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Trustworthy digital twinning data platform for power infrastructure construction projects using blockchain and semantic web

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Power infrastructure projects are characterized by complex supply chain structures and numerous stakeholders, presenting significant challenges in maintaining data integrity and ensuring seamless integration of project information. Previous Digital Twins (DTs) and Building Information Modeling (BIM) collaboration methods lack robust mechanisms for data traceability and immutable storage, leading to potential risks such as data loss or tampering. Furthermore, existing project information exchange and data management methods do not adequately integrate diverse data types, such as project documentation, onsite environment monitoring IoT sensor readings and CAD/BIM-based design information. This research introduces a novel DT data platform prototype, utilizing Blockchain and Semantic Web technologies, to establish a trustworthy DT data environment for power infrastructure projects. This system collects heterogeneous data, including manual inputs and IoT-generated data, and processes them into RDF format on dedicated devices. The integrated data is then stored on a Permissioned Blockchain, ensuring traceability and immutability. The framework incorporates Distributed File Systems to enhance storage efficiency and features a semantic gateway that transforms heterogeneous data into RDF graphs, fostering interoperability and the potential for automated data linkage. The efficacy of this prototype was demonstrated through a case study, testing data consistency and showcasing prototype queries enhanced by Semantic Web, thus substantiating the platform's capacity to support multidisciplinary project management.

KEYWORDS

digital twin, blockchain, semantic web, data environment, power infrastructure project, construction project management

1 Introduction

The power sector in China has seen a surge in electricity consumption, particularly in regions like its eastern coastal provinces (Li et al., 2023). The urgency of addressing the growing electricity demands and infrastructure challenges has led to the adoption of increasing power infrastructure projects to enhance resource allocation efficiency (Li et al., 2020). These projects require seamless integration of continuously updating diverse data types from sensors, design information and project requirements. The complexity of power infrastructure projects, influenced by multi-disciplinary collaborations, diverse data sources and intricate government and contractual relationships, underscores the necessity for advanced data integration and management systems (Zhou et al., 2022).

The Architecture, Engineering, and Construction (AEC) industry has increasingly adopted digital technologies such as Building Information Modeling (BIM) to improve information sharing and project collaboration (Zhao and Taib, 2022; Sacks et al., 2020; Wang et al., 2022). BIM facilitates effective communication between collaborators and within organizations (Zhang et al., 2017; Bradley et al., 2016). The concept of a Common Data Environment (CDE) has emerged, utilizing BIM to ensure seamless data exchanges among stakeholders (Tan et al., 2023). Additionally, the rise of Digital Twin (DT) technology has enabled real-time data integration, enhancing operational efficiency across various sectors, including the AEC industry (Zhou et al., 2020; Chen et al., 2024b; Agrawal et al., 2022). However, despite these technological innovations, existing frameworks predominantly focus on integrating and updating specific elements of project information, such as geometric details (Lu et al., 2020b; Lu et al., 2020a) or design information (Tao et al., 2021). Current DT platforms, while coordinating data management in construction projects, lack comprehensive integration of diverse data types such as IoT sensors for environmental monitoring, project requirements documents, and Computer-Aided Design (CAD)/BIM design information (Lu et al., 2020a; Tao et al., 2021; Bedoiseau et al., 2022). More critically, these systems often do not incorporate robust mechanisms for data traceability and immutable storage, which are vital for maintaining a secure and reliable data environment. This gap underscores the need for a novel approach that not only integrates various types of project data into a unified system but also enhances the reliability and security of this information.

Blockchain technology offers promising solutions to these deficiencies. Known for its application in various sectors, from finance to healthcare, Blockchain enhances data transparency and increases stakeholder trust by providing a framework for data immutability, security, and traceability (Nakamoto, 2008; Xu et al., 2016; Agbo et al., 2019). In the construction sector, Blockchain supports critical functions such as contract management, supply chain management, and information management—areas requiring robust data security due to the industry's fragmented and dynamic supply chain (Celik et al., 2023; Vrijhoef and Koskela, 2000; Yoon and Pishdad-Bozorgi, 2022). However, while Blockchain enhances data security and traceability, integrating various data types remains a challenge. Here, the Semantic Web (Berners-Lee et al., 2001) can play a crucial role. With its standardized frameworks such as Resource Description Framework (RDF) (W3C RDF Working Group, 2014), the Semantic Web improves data interoperability and management, facilitating a better integration across diverse systems (Lassila et al., 2001; Hitzler, 2021).

This paper proposes a novel integration of Blockchain and Semantic Web technologies to create a robust, trustworthy DT data platform for power infrastructure projects. This integrated approach aims to not only support the seamless integration of diverse data types but also ensure their integrity and security. By combining Blockchain's capabilities for data security with the Semantic Web's facilitation of interoperability, this research seeks to address the critical needs of data management in complex, multidisciplinary project environments. This approach promises to significantly enhance project management efficiency, reduce operational risks, and provide a transparent and secure framework for stakeholder collaboration.

The rest of this paper is structured as follows: Section 2 outlines existing methods in promoting data sharing and management in the AEC industry; Section 3 details the methodologies employed in the development of the proposed DT data platform; Section 4 presents a case study of the prototype implementation combining Blockchain and Semantic Web technologies and Section 5 discusses the results, limitations and broader implications. Finally, the paper concludes in Section 6 with an overview of potential future research directions and the expected impact of the research on the field of power infrastructure development.

2 Related work

2.1 Existing data sharing and project management methods

Modern power infrastructure projects face significant challenges in data sharing and project management, driven by the increasing complexity of project requirements and the diversity of data sources. Traditional approaches such as BIM have laid the groundwork for improved information exchange and project coordination. Porwal and Hewage (2013) emphasize the importance of early contractor integration and client readiness in public construction projects, highlighting that these elements are crucial for enhancing BIM adoption, reducing errors, and improving productivity.

Building on the foundational principles of BIM, recent studies have explored the integration of advanced technologies to address the evolving demands of construction projects. Rafsanjani and Nabizadeh (2023) investigate the synthesis of Virtual Design and Construction (VDC) with DT technologies. Their model not only underscores the real-time monitoring and predictive capabilities beneficial during various construction phases but also enhances proactive project management, which is critical in preempting potential issues and streamlining operations. Further addressing the challenges of digital collaboration, Liu et al. (2023) present a digital thread-driven mechanism to improve the integration and functionality of DT technologies across manufacturing units. Their research tackles the traditionally fragmented manufacturing processes, aiming to streamline operations and enhance the overarching efficiency of production systems.

