

InfraChain: A Sensor Enabled Bridge Management Application Using Blockchain

by

Sadia Hossain Rumpa (191014007)
Samia Ishrat (191014051)
Sheikh Tajrean Reza (191014063)
Md. Shafiqul Islam Suman (192014036)
Md. Faysal Ahmmed (193014075)

*Project/Thesis report (CSE499) submitted in partial fulfillment of the
requirements for the degree of*

Bachelor of Science in Computer Science and Engineering

Under the supervision of

Nafees Mansoor, SMIEEE



DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING
UNIVERSITY OF LIBERAL ARTS BANGLADESH

SUMMER 2024

© *Sadia Hossain Rumpa*
© *Samia Ishrat*
© *Sheikh Tajrean Reza*
© *Md. Shafiqul Islam Suman*
© *Md. Faysal Ahmmed*
All rights reserved

DECLARATION

Project Title InfraChain: A Sensor Enabled Bridge Management Application Using Blockchain

Authors *Sadia Hossain Rumpa, Samia Ishrat, Sheikh Tajrean Reza, Md. Shafiqul Islam Suman and Md. Faysal Ahmmed*

Student IDs 191014007, 191014051, 191014063, 192014036 and 193014075

Supervisor Nafees Mansoor, SMIEEE

We declare that this project/thesis report entitled *InfraChain: A Sensor Enabled Bridge Management Application Using Blockchain* is the result of our own work except as cited in the references. The project/thesis report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Sadia Hossain Rumpa
191014007

Department of Computer Science and Engineering
University of Liberal Arts Bangladesh

Samia Ishrat
191014051

Department of Computer Science and Engineering
University of Liberal Arts Bangladesh

Sheikh Tajrean Reza
191014063

Department of Computer Science and Engineering
University of Liberal Arts Bangladesh

Md. Shafiqul Islam Suman
192014036

Department of Computer Science and Engineering
University of Liberal Arts Bangladesh

Md. Faysal Ahmmed
193014075

Department of Computer Science and Engineering
University of Liberal Arts Bangladesh

Date: October 14, 2024



Department of Computer Science and Engineering
University of Liberal Arts Bangladesh
Mohammadpur, Dhaka - 1207

CERTIFICATE

This is to certify that the project/thesis report entitled **InfraChain: A Sensor Enabled Bridge Management Application Using Blockchain**, submitted by **Sadia Hossain Rumpa** (Student ID: 191014007), **Samia Ishrat** (Student ID: 191014051), **Sheikh Tajrean Reza** (Student ID: 191014063), **Md. Shafiqul Islam Suman** (Student ID: 192014036) and **Md. Faysal Ahmmed** (Student ID: 193014075) are undergraduate students of the **Department of Computer Science and Engineering** and it has been examined. Upon recommendation by the examination committee, we hereby accord our approval of it as the presented work and submitted report fulfill the requirements for its acceptance in partial fulfillment for the degree of *Bachelor of Science in Computer Science and Engineering*.

Nafees Mansoor, SMIEEE, Associate Professor
Dept. of CSE, University of Liberal Arts Bangladesh

Muhammad Golam Kibria, PhD, SMIEEE, Professor
Dept. of CSE, University of Liberal Arts Bangladesh

Mohammed Ashikur Rahman, Assistant Professor
Dept. of CSE, University of Liberal Arts Bangladesh

Jannatul Ferdous Ruma, Lecturer
Dept. of CSE, University of Liberal Arts Bangladesh

Place: Dhaka

Date: October 14, 2024

ACKNOWLEDGEMENTS

We would like to express our deep and sincere gratitude to our research supervisor, *Nafees Mansoor, SMIEEE*, for giving us the opportunity to conduct research and providing invaluable guidance throughout this work. His dynamism, vision, sincerity and motivation have deeply inspired us. He has taught us the methodology to carry out the work and to present the works as clearly as possible. It was a great privilege and honor to work and study under his guidance.

We are greatly indebted to our honorable teachers of the Department of Computer Science and Engineering at the University of Liberal Arts Bangladesh who taught us during the course of our study. Without any doubt, their teaching and guidance have completely transformed us to the persons that we are today.

We are extremely thankful to our parents for their unconditional love, endless prayers and caring, and immense sacrifices for educating and preparing us for our future. We would like to say thanks to our friends and relatives for their kind support and care.

Finally, we would like to thank all the people who have supported us to complete the project work directly or indirectly.

*Sadia Hossain Rumpa, Samia Ishrat, Sheikh Tajrean Reza,
Md. Shafiqul Islam Suman and Md. Faysal Ahmmed*

University of Liberal Arts Bangladesh

Date: October 14, 2024

Dedicated to
my beloved Parents and Siblings
my biggest cheerleaders and the fuel that keeps me moving
– Sadia Hossain Rumpa

Dedicated to
my beloved parents and Siblings
the source of my inspiration and constant support.
– Samia Ishrat

Dedicated to
my loving mother
an encouraging soul.
– Sheikh Tajrean Reza

Dedicated to
my parents
for always supporting me.
– Md. Shafiqul Islam Suman

Dedicated to
my parents
for always guiding me to the right direction.
– Md. Faysal Ahmmed

ABSTRACT

The integrity of bridges is crucial for safe and efficient transportation. Traditional infrastructure monitoring methods, however, often face challenges such as data inconsistency, lack of transparency, and delayed maintenance actions. This project proposes InfraChain, a sensor enabled bridge maintenance system that leverages sensor and blockchain technology to address these limitations. InfraChain utilizes a variety of sensors including strain gauge and fiber optic sensors to collect real-time data on bridge health, encompassing structural strain and traffic noise patterns that may indicate road surface changes. The collected data is monitored and analyzed for any anomalies. The analyzed data is integrated with a blockchain platform which provides several advantages for this application, including immutability, transparency and traceability. These features ensure the integrity and security of the data, enabling reliable and timely maintenance decisions. By combining real-time sensor data with blockchain technology, InfraChain aims to achieve early detection of road damage, improved maintenance efficiency and enhanced transparency. The methodology involved deploying a network of sensors on bridges to continuously monitor critical structural health indicators. The data is processed and analyzed to predict maintenance needs, and a blockchain ledger records the data points related to maintenance needs and maintenance activities. This integration ensures that the data is tamper proof and transparent. The anticipated results include significant improvements in the detection and management of infrastructure issues, leading to safer and more reliable bridge maintenance practices. The performance and effectiveness of InfraChain were evaluated in a simulated environment, demonstrating its potential to revolutionize infrastructure monitoring. The findings suggest that InfraChain can lead to more proactive and cost effective maintenance strategies, ultimately enhancing roadway safety and reliability.

