussed in the following section.

3.1 Mathematical model

The integration of the BTF into the BAS involves an analysis of CSFs across the four dimensions outlined above, which are essential for managing transportation systems during large-scale events. Table 4 compares the dimensions—people P_1, technology P_2, environment P_3, and organization P_4—and their CSFs, highlighting this study's contributions and addressing blockchain implementation challenges.

The identified issues with blockchain and its application in transportation and logistics by our new CSFs have a well-structured solution to the issues arising due to its integration in complex transportation systems. The model categorizes CSFs as P_1, P_2, P_3 and P_4 for People, Technology, Environment, and Organization, respectively, with i and j as indices for dimension and subcategory. The importance of each CSF is represented by w_{ij}.

A systematic methodology based on the DEMATEL approach and previous research (Grida et al., 2022; Mishra et al., 2023) was used to develop the equations for evaluating CSFs. Equation 1 maximizes the objective function (z), which represents the weighted impact of CSFs. Each weight (w_{ij}) reflects the significance of CSF j within dimension i, prioritizing the most impactful CSF dimension as identified in the investigation, weighted by the relative importance of each dimension.

Equations 2–5 then evaluate the percentages and cumulative impact of the CSFs across the four dimensions. These equations estimate the total CSF impact for each dimension, represented as $CSF_{People,Total}$, $CSF_{Technology,Total}$, $CSF_{Enviroment,Total}$, $CSF_{Organization,Total}$ by summing the impact scores of their sub-categories, denoted by CSF_{ij} where i represents the dimension and j the subcategory. This dimension-level evaluation enables a comprehensive calculation of each dimension's influence, certifying that it captures both the relative percentages and the cumulative impact of the CSFs for effective investigation (Grida et al., 2022).

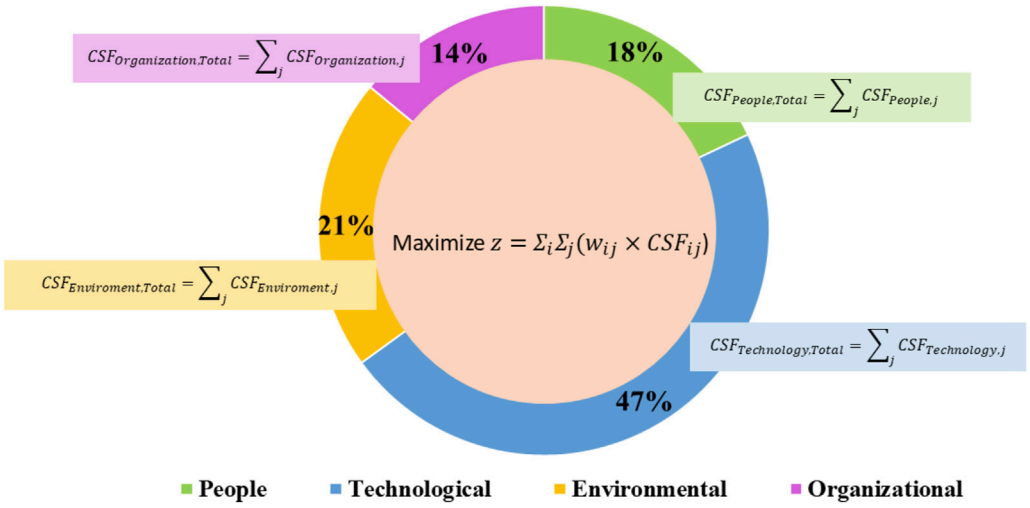

FIGURE 5
Dimension calculations through the proposed Mathematical Model.

TABLE 5 CSFs and problem for blockchain implementation in BAS with solution.