Further advancing the concept of data environments, Patacas et al. (2020) propose a novel data environment framework that incorporates both structured and unstructured data for the realm of Facilities Management (FM). Their framework was tested through iterative expert interviews and real-world scenarios, and proved effective in managing preventive and reactive maintenance, underscoring the need for continuous refinement in BIM processes for FM. Seidenschnur et al. (2022) introduce an innovative approach with a cloud-based data environment for the commissioning of HVAC systems before physical setup. This method utilizes a new 'FSC diagram' to represent HVAC BIM models within the data environment, demonstrating the potential of microservices for scalable and flexible solutions. This technology allows for preemptive troubleshooting and system optimization, showcasing the transformative potential of advanced data environments in complex infrastructure projects.

While these advancements represent significant progress in the field, they also highlight persistent gaps, particularly in the areas of data traceability, security, and the seamless integration of diverse data types. Existing frameworks, though increasingly sophisticated, still struggle to meet the comprehensive needs for secure and interoperable data management in multifaceted infrastructure projects. This shortfall highlights a critical area where the integration of Blockchain and Semantic Web technologies could provide transformative benefits, addressing these persistent challenges by enhancing data security, traceability, and the seamless integration of diverse data streams.

2.2 Blockchain technology

Blockchain technology is a decentralized, distributed ledger system that records transactions across multiple computers to ensure that the data cannot be altered retroactively without the alteration of all subsequent blocks and the consensus of the network (Priyadarshini, 2019; Treiblmaier and Beck, 2019). This technology operates on a peer-to-peer network, where each node maintains a copy of the digital ledger, making it resistant to tampering and cyberattacks (Helliar et al., 2020). The Blockchain is composed of a series of blocks, each containing a timestamp, transaction data, and a cryptographic hash of the previous block, which ensures the chronological order and integrity of the data (Engelhardt, 2017).

One of the primary benefits of Blockchain is its ability to provide a secure, transparent, and immutable record of transactions, which is particularly valuable in industries such as finance, healthcare, supply chain management, and cybersecurity (Helliar et al., 2020; Gad et al., 2022). Blockchain ensures data immutability through its consensus mechanisms, which require agreement from the majority of nodes before any new transaction can be added to the ledger. This decentralized validation process eliminates the need for a central authority and makes it nearly impossible for a single entity to alter the data without detection (Efanov and Roschin, 2018). The cryptographic techniques used in Blockchain, such as hashing and digital signatures, further enhance security by ensuring that once data is recorded, it cannot be modified or deleted (Engelhardt, 2017). Additionally, the transparency of Blockchain allows all participants in the network to view and verify transactions, fostering trust and accountability without the need for intermediaries (Zheng et al., 2017). In terms of traceability, Blockchain provides an end-to-end tracking system that is particularly beneficial in supply chain management. For instance, in the pharmaceutical industry, Blockchain can track the entire journey of a drug from the manufacturer to the end-user, ensuring authenticity and preventing counterfeit products from entering the market (Panda and Satapathy, 2021). Similarly, in agriculture, Blockchain can enhance the traceability of food products, ensuring quality and safety by providing complete visibility into the supply chain (Hasan and Habib, 2022).

To summarise, Blockchain technology offers a promising solution across various sectors. Its decentralized nature, combined with advanced cryptographic techniques, ensures that data remains secure and immutable. This provides a robust foundation for effectively addressing the shortcomings of previous data management and DT platforms in power infrastructure projects.

2.3 Blockchain in construction

The integration of Blockchain technology within the AEC industry has significantly advanced the reliability and security of project management processes, particularly when combined with BIM technology. Blockchain's ability to secure the storage and dissemination of BIM data is a key development, as highlighted by Hijazi et al. (2021), who emphasize the role of Blockchain in ensuring that modification records are immutable and tamper-proof. This capability enhances the overall trustworthiness of digital records, a crucial factor in maintaining the integrity of construction projects (Das et al., 2021). Additionally, Tao et al. (2021) propose a Blockchain-based distributed data environment for collaborative BIM design, supporting robust data sharing and management functionalities through smart contracts and a transaction data model.

The role of Blockchain in managing BIM data provenance is exemplified by Celik et al. (2023), who demonstrate how Blockchain can enhance the reliability and security of data exchanges among stakeholders. Their real-world implementation in a bridge construction project improved stakeholder confidence, optimized cost efficiency, and reduced risk. Further expanding its application, Xue and Lu (2020) introduced a semantic differential transaction technique that reduces information duplication in the integration of BIM and Blockchain, thereby streamlining data management across platforms.

Beyond securing BIM data, Blockchain has also proven effective in facilitating transparent and traceable exchanges of responsibility information within building projects. Lee et al. (2021) demonstrate how Blockchain can improve accountability and reduce disputes by making all data transfers within a project traceable. Similarly, Hunhevicz et al. (2022) explored the synergy between Blockchain and DTs, particularly in performance-based contracts, where Blockchain's verifiable and immutable data logs underpin contractual agreements. Li et al. (2022) developed an IoT-based platform using Blockchain to ensure the integrity and confidentiality of supply chain information in modular construction, where secure data environments are critical. Similarly, Jiang et al. (2023) discuss a Blockchain-enabled DT platform that enhances the management of fit-out operations in Modular Integrated Construction (MiC), showcasing how Blockchain can overcome traditional information-sharing barriers.

However, despite these advances, a significant gap remains in the comprehensive integration of heterogeneous data types essential for power infrastructure projects. Current Blockchain applications in construction primarily focus on structured BIM data and do not fully address the integration needs of diverse data types, such as environmental IoT sensor data. This limitation presents a critical challenge in developing robust data management solutions for complex infrastructure projects.

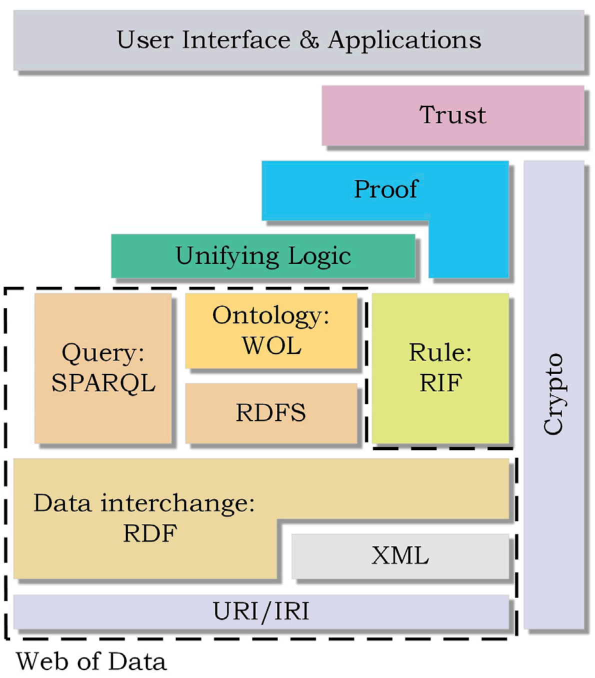

FIGURE 1
The technological stack of Semantic Web proposed by W3C.