Keywords: Infrastructure, Blockchain, Sensor, Bridge, Management, Maintenance

Contents

1	Introduction	1
1.1	Background and Motivation	2
1.2	Problem Statement	4
1.3	Aims and Objectives	4
1.4	Significance	5
1.5	Scope & Limitation	5
2	System Components	7
2.1	Strain Gauge	7
2.2	Smart Contract	7
2.3	Blockchain	8
3	Literature Review	10
3.1	Literature Review and Comparative Analysis	10
4	Methodology	18
4.1	Research Design	18
4.2	Project management and planning	18
4.3	Proposed Systems' Architecture	19
4.4	Implementation Procedures	21
4.5	Validation and Testing	21
5	Design and Development	23
5.1	Financial Activities	23
5.2	Adopted Tools and Techniques	23
5.2.1	Sensors and Data Collection	23
5.2.2	Blockchain Platform	24

5.2.3	Development Environments	25
5.3	Designing the Solution	25
5.4	Implementation	26
5.5	Web Application View	29
6	Performance Analysis	36
6.1	Performance Analysis and Validation	36
7	Business Model	40
7.1	Customer Segmentation	40
7.2	Value Proposition	41
7.3	Revenue Sources	41
7.4	Principal Activities	42
7.5	Important Partnerships	42
7.6	Cost Structure	43
7.6.1	Prototype Development Cost	43
7.6.2	Full Scale Business Costs	44
7.6.3	Revenue and Break Even Point	45
8	Conclusion	47
8.1	Societal, Health, Safety, Legal, and Cultural Aspects	47
8.2	Impact on Environment and Sustainability	48
8.3	Ethical and Professional Principles	49
8.4	Future Work	49
	Bibliography	51

List of Figures

2.1	Blockchain Diagram	9
4.1	Proposed Systems' Diagram	20
5.1	Login Interface 01	30
5.2	Login Interface 02	30
5.3	Sign up Interface	30
5.4	Home Page Interface	31
5.5	Users Details Page Interface	31
5.6	Sensor Specification Page Interface	31
5.7	Sensor Data Page Interface	32
5.8	Monitoring Data Page Interface	32
5.9	Maintenance Data Page Interface	33
5.10	Blockchain Events Page Interface	33
5.11	Blockchain Events: Data Fetching using Sensor ID 01	34
5.12	Blockchain Events: Data Fetching using Sensor ID 02	34
5.13	Blockchain Events: Data Fetching using Sensor ID 03	35
5.14	Blockchain Events: Data Fetching using Requested ID 01	35
5.15	Blockchain Events: Data Fetching using Requested ID 02	35
6.1	TPS Graph Comparison between Public and Private Blockchain Networks	37
6.2	Latency Comparison between Public and Private Blockchain Networks	38
6.3	Block Data Fetching Time Comparison between Public and Private Blockchain Networks	39

List of Tables

3.1	Comparative Analysis of Literature Review	17
-----	---	----

Chapter 1

Introduction

Bridge infrastructure forms a vital component of modern transportation systems, enabling the seamless movement of people and goods across various regions [Quinci et al. \(2022\)](#). The maintenance and integrity of these structures are paramount to ensuring safety, economic stability, and the overall quality of life [Catbas & Avci \(2022\)](#). Despite their importance, traditional bridge monitoring methods primarily rely on manual inspections [Poli et al. \(2023\)](#). These methods are often labor-intensive, subjective, and susceptible to human error, leading to potential safety hazards, increased maintenance costs, and prolonged disruptions.

In this context, InfraChain presents a novel approach to bridge maintenance by leveraging advanced sensor networks and blockchain technology. This integration aims to address the limitations of conventional monitoring techniques by providing real-time, accurate, and immutable data on bridge health. InfraChain not only facilitates early detection of structural issues but also enhances transparency and accountability among stakeholders through the secure and traceable nature of blockchain.

This chapter provides an overview of the background literature, outlines the problem statement, and defines the objectives and significance of the project. It also discusses the scope and limitations of the study, setting the stage for a detailed exploration of InfraChain's design, implementation, and potential impact on the future of bridge maintenance.

1.1 Background and Motivation

The integrity of bridge infrastructure is paramount for the safe and efficient transportation of people and goods. Traditional methods of bridge monitoring primarily rely on manual inspections, which are labor-intensive, time-consuming, and susceptible to human error [Quinci et al. \(2022\)](#) [Catbas & Avci \(2022\)](#). These limitations often result in delayed detection and maintenance of structural issues, potentially leading to safety hazards, increased maintenance costs, and traffic disruptions [Poli et al. \(2023\)](#).

Recent advancements in sensor technology offer promising solutions to the limitations of manual inspections. Strain gauges and fiber optic sensors have been widely researched and utilized in structural health monitoring (SHM) systems due to their ability to provide real-time data on structural integrity [Hassani & Dackermann \(2023\)](#). Strain gauges measure the deformation of materials under stress, offering insights into the load and stress distribution within bridge components [H. Li et al. \(2020\)](#). Fiber optic sensors, on the other hand, are known for their high sensitivity and durability, making them suitable for long-term monitoring in harsh environmental conditions [Lanciano & Salvini \(2020\)](#).

Several studies have demonstrated the efficacy of these sensors in detecting anomalies in bridge structures. For instance, [Lanciano et al. \(2020\)](#) utilized fiber optic sensors to monitor the strain distribution in a cable-stayed bridge, successfully identifying potential failure points before they could develop into critical issues [Lanciano & Salvini \(2020\)](#). Similarly, it is reported that the integration of strain gauges in bridge girders provided valuable data on stress concentrations, facilitating timely maintenance interventions [Feng et al. \(2022\)](#).

Blockchain technology, characterized by its decentralized, immutable, and transparent nature, has gained traction as a potential solution for enhancing data security and transparency in various applications [Scott et al. \(2021\)](#). In the context of bridge monitoring, blockchain can address issues related to data integrity and trust among stakeholders by providing a tamper-proof ledger of all recorded data and maintenance activities [Celik et al. \(2023\)](#).