CSFs Category	Problem	CSFs Significance	BTF Solution
Cooperation Between Stakeholders (Basahel et al., 2021)	Ineffective communication	Teamwork for success	✓
Government Leadership (Binsawad and Albahar, 2022)	Lack of official leadership	Govt. Initiative for cooperation	✓
Blockchain's Benefits	Inadequate knowledge	Understanding advantages	✓
Accuracy of Data Transmission (Farshidi et al., 2020)	Inaccurate data transmission	Critical for dependability	✓
Metrics of Performance (Mandourah and Yamin, 2022)	Deviations from project timeline	Essential for project schedules	✓
Engagement of Users (Owaidah et al., 2023)	Lack of user interaction	Dependence on user engagement	✓
Dependability and Data Privacy	Questions on Confidentiality	Ensure privacy and integrity	✓
Support from Top Management (Geng et al., 2024)	Inadequate leadership assistance	Necessary for a seamless transition	✓
Management Tasks and Project Scope	Confusion about project scope	Essential for planning and organizing	✓
Business Model Adaptation (Jabbar et al., 2022)	Traditional models may not be suitable	Modify for Blockchain technology	✓

Equation 6 is used as normalization stage by restricting the sum of the weights for all dimensions and sub-categories to 100% (Mishra et al., 2023). This normalization allows for a balanced comparison across different dimensions, aligning each dimension's impact within a unified framework. Figure 5 illustrates the distribution of these weights and percentages across the four dimensions, highlighting each dimension's contribution to the total CSF impact.

$$\text{Maximize } z = \sum_i \sum_j \left(w_{ij} \times CSF_{ij} \right) \quad (1)$$

$$CSF_{People,Total} = \sum_j CSF_{People,j} \quad (2)$$

$$CSF_{Technology,Total} = \sum_j CSF_{Technology,j} \quad (3)$$

$$CSF_{Enviroment,Total} = \sum_j CSF_{Enviroment,j} \quad (4)$$

$$CSF_{Organization,Total} = \sum_j CSF_{Organization,j} \quad (5)$$

$$\sum_i . \sum_j . w_{ij} = 100\% \quad (6)$$

The mathematical model for the proposed solution involves using blockchain technology to improve decision-making processes for stakeholders and enhance efficiency. This approach aims to provide a safe, efficient, and sustainable transport solution. The framework addresses the CSFs that enable large-scale events and make their management more accessible and better for attendees and coordinators.

3.2 Re-Structuring blockchain implementation for BAS based on CSFs

The effective implementation of the above model uses DEMATEL analysis, which analyzes each CSF with the problems and proposed solutions. This analysis is summarized in Table 5.

TABLE 6 Comprehensive Quantitative Analysis of all dimensions, Sub-categories with its formulas and Weighted Summation Impact.

Dimension	%	Sub-category	Sub-category formula	%	Weighted Summation Formula $\sum_{i=1}^{n}(Weight_i \times Score_i)$
People dimension (P_1)	18%	Individual	($S_{11} = 0.40$): $E_{11} = D_1 \times S_{11}$	40%	0.072%
		Public	($S_{12} = 0.60$): $E_{12} = D_1 \times S_{12}$	60%	0.108%
Technological dimension (P_2)	47%	System	($S_{21} = 0.23$): $E_{21} = D_2 \times S_{21}$	23%	0.108%
		Data	($S_{22} = 0.31$): $E_{22} = D_2 \times S_{22}$	31%	0.146%
		Blockchain	($S_{23} = 0.46$): $E_{23} = D_2 \times S_{23}$	46%	0.216%
Environmental dimension (P_3)	21%	Policies	($S_{31} = 0.33$): $E_{31} = D_3 \times S_{31}$	33%	0.069%
		Business	($S_{32} = 0.67$): $E_{32} = D_3 \times S_{32}$	67%	0.141%
Organizational dimension (P_4)	14%	Management	($S_{41} = 0.75$): $E_{41} = D_4 \times S_{41}$	75%	0.105%
		Financial Concerns	($S_{42} = 0.25$): $E_{42} = D_4 \times S_{42}$	25%	0.035%

By inspecting Table 5, one can observe that the successful implementation of our proposed BAS based on newly derived CSFs validated the DEMATEL analysis. Implementing these aspects allows for enhancement of the Saudi Arabia transportation infrastructure, providing enhanced effectiveness, openness, and contingency throughout the massive religious pilgrimages.