2.4 Semantic web technology in improving data interoperability

The Semantic Web, introduced by the World Wide Web Consortium (W3C) (Berners-Lee et al., 2001), is a framework designed to make data on the web machine-readable, thereby enabling more intelligent and automated ways of accessing, relating, and analyzing information. Central to the Semantic Web is the Resource Description Framework (RDF), a standard model for data interchange. RDF uses triples, composed of a subject, predicate, and object, as its fundamental units to describe and link data (Lassila et al., 2001). Each element within an RDF triple can be uniquely identified using a Uniform Resource Identifier (URI), which facilitates precise data location and querying across the web.

The significance of RDF lies in its ability to represent complex relationships between data entities, making it a powerful tool for integrating diverse data types. By providing a common framework for data description, RDF enables the interoperability of heterogeneous data sources, which is crucial in complex, multidisciplinary fields like the AEC industry.

The technological stack of the Semantic Web (W3C, 2007), as depicted in Figure 1, includes various layers that support the creation, storage, and querying of semantically rich data. These layers collectively enable the transformation of raw data into a structured and meaningful format, allowing for enhanced data sharing and interoperability across different systems and platforms.

The application of Semantic Web technologies in the AEC sector has been extensively studied. Pauwels et al. (2017) demonstrate how these technologies can create well-defined semantic frameworks that facilitate data sharing and understanding across different software platforms and among various stakeholders. This capability is particularly valuable in integrating Building Information Modeling (BIM) with other data systems, such as Geographic Information Systems (GIS). Studies by Karan et al. (2016) and Zhu and Wu (2022) highlight the seamless merging of spatial and structural data through Semantic Web technologies, enabling more coherent and accessible data environments.

Beyond traditional data types, the Semantic Web also supports the integration of BIM with emerging technologies like the Internet of Things (IoT) and virtual reality. This integration opens new avenues for real-time, interactive project management, as explored by Tang et al. (2022) and Khalili (2021). The potential for Semantic Web technologies to enhance the functionality of Digital Twins (DTs) in construction projects is further emphasized by Boje et al. (2020), who illustrate its role in developing systems that require dynamic data interaction across multiple platforms.

The combination of Semantic Web and Blockchain technologies represents a promising approach to enhancing both the semantic richness and security of data environments in construction. Cano-Benito et al. (2019) discuss how the Semantic Web provides robust methodologies for defining, modeling, and linking data, while Blockchain ensures secure and reliable data exchanges. In the context of supply chains and Industry 4.0, Ruta et al. (2017) and English et al. (2016) investigate how a semantically enriched Blockchain can enhance scalability and transaction management, underscoring the broader applicability of these technologies. This synergy is further explored in various domains, such as healthcare and social media, where secure smart contracts and copyright management systems have been developed using these combined technologies (Chondrogiannis et al., 2022; García and Gil, 2019).

Despite these advancements, the development of a comprehensive DT data environment for construction management that effectively integrates the Semantic Web with Blockchain technology remains largely unexplored. This represents a significant research opportunity to leverage the strengths of both technologies to address the complex requirements of modern power infrastructure projects. Our research aims to fill this gap by integrating these technologies into a robust and trustworthy DT data platform, enabling seamless data integration, enhanced interoperability, and secure data management across diverse and complex datasets.

3 Methodology

3.1 Proposed architecture

The proposed DT data platform architecture is designed to cater specifically to the complex requirements of power infrastructure construction projects. Central to this architecture is the integration of Blockchain and Semantic Web technologies, which work in concert to address the needs for secure data management, traceability, and collaborative multi-disciplinary engagement across various project stages.

Figure 2 depicts the proposed data platform architecture. At its heart is a permissioned Blockchain network. This ensures that only authorized project participants, such as engineers, designers, and project managers, can access, contribute to, and modify the stored data. The Blockchain serves as an immutable ledger, where each

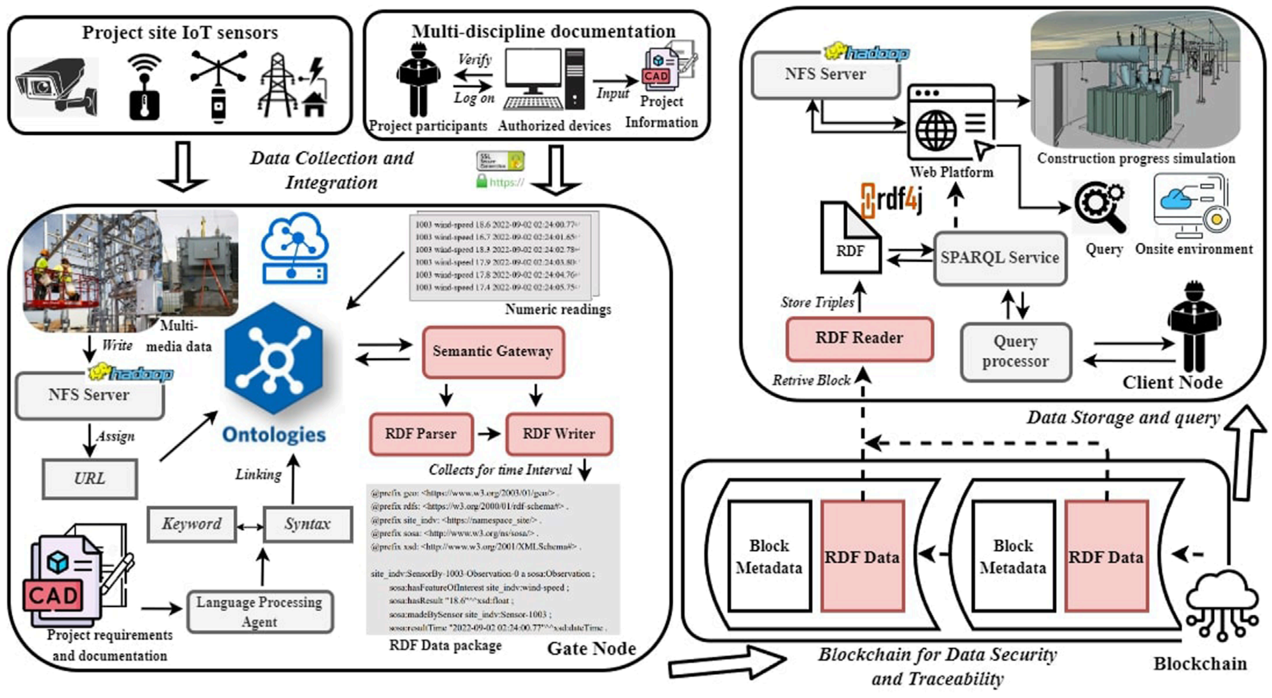

FIGURE 2
Construction digital twin data platform framework.