Research by Le et al. (2021) highlighted the benefits of blockchain in infrastructure projects, emphasizing its ability to ensure the authenticity and traceability of maintenance records [Le & Hsu \(2021\)](#). Furthermore, the integration of sensor networks with blockchain, demonstrates how this combination can enhance the reliability and transparency of Structural Health Monitoring systems [Guerrero-Sanchez et al. \(2020\)](#).

Despite the advancements in sensor and blockchain technologies, a comprehensive approach that seamlessly integrates these technologies for bridge monitoring remains underdeveloped. Existing systems often operate in silos, with sensor data being collected and analyzed independently of the platforms used for data storage and management [Ramasamy et al. \(2021\)](#). This disconnect can lead to inefficiencies and a lack of cohesive data analysis, undermining the potential benefits of real-time monitoring and predictive maintenance.

InfraChain aims to bridge this gap by integrating sensor networks with a blockchain platform, providing a unified solution for real-time monitoring, data analysis, and secure data management. This integration not only enhances the early detection of structural issues but also fosters transparency and accountability among all stakeholders involved in bridge maintenance.

The integration of advanced sensor technology and blockchain represents a significant leap forward in the field of bridge monitoring. By addressing the limitations of traditional methods and leveraging the strengths of both technologies, InfraChain has the potential to revolutionize infrastructure maintenance, leading to safer and more reliable transportation systems. This literature review underscores the necessity of such integrated solutions and sets the stage for the detailed exploration of InfraChain's design and implementation in the following chapters.

The motivation behind InfraChain stems from the critical need to enhance the safety and reliability of bridge infrastructure. Traditional monitoring methods are insufficient to address the growing demands for timely and accurate maintenance. By integrating sensor networks with blockchain, InfraChain aims to overcome

these limitations, providing a modern, efficient, and reliable solution for bridge maintenance.

1.2 Problem Statement

The safety and reliability of bridge infrastructure are essential for efficient transportation. Current bridge monitoring practices, which rely heavily on manual inspections, are time-consuming, error-prone, and often result in inconsistent data and delayed maintenance. These limitations can lead to safety hazards and increased maintenance costs. Furthermore, the lack of integrated real-time data collection and secure management hinders effective decision-making and transparency among stakeholders. To address these challenges, there is a need for an innovative solution that combines advanced sensor technology with blockchain to enhance the efficiency, accuracy, and transparency of bridge monitoring and maintenance.

1.3 Aims and Objectives

The primary aim of this project is to develop InfraChain, an integrated bridge maintenance system that leverages advanced sensor technology and blockchain to enhance the monitoring, detection, and management of structural health issues in bridges. This system aims to provide a reliable, real-time solution for ensuring the safety and longevity of bridge infrastructure. The objective of this project is to:

- Develop a Sensor Network
- Integrate bridge maintenance with Blockchain
- Real-time Monitoring and Analysis
- Trigger Maintenance Actions

1.4 Significance

- **Improved Safety:** InfraChain's real-time monitoring capabilities ensure early detection of structural issues, significantly reducing the risk of catastrophic failures and enhancing public safety.
- **Cost Efficiency:** By enabling predictive maintenance, InfraChain helps in optimizing resource allocation and reducing overall maintenance costs. Preventive measures can be taken before issues escalate, saving both time and money.
- **Enhanced Transparency and Accountability:** The use of blockchain ensures that all data related to bridge health and maintenance activities are securely recorded and transparent. This fosters trust among stakeholders, including government agencies, maintenance crews, and the public.
- **Scalability and Adaptability:** InfraChain can be scaled to monitor multiple bridges and adapted to various types of infrastructure, making it a versatile tool for infrastructure management.
- **Contribution to Smart Infrastructure:** This project contributes to the advancement of smart infrastructure solutions, integrating cutting-edge technologies to improve the management and maintenance of critical public assets.

1.5 Scope & Limitation

The scope of this project is to develop and evaluate InfraChain, an innovative bridge maintenance system that integrates advanced sensor technology with blockchain. The project involves designing and deploying a network of sensors, like strain gauges across bridge structures. This sensor will continuously monitor critical structural health indicators such as strain, temperature, and displacement in real-time. The data collected from this sensor will be securely stored and managed using a blockchain platform. This platform ensures the immutability, transparency, and traceability of the data, addressing issues of data inconsistency and lack of transparency found in traditional infrastructure monitoring methods.

InfraChain will employ algorithms for real-time monitoring and analysis of sensor data to detect anomalies and predict maintenance needs accurately. By automatically triggering maintenance alerts based on the analysis of sensor data, the system aims to facilitate timely and targeted maintenance interventions, thereby reducing the risk of catastrophic failures and minimizing downtime for bridge maintenance.

The project will also include simulations to evaluate the performance, reliability, and effectiveness of InfraChain in a controlled environment. These simulations will help validate the system's capabilities and identify any potential operational challenges. Throughout the development process, detailed documentation will be maintained to record the design, implementation, and evaluation stages, culminating in a comprehensive project report.

However, there are several limitations and constraints that must be acknowledged. The project is constrained by limited resources and budget, which may impact the extent of sensor deployment and the scope of simulation scenarios. The focus will be on demonstrating the functionality of InfraChain within the available resources. On the other hand, compliance with regulatory requirements and legal constraints related to data privacy and infrastructure management is essential. Adherence to these regulations will ensure the legality and ethical use of InfraChain. Moreover, there are inherent risks associated with integrating emerging technologies such as sensors and blockchain. Technical compatibility issues and unforeseen challenges during implementation could potentially impact the project timeline and deliverables. Contingency plans will be in place to address these risks as they arise.

Despite these limitations, the development and implementation of InfraChain are expected to significantly advance the field of infrastructure monitoring and maintenance. By addressing these challenges, InfraChain aims to provide a scalable and reliable solution for enhancing the safety, efficiency, and transparency of bridge management practices. The project will contribute valuable insights into the feasibility and benefits of integrating sensor networks with blockchain technology, paving the way for future innovations in smart infrastructure management.

Chapter 2

System Components

2.1 Strain Gauge

Strain gauges are a type of mechanical sensor that measure the deformation (strain) of an object under stress. They typically consist of a thin wire or foil bonded to the surface of the object being monitored. As the object undergoes stress, the strain gauge deforms, causing a change in its electrical resistance. This change in resistance can then be accurately measured and converted into a strain value. In InfraChain, strain gauges can be strategically embedded in the roadway pavement to detect strain caused by traffic loads. By monitoring strain variations over time, InfraChain can identify potential cracks or weaknesses in the road structure before they escalate into major problems [Huang et al. \(2020\)](#).