4 Analysis and findings

4.1 Evaluation of performance metrics of CSFs based BAS

In this section, we evaluate our derived model BTF based on newly derived CSFs. We evaluate the performance metrics for CSFs that improve the integrity of the transactions, security, and reliability. CSFs have high visibility, enhancing data openness, accessibility, and the quality of user experience. We have evaluated the performance impact of implementing each CSF dimension and its subcategories. Table 6 shows the significant contribution for each CSF and its subcategory.

The above approach directly fulfills the gaps in the proposed framework. The subscripts *ind, pub, sys, data, bc, pol, bsn, mng,* and *fin,* represent the individual, public, system, data, blockchain, policies, business, management, and financial sub-categories of the CSFs respectively. This method ensures a nuanced understanding of each sub-category's role within its broader dimension. Furthermore, we can derive the respective effects in sequel as $(EF_{ind} = P \times P_{ind})$, $(EF_{pub} = P \times P_{pub})$, $(EF_{sys} = T \times P_{sys})$, $(EF_{data} = T \times T_{data})$, $(EF_{bc} = T \times T_{bc})$, $(EF_{pol} = E \times E_{pol})$, $(EF_{bsn} = E \times E_{bsn})$, $(EF_{mng} = O \times O_{mng})$, and $(EF_{pub} = O \times O_{fin})$ respectively.

The estimation performance impact using above formulation for each sub-category is summarized in Table 6, where the legends, E represents the Effect, D represents Dimension, and S represents the percentage of achieved by each subcategory, while i and j represent the running indices. Each dimension's percentage value describes the system's proportion, while the subcategories elaborate the results.

A systematic and tiered analysis with this algebraic derivation provides the impact of each sub-category. The largest percentages reflect the high impact and greater relative influence, while the smallest percentages mimic the weakest impact within the framework. An effective established weighted significance within these sub-categories creates a robust context for assessing and ranking CSFs in BTF. This weighted importance is given in Equation 7, Zafar et al. (2021), Ilieva et al. (2021).

Weighted Importance

$$= \frac{Importance\ in\ Dimension \times Dimensional\ Weight}{100} \tag{7}$$

$$Weighted\ Sum = (Dimension\ Percentage \times Subcategory\ Percentage) \tag{8}$$

Equations 7, 8 are based on approaches addressed in previous studies, such as (Zafar et al., 2021; Ilieva et al., 2021). These studies analyze the relative importance of criteria in blockchain systems using DEMATEL methodologies and weighted scoring models. Developing these concepts further, we adapted the formulas to meet the unique requirements of BTF, enabling a systematic evaluation of the CSFs.

The weighted summation value for each sub-category, calculated using Equation (8), is visually represented in Figure 6. Within the technological dimension (P_2), the blockchain sub-category value scores the highest impact (21.62), indicating its important role in enhancing security and transparency. Moreover, the financial sub-category within the organizational dimension (P_4) has the lowest impact score (3.5), indicating lower relative importance. This emphasizes the dominance of technological dimension (P_2) among all dimensions. This visual representation supports the quantitative analysis by clearly presenting the diverse and proportionate impacts of the sub-categories within the framework.

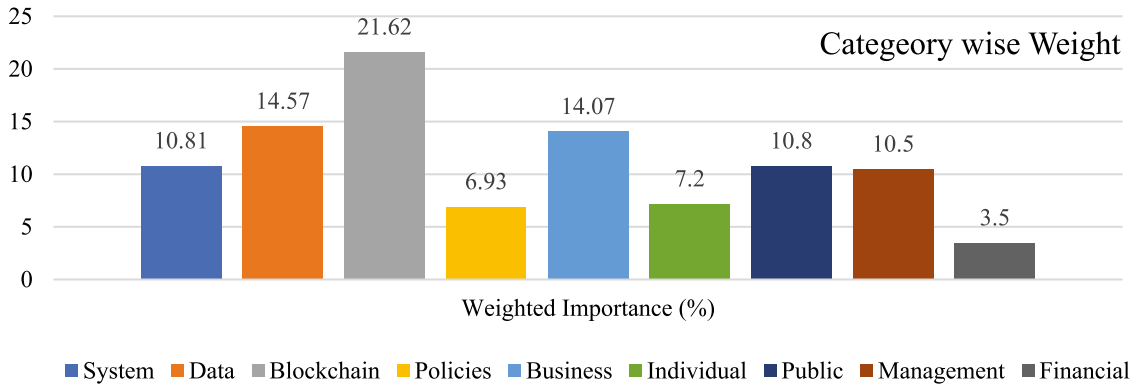

FIGURE 6
CSFs Category wise Weight Importance.