data transaction is recorded, ensuring traceability and security. This aspect is crucial for managing frequent updates and revisions to design documents, including 2D and 3D CAD files, throughout the construction lifecycle. A Semantic Web gateway converts various data inputs into a unified RDF format to enhance interoperability among diverse data formats and sources. This gateway processes data collected from IoT sensors and manual inputs, including design changes and project requirements. The system supports complex data relationships and enables enhanced querying capabilities by using RDF and Semantic Web technologies, crucial for multi-disciplinary collaboration. Distributed throughout the construction site and project offices, Gate nodes are specialized computer devices tasked with data collection and initial processing. These nodes handle the conversion of raw data into RDF data, sign the data with a unique cryptographic signature, and prepare it for Blockchain integration. This setup secures the data and maintains its fidelity from the point of collection to storage. Client nodes are operated by various stakeholders to interact with the Blockchain. They validate incoming data packets, contribute to the Blockchain's consensus mechanism, and retrieve RDF data for local processing and querying. Client nodes play a pivotal role in ensuring that all project participants have access to up-to-date and accurate project data, facilitating real-time decision-making and design modifications.

The operational workflow begins with data collection at the Gate nodes, which capture and preprocess data from multiple sources, including environmental sensors and manual design inputs. Once processed, this data is converted into RDF format by the Semantic Web Gateway and then transmitted to the Blockchain network. Here, data integrity and traceability are ensured as each transaction is recorded with timestamps and cryptographic proofs.

Subsequently, client nodes retrieve and utilize this data, employing tools such as SPARQL for advanced querying. This allows for complex interactions with the data, such as tracing the evolution of design documents or simulating construction progress scenarios. These capabilities are essential for accommodating the dynamic nature of large-scale construction projects where design parameters can frequently change and require rapid, informed adjustments by all disciplines involved.

3.2 Data collection and integration

Data collection and integration are critical components designed to enhance project efficiency and accuracy within the proposed DT data platform for power infrastructure construction projects. The integration of advanced Semantic Web technologies plays a pivotal role in ensuring seamless fusion of diverse data types, thereby supporting complex project demands and enabling robust multi-disciplinary collaboration.

The data collection mechanism is twofold, involving both automated and manual inputs. Strategic deployment of IoT sensors across the construction site facilitates real-time monitoring of crucial parameters such as temperature, pressure, and structural integrity. These sensors generate a continuous stream of numeric and multimedia data that is integral to tracking construction progress and environmental conditions. This sensor data becomes a foundational layer of real-time, actionable insights that help in quick decision-making and proactive project management.

Complementing this, manual data inputs are provided by project participants, including architects, engineers, and construction

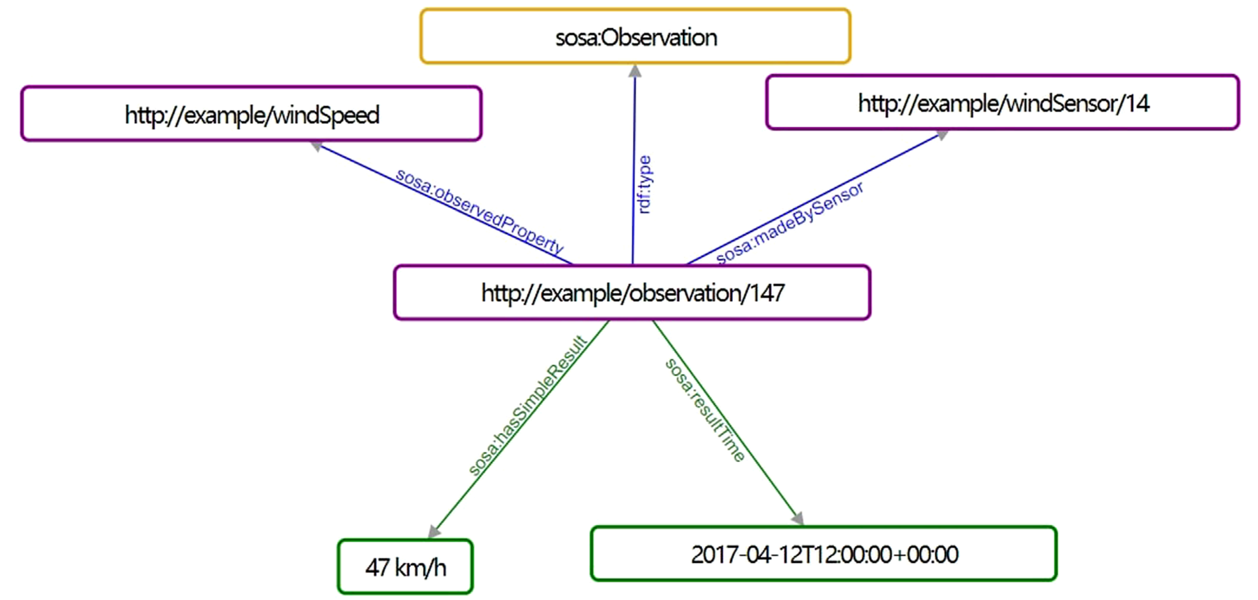

FIGURE 3
Anemometer reading express in Semantic Sensor Network ontology.

managers. These inputs primarily consist of detailed 2D and 3D CAD files and BIM models, which are central to the construction design process. Given the dynamic nature of construction projects, these documents frequently undergo updates during the construction phase to reflect the evolving project requirements and onsite conditions. These manual entries are integrated into the data platform through secure interfaces of Hypertext Transfer Protocol (HTTP) (Fielding and Reschke, 2014) with Transport Layer Security (TLS) (Rescorla, 2018) on authorized devices, ensuring that all data entries are authenticated and integrity maintained.