2.2 Smart Contract

A smart contract is a self-executing contract whose terms of the agreement between the contract's counterparties are embedded into lines of code. The use of smart contract technology is changing traditional business and industry practices. Smart contracts, which are integrated into blockchains, allow an agreement's terms to be automatically enforced without the need for a third party to be contacted. Thus, smart contracts can lower risks, increase the effectiveness of company processes, and save money on administration and services. While smart contracts have the potential to spearhead a new wave of innovation in corporate operations, some obstacles still need to be overcome [Efanov & Roschin \(2018\)](#).

2.3 Blockchain

A blockchain is a growing chain of blocks created with every new transaction of data. In blockchain technology data is stored through cryptography that ensures only eligible participants can access the corresponding data [Al Omar et al. \(2021\)](#). It is a decentralized, distributed and public digital ledger. Thus, blockchain is change sensitive which ensures data authenticity at its best [Zarate Garnica et al. \(2022\)](#). The whole network of nodes owns a copy of the blockchain and constantly monitors it which makes it impossible for malicious users to enter false blocks into the public or private ledger without others catching them right away. Therefore the integrity of the records in the blockchain cannot be compromised. Its ability to store transactions without the involvement of any third parties in a centralized manner has led to its success [Zheng et al. \(2020\)](#).

As we can see in the Fig 2.1, A block has a block header and block body or data. Block Header consists of the following things: The block number, also known as block height in some blockchain networks, the previous block header's hash value, a hash representation of the block data, a timestamp, the size of the block. On the other hand, Block Data consists of a list of transactions and ledger events included within the block and other data may be present based on the system characteristics. Each participant in the block network owns a set of keys, a private and public key, which are used to encrypt and decode product lifecycle data. The public key identifies the current owner, while the private key indicates a change in ownership. The timestamp records the transaction's creation time. Encrypted data is only decrypted by the matching key [Zarate Garnica et al. \(2022\)](#). For the proposed bridge management system, data management will be built on a peer-to-peer (P2P) network, ensuring a decentralized and distributed method of recording and storing information. In this system, the lifecycle of bridge infrastructure is treated as a product, involving numerous participants. Each participant plays a vital role at different stages of the bridge's lifecycle, from the initial design phase, through construction, maintenance, and, eventually, potential decommissioning or reconstruction. Each activity generates critical data, which can include design approvals, construction progress, inspections, material deliveries, and routine maintenance tasks.

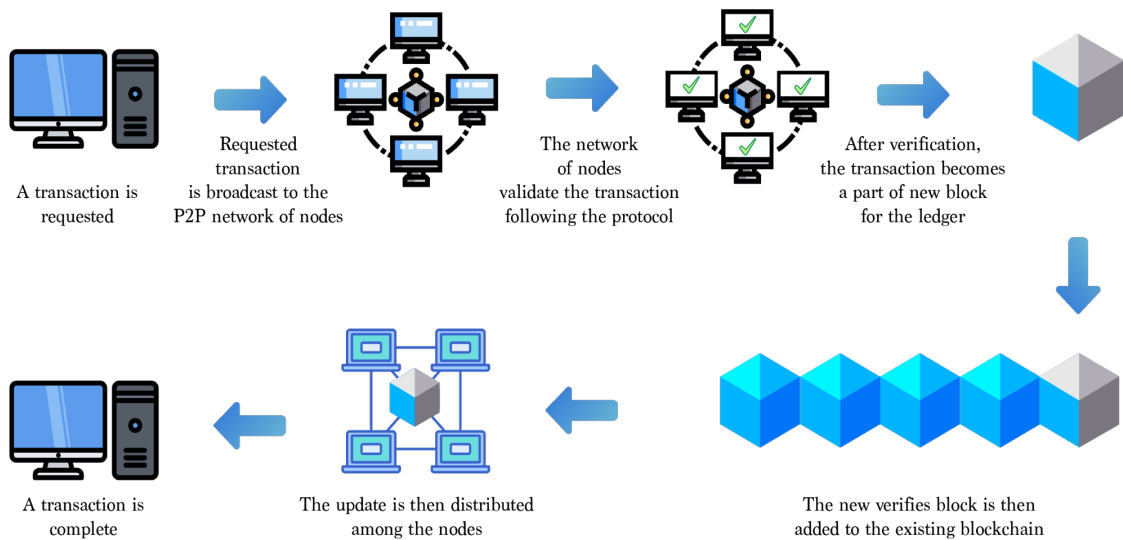


Figure 2.1: Blockchain Diagram

In this blockchain-based system, data related to maintenance stages will be recorded as transactions. These transactions are then verified by network participants to ensure the validity and accuracy of the data. Once verified, the transactions are grouped together to form a block. Each block contains a timestamp and a reference to the previous block, ensuring that all recorded data is securely linked in a chronological sequence. As new blocks are added to the chain, they are cryptographically secured, and any tampering attempts would be immediately evident. This creates a transparent and immutable ledger that contains the entire lifecycle history of a bridge.

In summary, the bridge management system leverages blockchain to securely and efficiently record, store, and manage data from all stakeholders involved in the bridge's lifecycle, fostering better coordination, accountability, and long-term infrastructure integrity.

Chapter 3

Literature Review

3.1 Literature Review and Comparative Analysis

The demand for effective and sustainable infrastructure management that has been increasing with time has caused the development of innovative techniques. Development of infrastructures, migration from rural to urban areas, climate change, and financial limitations are putting a pressure on infrastructure systems, rendering traditional management options ineffective [Sánchez-Silva & Baker \(2024\)](#). A significant portion of global infrastructure has aged and not to mention degrading, with many structures outliving their intended lifespans or the lifespan predicted by the Engineers. According to the World Economic Forum, resolving these challenges would need an estimated \$ 3.7 trillion in annual infrastructure investments by 2035 [Denis & Florentin \(2024\)](#). The primary features of Blockchain technology are transparency, immutability and security. It can be considered that due to these features, it can be a viable alternative for revolutionizing the transportation management industry or for a management process in general. This literature review on the existing and related work covers the possible uses of smart contracts, a major aspect of blockchain technology, how to improve the efficiency and transparency of bridge infrastructure maintenance, as well as the advantage of using various sensors.