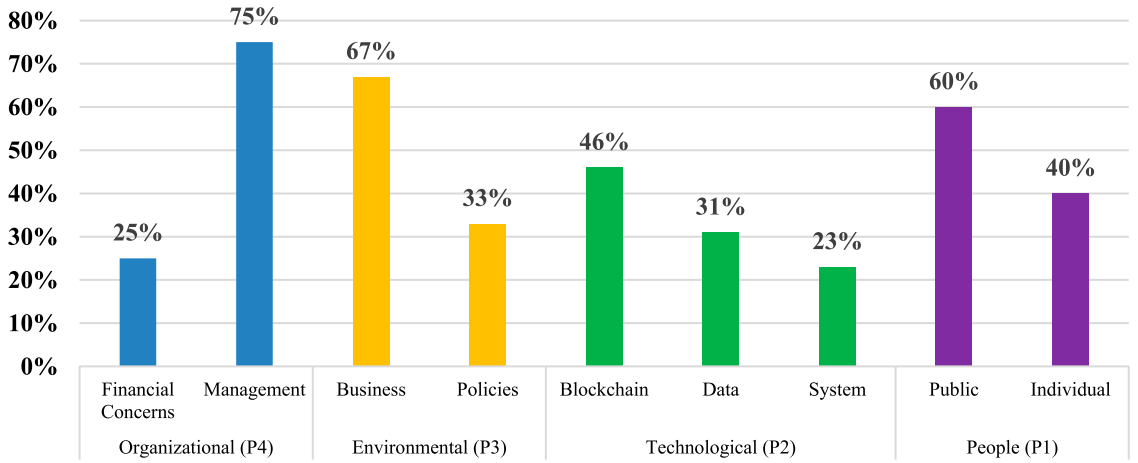

FIGURE 7
Dimension vs. Category Percentage.

Figure 7 and Table 6 show further analysis for the breakdown of the importance level in terms of the dimensions and subcategories identified. Technology is the largest, with 47%, where the major contribution is by blockchain at 46%, showing its importance. The environmental dimension is next at 21% it concerns sustainability. The people dimension, which accounts for 18%, contrasts the social and personal aspects of the company. The organizational dimension, which accounts for 14%, emphasizes the concern of management practices over money. As seen from the breakdown, there are disparities in the focus and difficulties that may come about while developing blockchain-based transportation systems for huge religious events.

Table 7 illustrates an analysis of the CSFs dimensions and sub-factors for the bus approval process.

4.2 Analysis of organizational, technological, environmental, and people dimension

The structure of the contemporary business environment is characterized by new technologies, new organizational forms, a constantly changing environment, and people. Knowledge of these dimensions enables informed decisions and fosters sustainable development. The following Table 8 organizes the findings from cited studies against the findings of this study in terms of organizational, environmental, and human antecedents.

This research stipulates that blockchain implementations in modern organizations with reference to organizational, technical, environmental, and human factors require a high impact CSFs based system. Findings reveal that organizational dimension features are personnel types and financial resources are significant. With regard to technology, CSFs attributed to management systems and blockchain range from 39% to 75%. The environmental component is characterized by data management and adherence issues and may consume between 11 and 46 percent of CSFs. The personnel dimension is also important and has user engagement and management participation contributing to CSFs ranging between 27% and 60%. As shown in Figure 8, the employee type of organization is more relevant in 25% of organizational CSFs, and for technology, the system type is highly important at 75%. Finally, the research highlights the implications of the examined factors for the proper application of blockchain logistics in large religious events.

TABLE 7 Analysis of CSFs dimensions for bus approval process for major religious gathering.