All collected data, whether from IoT sensors or manual inputs, is funneled through the Semantic Web Gateway, with its RDF parser and RDF writer proxy to convert the data into RDF format. Here, data is standardized to ensure that the diverse data types are interoperable and can be effectively linked and queried. Figure 3 illustrates a sample of anemometer data reading converted to its RDF format via the Semantic Gateway. The RDF format encapsulates data in a structured manner, using triples (subject, predicate, object), which allows for precise and flexible data manipulation.

RDF inherently supports the representation of semantic information, particularly for textual and numerical data. However, graphical data types like design information in CAD drawings and blueprints are not directly expressible in RDF. To address this, advanced blueprint interpretation techniques, such as those developed by Chen et al. (2024a) are employed to automatically extract key design parameters and information. This process enables the seamless integration of these traditionally non-RDF data types into the Semantic Web framework, enhancing the system's capacity to link and query diverse datasets effectively.

For multimodal data that cannot be directly converted to RDF format, such as multimedia files of on-site pictures, CCTV footage, and original CAD/BIM files, the Gate node responsible for collecting these data uploads them to a Network File System (NFS). This system is dedicated to storing these project files. The Gate node assigns each uploaded file a Universal Resource Locator (URL) for access. The URLs of these multimodal data files are then used as the 'object' in the RDF triples. These triples are linked to metadata such as the time of upload, location, and other relevant information. Details on the storage of large multimedia files can be found in Section 3.4.

After conversion to RDF, data is fused to create a comprehensive data environment that represents all aspects of the construction project. This integration is facilitated by semantic linking, which connects related data points across different sources, enhancing the richness and usability of the data. For example, sensor data indicating a structural anomaly can be directly linked to the specific section of the CAD model it affects, enabling quick assessment and decision-making.

The integration of Semantic Web technologies facilitates the standardization and linkage of diverse data and ensures that the data remains queryable and actionable throughout the project lifecycle. This capability is particularly beneficial for multidisciplinary teams that rely on up-to-date and accurate data for collaborative decision-making. By providing a unified view of all project-related data, the proposed DT significantly reduces the potential for errors and miscommunications that can arise from disparate data systems.

3.3 Blockchain for data security and traceability

As data collected from IoT sensors and manual inputs are processed into RDF formats, the Gate node temporarily stores

```
PREFIX ssn: <http://www.w3.org/ns/ssn/>
PREFIX time: <http://www.w3.org/2006/time#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT ?date ?temperature ?windSpeed
WHERE {
  ?obs a ssn:Observation;
       ssn:observedProperty ssn:WindSpeed;
       ssn:observationResultTime ?time;
       ssn:observationResult [ssn:hasSimpleResult ?windSpeed].

  ?tempObs a ssn:Observation;
           ssn:observedProperty ssn:Temperature;
           ssn:observationResultTime ?tempTime;
           ssn:observationResult [ssn:hasSimpleResult ?temperature].

  BIND (xsd:date(?time) AS ?date)
  FILTER ((?windSpeed >= 20.0 || ?temperature > 35.0) && xsd:date(?tempTime) = ?date)
}
ORDER BY ?date
```

Listing 1. SPARQL Query for Analyzing Temperature Fluctuations and Wind Speed Events.

the data in RDF data packages. These packages are accumulated every 10 min or until reaching a size of 1 MB, whichever occurs first. Following this accumulation, the Gate node signs the data package as a single transaction and pushes it to the Blockchain. Each Gate node is equipped with a private key used to encrypt and sign the transaction of the RDF data package. The Gate node employs SHA-256 (National Institute of Standards and Technology, 2015), a cryptographic hash algorithm, to generate a verifiable digital signature that combines the RDF data content with its private key.

Client nodes within the network act as validators, verifying the validity of data packets to ensure they conform to project standards and security protocols. Valid data packets are then grouped into blocks, with each block containing a cryptographic hash of the previous block, thereby chaining them together in a secure and traceable manner. This chain forms an unbreakable link that ensures the integrity and provenance of the data within the Blockchain. The proposed DT employs a permissioned Blockchain, accessible only to verified project participants, enhancing the security and privacy of the data. Each block generated includes a set of transactions, with the block header encrypted with a hash value and a digital signature. Additionally, the metadata of each block contains the hash of the previous block, linking the blocks in a chronological and tamper-proof sequence.

Project participants at the Client nodes can query the Blockchain to retrieve data for various purposes, such as progress monitoring, compliance checks, and design verification. The immutability and traceability of the data stored on the Blockchain ensure that all retrieved information is accurate and reliable. This mechanism certifies the provenance and integrity of data collected from each node.

Once blocks containing chained RDF data transactions are confirmed and added to the Blockchain, the RDF data becomes immutable and is permanently stored over the network. This feature is critical for power infrastructure projects, where data integrity and security are paramount. The use of Blockchain technology in the proposed DT provides a robust foundation for multi-disciplinary collaboration, preventing disputes and misunderstandings that can arise from data mishandling or misinterpretation. By ensuring that all project data is secure, immutable, and traceable, Blockchain technology underpins an accurate and accountable construction process.

3.4 Data storage and query

The proposed DT integrates numerical and textual data as well as large-sized files such as camera footage and full CAD drawings. Due to the inherent unsuitability of Blockchains for storing such large files (Lee et al., 2021), alternative storage solutions are employed. An NFS is utilized for storing files needed for the project, while the Hadoop File System (HDFS) (Apache Hadoop Project, 2024), a distributed file system, enables authorized users to conveniently share and access extensive-size files on remote distributed servers. HDFS is deployed on remote commodity hardware, leveraging an NFS Gateway to mount the HDFS as storage for large files.

The Gate node device uploads the file to the NFS server and assigns it an URL for access. Concurrently, the Gate node integrates the file information into a set of RDF data, which includes the file's hash value, provenance, and other metadata properties. The uniqueness of a file's hash value means that any modification to the original file will drastically alter this value. As RDF data about a file is sent to the Blockchain network for permanent storage, project participants can verify the originality and authenticity of the file by comparing its hash value.

Client nodes access and verify each block's hash as new data arrives. Validated blocks are then replicated into local databases using RDF reader proxies to interpret and structure the semantic information within the blocks. This structured data is stored in an Eclipse RDF4j (Eclipse RDF4J Project, 2024) framed database, designed to manage complex data relationships efficiently, even with partial information. These databases support real-time data access and sophisticated querying capabilities with SPARQL endpoints. Project participants can utilize SPARQL to query interconnected data across various domains, such as querying the impact of environmental factors on material durability or tracking changes to architectural designs. Listing 1 outlines a SPARQL query utilized to interrogate the RDF4j database storing environmental sensor data from a power infrastructure construction site. This query identifies days when notable weather events of high wind speeds exceeding 20.0 m per second or temperatures above 35°C occur, which potentially impacts construction activities. Client nodes provide interfaces for real-time data access and monitoring, facilitating immediate updates and insights into project status. This capability is crucial for project managers and engineers who need to make timely decisions based on the latest available data.