Smart contracts are known as self-executing contracts that have preset terms and conditions that are stored on the blockchain network. These contracts automate the implementation of agreements when certain circumstances are satisfied. Smart contract execution automation not only improves operational efficiency but also considerably reduces administrative expenses compared to traditional management approaches [Ogungbemi \(2024\)](#). The fundamental qualities of the Smart Contract

concept are immutability, transparency and security. After a successful implementation of smart contract on a system, the smart contract cannot be modified. This feature preserves data integrity and unauthorized alterations [Rahman \(2024\)](#). Because there are many parties participating in public infrastructure projects and confidence is crucial amongst them, these smart contract characteristics are quite helpful. There are often conflicts and delays when contract execution is left to a centralized authority. But because smart contracts are autonomous and verifiable, they lessen these issues [Gupta & Jha \(2023\)](#) [Wahab et al. \(2022\)](#).

Every transaction and data related with a smart contract are easily available to be checked by the authorized parties via the blockchain network. This increases trust and transparency. Moreover, smart contracts may be used to incorporate real-time data inputs, allowing the authorized parties to respond to changing circumstances and requirements. This adaptable feature is highly important for projects which are in dynamic settings such as building an infrastructure and making sure of its spontaneous maintenance according to necessity [Hwang et al. \(2024\)](#).

Now, smart contracts use cryptographic security measures like public-private key encryption to guarantee that only authorized parties begin transactions. This functionality is extremely important in situations with multiple stakeholders because it reduces risks of data modification and data being accessed by someone unauthorized [Zou et al. \(2019\)](#).

Bridge is an important link between rural and urban areas. It is important to guarantee the sustainability of and bridge infrastructure across the world. Several variables such as climatic conditions, traffic loads and structural degradation can have a significant impact on the bridge integrity [Ponzo et al. \(2023\)](#). According to the recent data from the American Society of Civil Engineers, approximately 30 % of bridges in the United States are structurally weak and outdated. Those bridges have a critical need for enhanced monitoring and maintenance systems [Qi \(2024\)](#).

With the advancement of science and technology there are advanced monitoring technologies. Those include— satellite data integration, in-situ sensor measurements, and innovative technologies like LiDAR, Photogrammetry, and Distributed Acoustic Sensing (DAS). These technologies are critical for detecting early damage, tracking structural health and predicting timely maintenance necessities [Liu et al. \(2022\)](#). Integrating these new technologies will not only increase the accuracy of the monitoring system but it will also enable real time examination of structural health

which will allow faster reactions to probable breakdowns. Recent case studies show that combining satellite data with ground-based sensors can improve the detection of small structural changes, allowing for early intervention and maintenance [Hu \(2024\)](#).

By continually monitoring indicators such as crack width, deformation, stresses, and vibrations, authorities may make educated judgements about maintenance, repairs, and strengthening interventions, eventually assuring public safety and serviceability of bridge structures [Han et al. \(2023\)](#). Moreover, a real-time monitoring system can greatly reduce the total cost of maintenance and unanticipated repairs due to the traditional system. Research shows that early diagnosis of structural faults can save maintenance costs by up to 40 %, emphasizing the necessity of real-time monitoring [Galdelli et al. \(2022\)](#). On this note, it has been found that, deploying a continuous monitoring system in a major bridge in the United Kingdom resulted in a 20 % decrease in maintenance expenditures over five years [Ye et al. \(2022\)](#). These systems must include a reasonable strategy for estimating the numerous uncertainties associated with bridge status, as well as the use of monitoring data to continually update infrastructure assessments [Al-Radaideh et al. \(2015\)](#).

In this setting, Bayesian frameworks have emerged as an effective technique for combining monitoring data into probabilistic models of bridge degradation [Taflanidis & Gidaris \(2011\)](#). These frameworks enable a more detailed knowledge of structural behavior across time, allowing engineers to assess risk and prioritize maintenance efforts using historical and real-time data [Taflanidis & Gidaris \(2011\)](#). These algorithms combine existing information about the bridge with freshly gathered sensor data, resulting in a resilient and adaptable approach to infrastructure evaluation. For example, [Ni et al. \(2020\)](#) use long-term monitoring data to offer a Bayesian technique for evaluating the condition of bridge expansion joints. This approach refines prediction models by combining historical performance data with real sensor inputs. This dynamic updating system improves the accuracy of maintenance schedules and resource allocations. Including this, Bayesian approaches have been used to construct decision support systems for bridge repair. These features allow stakeholders to prioritize and take actions accordingly. This results in sustainable, efficient and cost effective maintenance plans [Taflanidis & Gidaris \(2011\)](#).

Recent advances in data analytics and machine learning have enhanced the capability of bridge health monitoring systems. Machine learning algorithms may be trained to recognise patterns in sensor data, enabling predictive maintenance tactics that detect problems before they become crucial. This very feature of machine learning can be used to optimize maintenance plans as well as greatly lower the probability of unexpected failures [Gomez-Cabrera & Escamilla-Ambrosio \(2022\)](#). Neves, A. C. (2020) found that his machine learning models could anticipate structural problems with more than 85 % accuracy. This accuracy allows for prompt interventions that extend the life of infrastructure [Neves \(2020\)](#).

At the same time, developments in wireless sensor networks (WSNs) have significantly improved the scalability and reliability of data collection processes. It is now possible to transmit sensor data over long distances with minimal energy consumption by the use of low-power-wide-area networks (LPWAN). This will ensure the continuous monitoring of the infrastructure even in remote locations. Moreover, the incorporation of edge computing will allow preliminary data processing at the sensor level, reduce latency and enhance real time decision making capabilities [Mbandi & Kisangari \(2020\)](#).

To ensure low to zero latency and real-time data transfer, this system frequently makes use of wireless communication technologies such as— LoRaWAN or 5G [Zorbas & O'Flynn \(2018\)](#). These advanced communication methods are critical in areas where standard network infrastructures may be inadequate in order to ensure the consistency, reliability and efficiency of data flow. By maintaining seamless connectivity, stakeholders can obtain up-to-date information on bridge conditions, allowing for prompt actions [Mbandi & Kisangari \(2020\)](#) [Zorbas & O'Flynn \(2018\)](#).