CSFs	Sub-factor		Ref.
People dimension (P_1)	Type of User	Technology Awareness	Ćirić et al. (2019), Kayikci et al. (2022)
		Building Trust	Jabbar et al. (2022), Farshidi et al. (2020)
	Type of Management	Change Management	Basahel et al. (2021), Mandourah and Yamin (2022)
		Project Scope	Ande et al. (2024), Derhab et al. (2024)
Technological dimension (P_2)	Type of System	Scalability	Mandourah and Yamin (2022), Farshidi et al. (2020)
		Security Measures	Basahel et al. (2021), Binsawad and Albahar (2022)
	Type of Data	Data Accuracy	Basahel et al. (2021), Brdesee et al. (2013)
		Features for Privacy	Basahel et al. (2021), Owaidah et al. (2023)
Environmental dimension (P_3)	Type of Regularization	Legal Framework	Agi (2022); Kayikci et al. (2022)
		Setting Standard for System	Ćirić et al. (2019), Kayikci et al. (2022)
	Type of business	Stakeholder Collaboration	Ćirić et al. (2019), Kayikci et al. (2022)
		Business Continuity	Bugami (2022), Kayikci et al. (2022)
Organizational dimension (P_4)	Type of Employee	Training and Awareness	Basahel et al. (2021), Binsawad and Albahar (2022)
		Ability to work with others	Binsawad and Albahar (2022), Aina et al. (2023)
	Type of Organization	Leadership Support	Binsawad and Albahar (2022), Aina et al. (2023)
		Regular Compliance	Aina et al. (2023), Farshidi et al. (2020)

TABLE 8 Dimension features in organizational, technological, environmental, and people dimensions.

Ref.	Organization dimension (P_4)		Technology dimension (P_2)			Environment dimension (P_3)		People dimension (P_1)	
	Type of employee	Type of organization (management)	Type of system	Blockchain	Type of data	Type of regularization	Type of business	Type of user	Type of manag.
Basahel et al. (2021), Binsawad and Albahar (2022)	-	52%	19%	11%	-	-	43%	-	34%
Aina et al. (2023), Farshidi et al. (2020)	16%	-	-	16%	21%	23%	-	27%	41%
Mandourah and Yamin (2022), Owaidah et al. (2023)	-	39%	-	21%	-	18%	-	21%	34%
Jabbar et al. (2022), Kayikci et al. (2022)	13%	-	16%	25%	-	-	39%	23%	42%
Our Paper (BTF)	25%	75%	23%	46%	31%	33%	67%	40%	60%