Integration with data analytics tools enables complex analyses, such as predictive maintenance, optimization of resource allocation, and risk assessment. These analyses help in anticipating potential issues and planning interventions more effectively. Efficient data storage and sophisticated querying mechanisms are vital for multi-disciplinary teams involved in power infrastructure projects. By providing seamless access to integrated and up-to-date project data, the DT enables various specialists—from civil engineers to electrical technicians—to work collaboratively. This integrated approach ensures that all team members have access to the same accurate and comprehensive data, reducing conflicts and enhancing project execution efficiency.

4 Case study

The proposed framework was implemented with various data inputs collected from an actual power infrastructure construction project site to verify its feasibility. For this purpose, a Blockchain network was deployed using the Sepolia Ethereum test net (Ethereum Foundation, 2024). Sepolia is primarily utilized for application testing, where its cryptocurrency, Ether, holds no real-world value. The Ethereum platform was initially developed as a public Blockchain using a Proof of Work (PoW) consensus protocol. Permissioned Blockchain protocol based on Ethereum had also been developed for private transactions, such as the Quorum Blockchain Service (QBS) (ConsenSys, 2024). Its Raft-based consensus mechanism (Ongaro and Ousterhout, 2014) enables QBS to handle hundreds of transactions per second, faster than the current Ethereum main net. This research does not focus on specific Blockchain networks but the principles of a traceable and trustworthy data platform. Thus, the detail of the development of consensus mechanisms is beyond the scope of this paper. The authors aim to verify that employing a Blockchain network to store and distribute annotated semantic data is feasible via the Sepolia Ethereum test net.

An environmental sensor platform equipped with a thermometer, an anemometer, a decibel meter, and particulate matter sensors (PM 2.5 and PM 10) was deployed at the site.

```
1003 wind-speed 18.6 2022-09-02 02:24:00.77
1003 wind-speed 16.7 2022-09-02 02:24:10.65
1003 wind-speed 18.3 2022-09-02 02:24:20.78
1003 wind-speed 17.9 2022-09-02 02:24:30.80
1003 wind-speed 17.8 2022-09-02 02:24:40.76
1003 wind-speed 17.4 2022-09-02 02:24:50.75
```

FIGURE 4
Section of a raw anemometer sensor data.

These sensors varied in their sampling rates from every 10 s to every minute. The devices were connected to a Raspberry Pi (Raspberry Pi Foundation, 2024), which acted as the Gate node in the proposed framework. Figure 4 shows a section of the raw data collected from an anemometer, which was timestamped by the Gate node. The interface with sensor devices and later with the Ethereum Blockchain was developed using Python 3 (Python Software Foundation, 2024), with the Python package manager pip3 (PYPI, 2024) installed on the Gate node device.

A semantic gateway algorithm and an RDF agent, as described in Section 3, were developed and implemented primarily using Python 3. The semantic gateway was responsible for mapping sensor data to its corresponding ontology. For this case study, the Semantic Sensor Network (SSN) ontology (W3C Semantic Sensor Network Incubator Group, 2017), developed by the W3C and commonly used for sensor observation data, was adopted. However, for more tailored needs within construction projects and the AEC industry, the development of more complex ontologies is planned for future research.

Ethereum's Smart Contracts, automated programs deployed on the Blockchain network, facilitate the development of Distributed Applications (DAPPs). Solidity, a standard programming language for Ethereum, was used to develop these contracts. Truffle Suite (2024), a Node. js application (Nodejs Foundation, 2024), was employed to develop, compile, and deploy the Smart Contracts that stored and retrieved RDF data on Sepolia. The Gate node processed and sent RDF data as transactions to the Blockchain using the Smart Contract, which accessed sections of permanent storage on the Ethereum Blockchain network. Once the transactions with RDF data were validated and blocks were generated, the data became traceable and trustworthy.

At the Client node, a web platform with a RESTful API was developed to display the project's semantic data and provide prototype querying functions. This platform is essentially a DAPP powered by Ethereum Smart Contracts. Tests were conducted to verify the successful delivery and integrity of the semantic data across the Sepolia network. The Client node device utilized a Smart Contract with a View function to retrieve the stored data, requiring no additional computation power from the Blockchain.

To ensure the consistency and accuracy of the data captured by the Gate nodes, we utilized the Protégé platform (Musen, 2015), an open-source knowledge management system. Its embedded reasoning engine, Pellet (Sirin et al., 2007), was employed to assess

```
@prefix geo: <https://www.w3.org/2003/01/geo/> .
@prefix rdfs: <https://w3.org/2000/01/rdf-schema#> .
@prefix site_indv: <https://namespace_site/> .
@prefix sosa: <http://www.w3.org/ns/sosa/> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

site_indv:SensorBy-1003-Observation-0 a sosa:Observation ;
    sosa:hasFeatureOfInterest site_indv:wind-speed ;
    sosa:hasResult "18.6"^^xsd:float ;
    sosa:madeBySensor site_indv:Sensor-1003 ;
    sosa:resultTime "2022-09-02 02:24:00.77"^^xsd:dateTime .

site_indv:SensorBy-1003-Observation-1 a sosa:Observation ;
    sosa:hasFeatureOfInterest site_indv:wind-speed ;
    sosa:hasResult "16.7"^^xsd:float ;
    sosa:madeBySensor site_indv:Sensor-1003 ;
    sosa:resultTime "2022-09-02 02:24:10.65"^^xsd:dateTime .
```

FIGURE 5
RDF graph data retrieved by Client node device.

the RDF data for logical consistency, completeness, and alignment with the defined ontological data structures. The process involved loading the RDF data retrieved from the Blockchain into Protégé, where the Pellet reasoning engine was used to validate the data. This validation process checks whether the linked data is correctly structured according to the defined ontologies and whether there are any logical contradictions or missing elements. For instance, it verifies that all expected relationships between entities are present and correctly represented, and that no inconsistencies exist within the data model.

Figures 5, 6 illustrate the results of this validation process. Figure 5 shows a section of the RDF data as received by the Client node device. This data includes essential information such as observation values and timestamps, confirming that the sensor data (e.g., wind speed measurements) has been successfully transmitted and stored within the Blockchain network. Figure 6 demonstrates the interpretation of this data by the Protégé reasoning engine. It shows distinct wind speed observations/events captured by a sensor correctly linked within the RDF structure. This validated data can now be seamlessly combined with other heterogeneous data sources, supporting comprehensive analysis and decision-making in the wider context of the construction project. This successful interpretation affirms that the data captured, stored, and retrieved through the proposed framework is both accurate and reliable.