In order to interpret sensor data and forecast future degradation advanced algorithms and computer modes are required. Currently, machine learning and artificial intelligence techniques are widely used to analyze this data. This allows for identification of trends that might forecast future maintenance requirements. Anomaly detection algorithms may be used on sensor data to automatically identify fluctuations from anticipated behavior which allows for timely actions. This ability to predict has been proved in a number of case studies where machine learning models have accurately predicted maintenance requirements which has minimized unexpected failures by up to 30 %. Moreover, learning algorithms can optimize

maintenance plans using historical data resulting in better resource utilization and lower costs [Jiang et al. \(2023\)](#).

The integration of blockchain technology can improve each of these components by offering a secure, decentralized and transparent platform for managing bridge condition data. Blockchain is a distributed ledger system that enables the safe and tamper proof storing of data over a network of nodes [Zadeh & Safaei \(2023\)](#). This technology has numerous advantages in the context of bridge health monitoring such as— safe and tamper proof data storage, transparency of data and automatic decision making. These features of blockchain address multiple concerns in infrastructure management such as data integrity and trust among the stakeholders [Pallante et al. \(2024\)](#). Blockchain's decentralized and encrypted nature ensures the security of any kind of data by requiring a consensus algorithm everytime data needs to be added [Sobecki et al. \(2022\)](#). By storing all sensor data and analyzing the data, the stakeholders will have a complete history of the status of the infrastructure. Moreover, contract executing and payment disbursement ensure that all parties follow through on their pledges [Nawari & Ravindran \(2019\)](#).

Smart contracts on the blockchain may be configured to automatically notify for maintenance operations on the basis of established thresholds or degradation models, eliminating the chances of human error [Mi et al. \(2023\)](#). Even though the usage of smart contracts in infrastructure is relatively new, there are some developing instances in this industry. In infrastructure developing projects, smart contracts are used to track the flow of materials and tools which enables transparency and accountability across the supply chain [Singh et al. \(2023\)](#). This has proved the ability of smart contracts to improve project management and procedures, reducing delays in actions and improving the coordination among stakeholders. Projects may run efficiently with improved utilization of resources if essential procedures such as— material ordering and payment approvals are made automated [Sigalov et al. \(2021\)](#). Smart contracts can also enable alternative finance methods for projects such as fractional ownership and crowdfunding options [Tian et al. \(2022\)](#). This change of financing has the potential to enhance investment in projects and help get funding on previous projects. Blockchain systems can allow communities to participate in local projects instilling a sense of ownership and involvement among locals. Such solutions both increase financial availability and boost public trust in project management by involving citizens in decision making [Chen & Volz \(2022\)](#). Moreover,

using blockchain for data sharing reduces the administrative burden associated with traditional data sharing agreements, allowing for fast project execution [J. Li & Kassem \(2021\)](#). This improves cooperation and data utilization while ensuring data security [Xu et al. \(2021\)](#) [Z. Wang & Guan \(2023\)](#). Another article discusses the potential for blockchain and smart contracts to manage vast amounts of data efficiently. The notion of a Novelty Index (NI) for filtering data on the blockchain can be useful for management systems with large amounts of data [Gadiraju et al. \(2024\)](#).

Again, Wan et al. demonstrate the potential for combining blockchain and IoT to monitor subsurface constructions. Even though the emphasis was made on coal mines, the main ideas can be applied to transportation infrastructure as well [Jo et al. \(2018\)](#) [Alharbi et al. \(2023\)](#). This flexibility also demonstrates that blockchain and IoT technologies are versatile which can be adjusted to solve the specific issues encountered by various kinds of infrastructure. As these technologies develop with time they hold the potential to improve the resilience and efficiency of any kind of critical infrastructure [Arachchige et al. \(2024\)](#). Therefore, by utilizing blockchain technology stakeholders of any project can have transparency and accountability. On the other hand, by following the changes in infrastructure status data over time it is possible to understand the long term structural performance which can be a guidance for future design and maintenance procedures. The thorough report and maintenance operations and decisions can also be used to avoid any previously made mistakes which will constantly improve the management strategies [Wu et al. \(2021\)](#). Finally blockchain technology has the potential to automate commercial transactions and payment processes using smart contracts [Alzahrani et al. \(2020\)](#). This automation saves administrative chores and creates new opportunities to monetize data collected by infrastructure monitoring systems. Data collected by sensors may be made available to third party developers for analytical purposes and generate income streams for infrastructure management [H. Wang et al. \(2023\)](#).

While dealing with a large number of data from sensors or networks, blockchain may encounter scalability issues. Addressing these difficulties may necessitate the investigation of layer 02 scaling solutions. This can increase transaction throughput while maintaining the security of data and integrity of the underlying blockchain [Mahmudnia et al. \(2022\)](#). Exploring alternative blockchain systems or establishing data aggregation methodologies may be required [Marchang et al. \(2019\)](#).

Building upon the foundations of existing applications, smart contracts can be harnessed for various purposes in bridge management. Sensor data from roadways can be utilized for automated inspection in a smart monitoring system, enhancing maintenance processes through real-time data analysis and management, as presented in the paper [Gabbar et al. \(2023\)](#). This automation of the inspection procedure enhances accuracy, efficiency and lowers the dangers associated with manual inspections which are time consuming and prone to human error. Usage of drones with sensors for bird eye view inspections has resulted in considerable increases in data gathering speed and accuracy. This allows for thorough evaluations of bridge conditions without affecting the traffic slow [Ma et al. \(2023\)](#). Smart contacts can also help with the implementation of performance based maintenance work. It will utilize sensor data to ensure that maintenance work is successful. Using smart contract payments to the contractors can be delivered automatically following successful implementation via the smart contract resulting in a transparent and easy payment system ?. Smart contracts can also be utilized for safe and regulated data exchange methods. In case of large projects with multiple stakeholders data can be regulated so different stakeholders can view different data using specific rights as specified in the smart contract. This feature guarantees that sensitive data is shared appropriately and promotes cooperation among stakeholders for successful decision making.