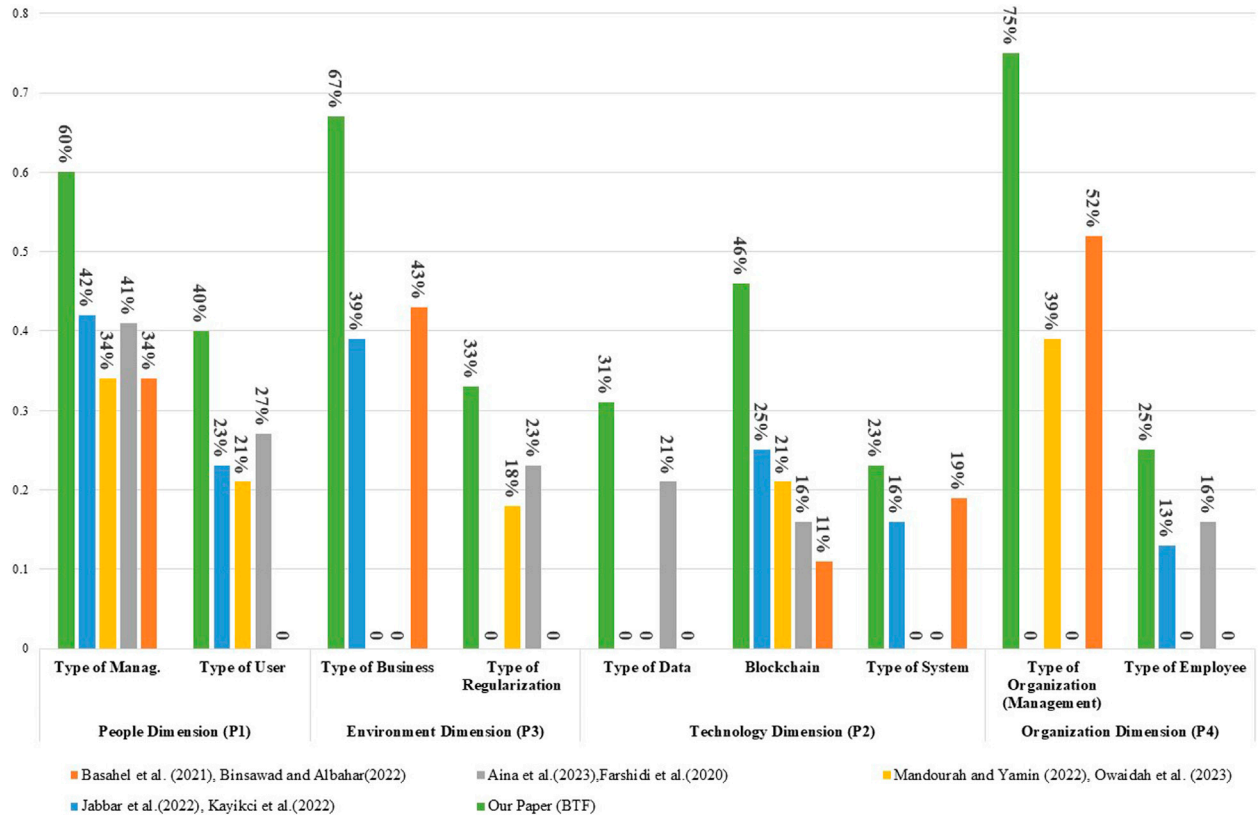

FIGURE 8
CSFs Bar Graph for Dimension Features.

TABLE 9 Comparison of Pre- and Post-Implementation data (Permissioned Blockchain).

#	Metrics	*Pre-Implementation*	*Post-Implementation (permissioned blockchain)*
1	Data Tampering Incidents	Maximum (25 incidents/month)	0 to 1 Incident/month
2	Transaction Processing Time	5 s (per transaction)	1–3 s (per transaction)
3	Transaction Throughput	800 TPS	3500 TPS
4	Reconciliation Errors	60 errors/month	0 to 1 errors/month
5	System Uptime	93%	99.5%–99.9% uptime

[a]Note: The pre-implementation data in Table 9 is sourced from the Higher Committee for Monitoring of Pilgrims Transportation (HCMT), as referenced in the Current Bus Approval Process document, retrieved on 3 November 2024, (Khanzada et al., 2023).

4.3 Comparison of impact of deployed CSFs for BTF with the legacy CSFs

The transition from Microsoft SQL Server and Oracle databases to a permissioned blockchain system, guided by CSFs, was evaluated based on integrity, efficiency, scalability, accuracy, and reliability. Analysis implies that blockchain technology provides enhanced security and transparency, notably increasing control over transportation management during large-scale events, such as religious mass gatherings. Data from system logs, transactions, and user inputs were collected before and after implementation, with automated scripts facilitating efficient data collecting. A subsequent rigorous study confirmed that shifting from centralized databases to a permissioned blockchain system substantially enhanced integrity, efficiency, scalability, accuracy, and dependability, showing effective in reinforcing data integrity and transparency while keeping reliable monitoring. Table 9 illustrates a comparative outline of pre- and post-implementation indicators.

They addressed issues such as data tampering and decreased the time taken for a transaction from 5 to 1–3 s. The system can process more transactions since transaction throughput is now at 3,500 Tera Byte per second (TPS) when it used to be 800 TPS. Reconciliation errors were reduced from 25 to 1 per month, while system availability increased from 93% to between 99.5% and 99.9%,