In addition to validating the reliability of the RDF data sent across the framework, a quantitative experiment was also conducted to evaluate the performance impact of querying IoT sensor data stored in the semantically rich RDF format, and in raw non-RDF tabular format. The goal was to evaluate how converting sensor data into RDF, which increases data volume and structure, affects query performance when stored on a Blockchain. The experiment was conducted under increasing data loads, ranging from 1,000 to 100,000 records, using the same IoT sensor data in the two distinct formats.

As shown in Figure 7, query times increased with the number of records for both formats. However, the RDF format consistently exhibited longer query times than the non-RDF format due to its larger data size. At 1,000 records, the RDF format required an average of 50 ms per query, while the non-RDF format required 30 ms. This performance gap widened as the number of records increased. For 100,000 records, the RDF query time was 2,200 ms, compared to 1,000 ms for the non-RDF format. The increase in query time for RDF data can be attributed to the overhead of processing RDF triples. Each data point in RDF is represented by multiple subject-predicate-object relationships, which leads to more data being stored and retrieved during each query.

While RDF provides enhanced semantics and interoperability, it also increases data size and introduces additional query complexity. This results in significantly slower query times as the number of records increases, especially at scale. For example, with a sampling rate of every 10 s, a single sensor can produce over 8,000 records per day. An installation of 10 sensors would mean that after 1 day of operation, the system would be handling close to 100,000 records, which in the experiment demonstrated an RDF query time of over 2 s per request. While this is manageable for low-frequency data retrieval, it may present challenges for applications requiring rapid querying, such as real-time safety monitoring.

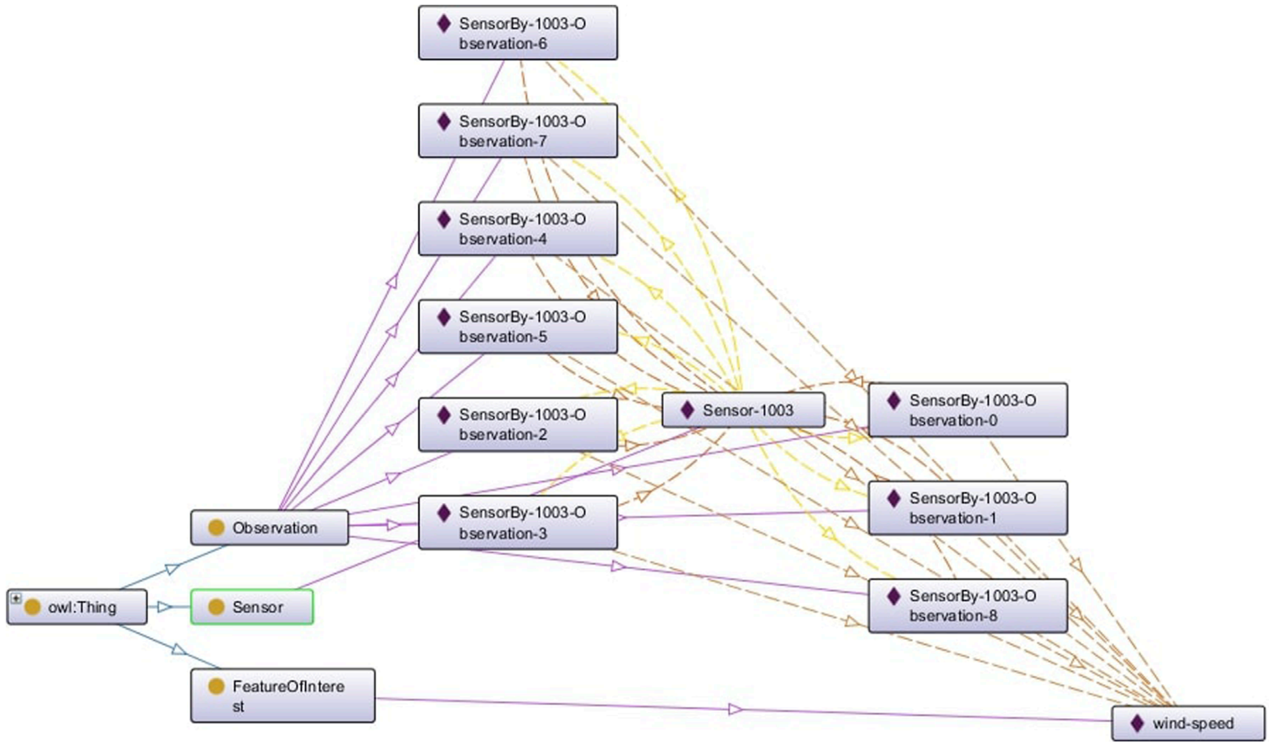

FIGURE 6
Sensor data interpretation by Protégé reasoning engine.

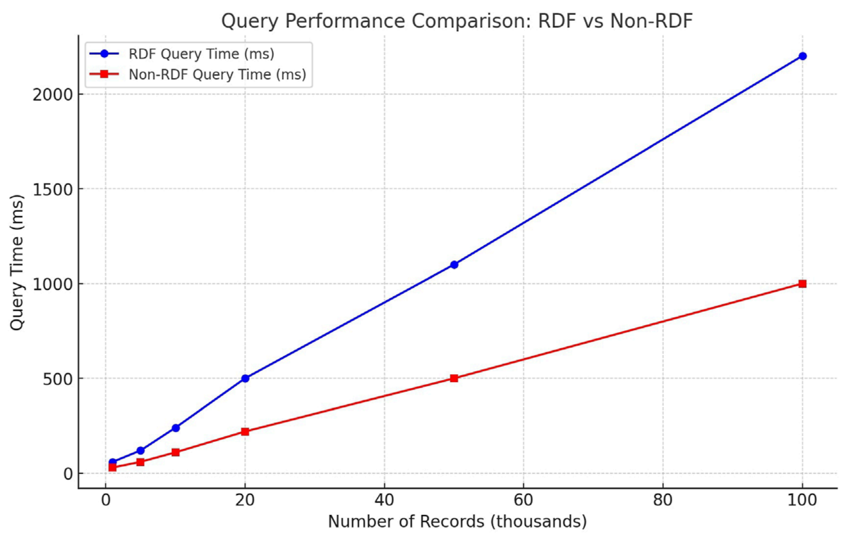

FIGURE 7
Query performance comparison: RDF vs. Non-RDF.