Table 3.1: Comparative Analysis of Literature Review

	Sensor Types Used	Data Collection Methods	Data Analysis Techniques	Blockchain Integration	Immutability	Transparency	Traceability	Real-time Monitoring	Anomaly Detection	Maintenance Prediction	Data Security	Deployment Feasibility	Scalability	Impact on Maintenance Efficiency	Reliability of Detection	Energy Consumption	Tamper Protection	Performance in Simulated Environment	Proactive Maintenance Capabilities	Overall Impact on Safety
Quinci et al. (2022)	Y	Y	Y	N	N	N	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y
Catbas & Avcı (2022)	Y	Y	Y	N	N	N	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y
Feng et al. (2022)	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	N	N	Y	Y
Scott et al. (2021)	N	N	N	Y	Y	Y	Y	N	N	N	Y	N	N	Y	N	N	N	N	N	Y
Celik et al. (2023)	N	N	Y	Y	Y	Y	Y	N	N	N	Y	N	N	N	N	N	N	N	N	Y
Le & Hsu (2021)	N	N	Y	Y	Y	Y	Y	N	N	N	Y	N	N	N	N	N	N	N	N	Y
Guerrero-Sanchez et al. (2020)	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	Y	N	Y	Y
Ramasamy et al. (2021)	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y
Huang et al. (2020)	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	Y	N	Y	N	Y	Y
Efanov & Roschin (2018)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y
Al Omar et al. (2021)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	N	Y	Y
Zheng et al. (2020)	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	N	Y	N	Y	N	N	N
Sánchez-Silva & Baker (2024)	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	N	Y	N	Y	N	N	N
Denis & Florentin (2024)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Chapter 4

Methodology

This section of the report outlines the approach taken in the design, development, implementation and evaluation of the InfraChain system. The methodology involves a series of structured steps designed to ensure the system's effectiveness in real-time bridge monitoring and maintenance.

4.1 Research Design

The research design for InfraChain involved initial exploratory research to understand the current challenges in bridge maintenance and the potential of integrating sensor networks with blockchain technology. This phase included a comprehensive literature review to identify relevant technologies and methodologies used in similar projects. The research design also encompassed defining the scope, objectives, and requirements for InfraChain based on the findings.

4.2 Project management and planning

Effective project management is crucial for the successful execution of InfraChain. The project was divided into distinct phases: initial research and requirements gathering, system design, prototype development, testing and evaluation, and final documentation. Each phase had specific deliverables and milestones to ensure progress and adherence to the project timeline. Regular meetings and progress reviews were conducted to address any issues promptly and adjust plans as necessary.

4.3 Proposed Systems' Architecture

InfraChain pitches an enhanced sensor-enabled roadway management system that leverages blockchain technology to rejuvenate the way road infrastructure health is monitored, maintained, and documented. The system begins with a network of strategically placed sensors embedded within the roadway pavement or installed on the surface. The sensor that has been proposed to use is Strain Gauge. This sensor continuously monitors stress and strain levels in the road, enabling early detection of potential cracks and weaknesses. Each sensor is connected to a dedicated Data Acquisition Unit (DAU), programmed to collect sensor readings at regular intervals. DAUs convert raw sensor signals into digital data and perform basic filtering and cleaning to ensure data quality. The processed data is securely transmitted to a central server using low-power wireless communication protocols like LoRaWAN.

There will be a central server serving as the central hub for all data collected by the sensor network. It houses a secure and efficient database to store the incoming data stream and performs data aggregation. This aggregation combines information from various sources to provide a holistic view of the overall roadway health.

Real-time analysis of the incoming data stream is crucial for proactive maintenance. Thus, InfraChain employs threshold-based monitoring and sophisticated algorithms to analyze the sensor data for unusual patterns or deviations from historical trends. When an anomaly or threshold breach is detected, InfraChain triggers an automated notification system, sending customized alerts to designated personnel responsible for road maintenance. The user interface, accessible via a web page of the central server, automatically updates to reflect the detected anomaly. InfraChain provides a user-friendly web page accessible to authorized personnel. The dashboard offers a comprehensive overview of the current health status of the roadway network. Users can delve into historical data for trend analysis and identification of long-term maintenance needs. They can also view and manage received alerts related to anomalies or threshold breaches.

The smart contract is a self-executing program stored on the blockchain network. It defines automated actions based on predefined conditions, such as triggering

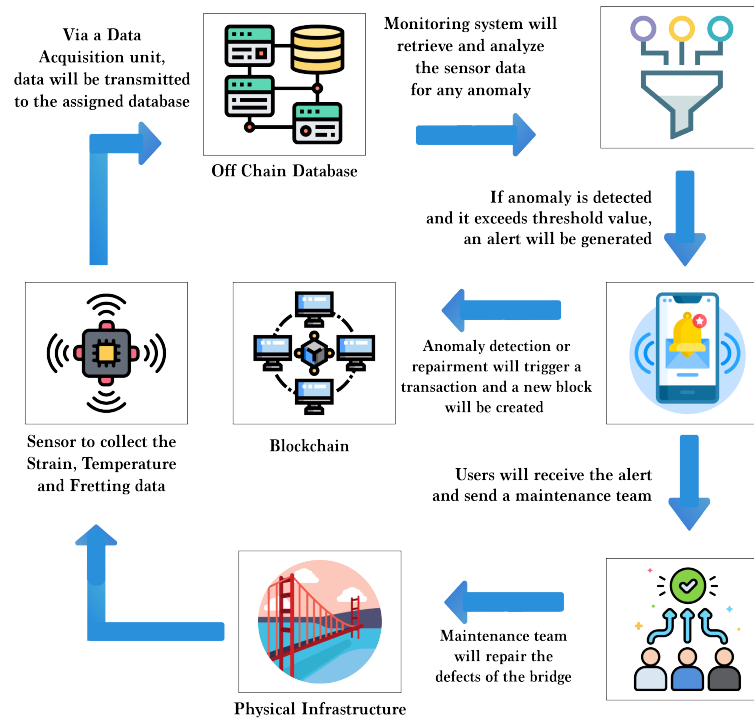


Figure 4.1: Proposed Systems' Diagram

workflows for maintenance activities or verifying the completion of repairs based on sensor data. This process is especially useful for performance-based maintenance contracts, where the smart contract can validate repairs and release payments automatically.

The blockchain network provides a secure and tamper-proof platform for storing sensor data and executing smart contracts. Once data is added to a block on the blockchain, it cannot be altered, ensuring data integrity and preventing unauthorized modifications. All transactions and data associated with the smart contract are visible to authorized participants on the blockchain network, fostering trust and accountability. By leveraging the power of blockchain technology, InfraChain moves beyond traditional bridge management systems. The combination of immutable data records, automated workflows through smart contracts, and secure data access control creates a more transparent, efficient, and trustworthy system for maintaining our critical road infrastructure.