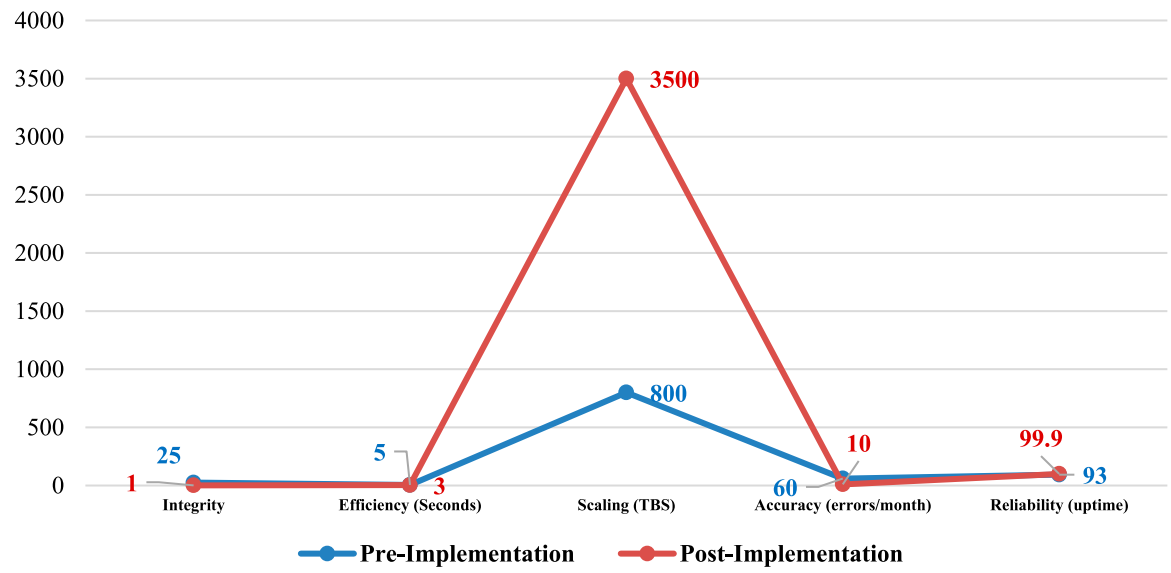

FIGURE 9
Performance Improvement Analysis for Transition from centralized databases to permissioned blockchain system.

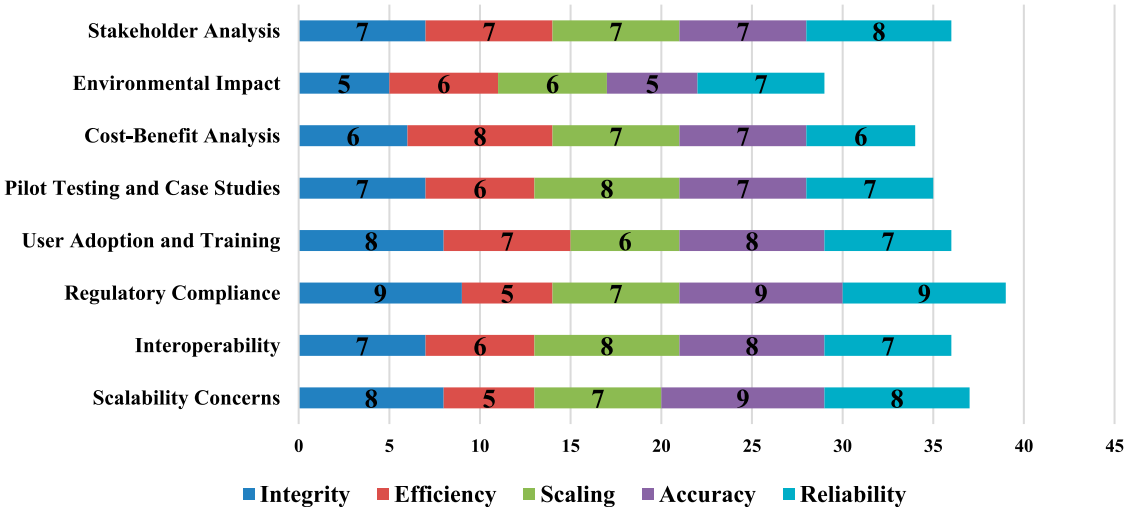

FIGURE 10
Impact of CSFs on key performance metrics in Blockchain-Based Transportation Systems.

suggesting enhanced system stability and reliability over time. These gains demonstrate that the permissioned blockchain can enhance performance and reliability, particularly for transportation during significant events. Table 9 and Figure 9 show that blockchain enhances the following characteristics: integrity, efficiency, scalability, accuracy, and reliability.