These scalability challenges are critical to address as the system moves from proof-of-concept to real-world deployment. Although the experiment demonstrates the feasibility of using Blockchain to store and query large amounts of IoT data, further optimizations will be necessary for larger-scale implementations. Such optimization strategies could include data sampling and off-chain storage to ensure that the platform remains practical when handling the large data volumes generated in a large power infrastructure construction site. It is also important to note that the framework is designed to integrate multiple heterogeneous data sources, where IoT data, being the most dynamic, generates the largest number of records, while other types of data, such as design files and contracts, require far fewer data transactions.

This case study successfully demonstrates the feasibility of using a Blockchain-based framework to store and query semantically rich RDF data. The framework's ability to handle diverse, heterogeneous data sources highlights its potential for managing interconnected datasets across various project components. The interoperability offered by RDF enhances data integration across systems, allowing for more dynamic and insightful management of construction site data. However, the experiment also revealed performance challenges, particularly when dealing with large volumes of high-frequency IoT data. Performance optimizations may be necessary for large-scale deployments to ensure the system remains scalable and efficient. Despite these challenges, the framework remains a promising solution for secure and transparent data management in construction projects.

5 Discussion

This research has successfully demonstrated a trustworthy data platform that aggregates heterogeneous data from construction sites and disseminates it among project stakeholders. By integrating Semantic Web and Blockchain technologies, the platform ensures the storage and distribution of reliable, traceable, and semantically linked data. The prototype, tested within a case study, confirmed the feasibility of this concept, showcasing how sensor data was effectively linked and disseminated across a public Blockchain and subsequently interpreted and stored in RDF databases.

However, several critical issues warrant consideration for further implementations of the proposed data platform. The primary concern relates to the storage and distribution of RDF data on the Blockchain, particularly due to its verbose nature when handling a substantial volume of linked IoT sensor data in RDF format. Since the data is permanently updated on the Blockchain via smart contracts, this process demands more computational power and resources compared to traditional methods. Storing large amounts of sensor data indiscriminately is inefficient and likely impractical on public chains. It is suggested that novel consensus algorithms be implemented within the dedicated Blockchain to minimize computational power consumption. Alternatively, strategies to reduce the volume of data should be considered, such as decreasing the original sampling rates of the IoT sensors—ensuring they still provide adequate information for project management—or employing random sampling of homogeneous sensors to diminish data redundancy.

Lee et al. (2021) proposed an approach where processed data, termed 'compliance statements', replace raw sensor data. This method involves an expert system that evaluates sensor data and outputs a human-readable result, which could be integrated into the proposed data platform to reduce the size of the sensor data before it is sent to the Blockchain. However, this preprocessing raises concerns regarding the originality and credibility of the data. This preprocessing framework processes IoT data remotely before transmission to the Blockchain, potentially compromising the credibility of the data. While one of the core benefits of Blockchain is the shared trust in reliable data, the data's originality and reliability must be ensured by all nodes once it is on the Blockchain. However, if the information has been altered prior to Blockchain transmission, other nodes have no means of verifying its authenticity, potentially leading to distrust. This challenge is known as the Oracle problem, where the Oracle possesses information that others do not. Future research is therefore recommended to ensure that IoT data collected is free from malicious tampering and can be more reliably trusted.

Moreover, with project data stored in RDF format, spatial and temporal reasoning can be conveniently applied to deduce complex information about the construction project. Future research should also focus on developing expert reasoning systems that further link project data and facilitate querying of complex information, thereby enhancing the operational efficacy and analytical capabilities of the construction management process.

6 Conclusion

This research has developed a novel DT data platform utilizing both Blockchain and Semantic Web technologies to address critical challenges in data management within power infrastructure construction projects. By integrating diverse data sources—from manual inputs and IoT sensor data to large-scale file storage—into a unified platform, this study presents a robust solution for enhancing interoperability, ensuring data security, and facilitating comprehensive data traceability. This research has primarily focused on addressing the challenges faced in power infrastructure projects. However, the proposed DT data platform framework is not limited to this specific industry. With appropriate adaptations, such as incorporating asset monitoring and expanding environmental monitoring, our framework can be applied to a wide range of construction management contexts. The benefits of data traceability, interoperability, and security are universally applicable, providing significant advantages in managing complex supply chains and ensuring reliable project data management.

Compared to previous systems, the data platform proposed in this research offers substantial advancements in handling the intricacies of power infrastructure projects. Previous systems in DTs and BIMs have been instrumental in project management but often fall short in areas like data traceability, security, and integration of diverse data types. These systems typically lack mechanisms for immutable data storage and robust traceability, exposing them to risks like data tampering and loss, which can undermine stakeholder trust and project integrity. Furthermore, while existing data environments attempt to centralize data management, they struggle with the seamless integration of heterogeneous data sources, such as combining IoT sensor data with traditional BIM or CAD designs. This limitation hampers the effective management of complex projects that require real-time data access and multidisciplinary collaboration. The developed DT leverages Semantic Web technologies to standardize data into the RDF format, thereby enabling complex data relationships to be navigable and meaningful. Additionally, the application of Blockchain technology guarantees that all data stored is immutable and traceable, thereby enhancing security against tampering and fostering trust among project stakeholders through verifiable data provenance. Furthermore, the integration of Blockchain with RDF also serves as a robust database solution. This capability is crucial for efficiently storing and distributing data collected from various sources across power infrastructure projects to multiple stakeholders, enhancing overall project management and coordination.

The feasibility of the proposed concept was underscored through a practical implementation within a real-world power infrastructure construction project. The prototype test results confirmed the platform's capability to successfully link and distribute sensor data across a public Blockchain, allowing it to be interpreted and stored in RDF databases. This practical application demonstrated the platform's operational viability and significantly improved existing data management practices.

However, the research also highlighted several areas for further exploration to enhance the platform's functionality. Future studies could investigate the development of advanced consensus mechanisms to reduce the energy consumption and computational overhead associated with Blockchain. Additionally, enhancing the data verification processes to address the Oracle problem remains a critical challenge. This would ensure that the integrity and authenticity of incoming data are maintained before it is processed and stored. Another promising area involves the integration of expert reasoning systems, which could facilitate more complex data analysis and decision-making, providing nuanced insights that are crucial for effective construction management.

In conclusion, this research significantly contributes to the digital transformation of power infrastructure construction by providing a secure, reliable, and efficient data management system. The innovative integration of Blockchain and Semantic Web technologies not only meets the complex demands of modern construction projects but also sets a new benchmark for future developments in the field.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

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

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Conflict of interest

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