4.4 Impact of deployed CSFs (for BTF) on performance metrics

Figure 10, a stacked bar chart, presents the impact of different CSFs on the performance indicators. Hence, by using different colors for each CSF, the chart directly compares the previously mentioned aspects and highlights the fields that need a strategic push. At the same time, it stresses the interdependency of those factors in creating an effective, expansive, and fault-tolerant blockchain-based transportation system for religious mass gathering.

Using the chart, CSFs for the BAS can be assessed with respect to stakeholder involvement, environmental implications, legal requirements, *etc.* The *Y*-axis illustrates the value added by CSFs to performance metrics such as integrity, efficiency, scalability, accuracy, and reliability, all of which have been rated on a scale of 0–10. The *X*-axis labels all factors by their impact score, with a cumulative inherent score that raises awareness on which aspects

improve systems' efficiency, security, and reliability in handling vast religious events. They identify the legal issues that influence integrity and reliability most, and user acceptance must precede pilot testing. In particular, it demonstrates that a permissioned blockchain system can solve the high transaction volume and enhance the transport management for large events, and hence, the CSFs proposed in this paper should be implemented.

5 Discussion

CSFs analysis reveals aspects influencing the feasibility of a blockchain-based transportation architecture for mass gatherings in Saudi Arabia. According to the above distribution, the most dominant distribution in CSFs is the technological dimension at 47%. Blockchain has the highest overall weighted summation impact of 46% by differentiated relevance and frequency. The above results demonstrate how the use of the blockchain system enhances the efficiency of the system and the accuracy of recorded information. The organizational dimension is at 14% and is centered on management structures and finances with slightly less significance than those of technology. It is therefore clear that for the environmental and the people components which at 21% and 18% respectively inform policy direction and formulation, and acceptance and conduct to ensure operations are not hampered require formulation of polices that can easily be accepted.

Assessment of the indicators before and after blockchain implementation confirms this technology's value in future transportation networks. Thus, the implementation decreases cases of data tampering from 25 monthly cases to none-1 and enhancing the throughput from 800 TPS to 3,500 TPS. The implementation also reduced the possibility of reconciliation errors and the system availability was raised to between 99.5% and 99.9%. The conclusions suggest that applications of blockchain enhance the availability of the transportation systems in handling religious mass gatherings, aside from achieving security and optimization goals. The study therefore propounds the success factors for the block chain application in Saudi Arabia's transport sector to provide the best and most credible solutions.

6 Limitations and practitioner implications

The identified CSFs may not apply universally across different contexts, and the research is more focused on a specific region and a unique mass gathering event. Additionally, factors such as technology readiness, infrastructure constraints, and end-user acceptance were not thoroughly examined. Future research should address these aspects and explore the long-term sustainability of blockchain in diverse cultural and operational environments.

For practitioners, this research offers valuable insights. Blockchain can enhance not only the organization and safety of transportation at mass gathering events but also increase the trust of transport authorities, passengers, and service providers. By testing and adopting blockchain technologies, practitioners can achieve a more reliable logistics system tailored to those events. It is crucial for stakeholders to collaborate in managing implementation challenges to fully realize the benefits of blockchain in transportation management within Saudi Arabia.

7 Conclusion and future work

In conclusion, this study demonstrates the significant potential of blockchain technology to enhance transportation systems during religious mass gathering events in Makkah. The findings indicate that weighted significance and DEMATEL analysis are effective in identifying CSFs for successful implementation. Our analysis evaluated the impact of the reformulated CSFs within the proposed BTF, revealing that the blockchain CSFs achieved the highest impact score of (21.62), while the financial CSF had the lowest impact at (0.25). These results show that blockchain can address key challenges, including data security, reconciliation errors, and transaction inefficiencies, fostering a more secure and efficient transportation framework. The proposed mathematical model serves as a guiding framework, facilitating the integration of blockchain to optimize performance in large-scale transport scenarios. Future research could explore the model's application in different contexts and further refine the identified CSFs for broader applicability.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to privacy and confidentiality agreements.

Author contributions

AM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. TK: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Resources, Project administration, Writing–review and editing. MS: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Resources, Project administration, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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