4.4 Implementation Procedures

Smart contracts were a critical component of InfraChain, ensuring automated and secure handling of maintenance triggers. The implementation involved the following steps:

- **Contract Deployment:** The smart contract was initialized with threshold values for strain, temperature, and displacement. These thresholds were used to evaluate incoming sensor data.
- **Data Handling:** The `receiveSensorData` function was implemented to process sensor readings. If the readings exceeded the predefined thresholds, a `Report-MaintenanceRequested` event was triggered, and the data was securely stored on the blockchain.
- **Anomaly Detection and Maintenance Alerts:** Anomalies in the sensor data were detected by calculating average values and comparing them against thresholds. If an anomaly was detected, the system triggered a maintenance request and logged the event on the blockchain to ensure transparency and traceability.
- **Cooldown Management:** A cooldown period was implemented to prevent redundant maintenance requests. If a sensor triggered a maintenance request, it entered a cooldown period during which no new requests could be triggered, avoiding data redundancy on the blockchain.

4.5 Validation and Testing

Aiming to inspect the proposed system's efficiency, an orchestrated approach was incorporated consisting of necessary applications, development environment and utilities.

- **Development and Testing:** To evaluate the proposed system's smart contract, the Ethereum blockchain has been used as the foundational technology. The testing was conducted on a Windows 10 operating system using an HP laptop with an Intel Core i5, 8th Generation processor. For developing and deploying the smart contracts, environment setup i.e., Ganache and Truffle, which

are essential tools in the Ethereum ecosystem, have been utilized. Utilities such as Web3 library and JavaScript to facilitate interaction with the smart contracts and manage transactions have been used. Additionally, a LabVIEW environment was set up to create a simulated environment as sensor data feed, connecting it seamlessly with the proposed system. This combination of tools and technologies allowed for a comprehensive evaluation of the smart contract functions, ensuring that the system met the necessary performance and reliability standards.

- **Performance Metrics:** The system performance has been studied in terms of metrics such as, throughput(transaction per second), latency, block data fetching time. With the aim to advocate an enhanced system , the proposed system's proficiency under different environmental conditions such as in both public and private blockchain environments, was also tested.
- **Throughput:** Throughput means the rate at which a blockchain network processes transactions or operations over a certain amount of time. It is normally measured in transactions per second (TPS) and indicates the capacity of the network to handle a certain volume of transactions. A blockchain's throughput is said to be 250 TPS, if at every second 250 transactions are handled by it.
- **Latency:** Latency is the time delay between submitting a transaction or request and the completion of that action on the blockchain. In simpler terms, it refers to how long it takes for a transaction to be confirmed and included in a block.
- **Block Data Fetching Time:** Block data fetching time is the time it takes to retrieve or query specific data from the blockchain, such as transaction details or smart contract state stored in a particular block. This metric includes the time needed to locate the block and extract the required data from it.

Chapter 5

Design and Development

5.1 Financial Activities

Financial management involved budgeting for sensor procurement, blockchain platform development, and web application development. A cost-benefit analysis was conducted to ensure that resources were allocated efficiently, and expenses were tracked meticulously throughout the project lifecycle.

5.2 Adopted Tools and Techniques

InfraChain utilized a variety of advanced tools and techniques to achieve its objectives, ensuring the accurate collection, secure management, and thorough analysis of data related to bridge health. Each tool and technique was selected based on its ability to meet specific requirements of the InfraChain system.

5.2.1 Sensors and Data Collection

To monitor the structural health of bridges effectively, a thorough study was run to select bridge segments and appropriate data feeds for respective parts. Prestress Concrete, Reinforced Concrete and Steel Bridges type have been considered to have the system applied on. The Strain Gauges and Fiber Optic Sensor provide parameters' readings that are most compatible to evaluate these types of bridges. So, InfraChain adopted the Strain Gauge and Fiber Optic sensors. These sensors were chosen for their precision and reliability in measuring critical indicators such as strain, temperature, and displacement.

- **Strain Gauges:** These sensors are known for their ability to detect minute changes in strain and displacement providing vital data on the structural integrity of the bridge. Strain gauges were strategically placed to capture stress points and potential weak areas in the bridge structure.
- **Fiber Optic Sensors:** Fiber optic sensors monitor various metrics by interpreting changes in light signals traveling along a fiber-optic strand, utilizing principles such as interferometry, polarization, spectroscopy, and light intensity. These sensors are capable of measuring strain, displacement, temperature, pressure, and other factors and can be embedded in or placed on concrete structures, such as bridges. While they offer the advantage of being immune to electromagnetic interference, careful installation is necessary, and temperature sensitivity may require compensation using a reference gauge.

The parameters were selected among myriad types of parameters are strain, displacement and temperature. Strain is the relative elongation or contraction occurring in specific areas of the bridge's concrete. Within the service load range, concrete exhibits linear behavior, which enables the estimation of stresses and displacements at designated locations within the bridge. Displacement indicates the overall linear movement of a bridge either in relation to its original position or on a global scale. It is possible to measure the displacement in one, two or three independent directions. The collected data from these sensors was continuously monitored and processed to detect any anomalies or signs of deterioration.

5.2.2 Blockchain Platform

For blockchain, Ethereum was chosen due to its robust smart contract capabilities and widespread adoption in the blockchain community. Ethereum's features ensure secure and transparent data handling, which is crucial for maintaining the integrity and traceability of maintenance records.

- **Smart Contracts:** Smart contracts were developed to automate the process of data verification, maintenance alerts, and record-keeping. These contracts ensure that once data is recorded, it cannot be altered, thereby providing a reliable and tamper-proof log of bridge health data.

5.2.3 Development Environments

Several development tools were employed to facilitate the programming and integration of sensors and the blockchain platform:

- **Remix IDE:** This integrated development environment was used for writing, testing, and deploying smart contracts on the Ethereum blockchain. Remix IDE supports Solidity, the programming language for Ethereum smart contracts, providing a user-friendly platform for development.
- **Ganache:** Ganache was used to create a local Ethereum blockchain for testing purposes. It allowed for rapid deployment and testing of smart contracts in a controlled environment, facilitating debugging and ensuring that the contracts functioned correctly before deployment on the main network.
- **Truffle:** Truffle, a development framework for Ethereum, was utilized to manage the smart contract lifecycle. It provided tools for compiling, testing, and deploying smart contracts, integrating seamlessly with Ganache for a streamlined development process.

By integrating these tools and techniques, InfraChain was able to create a robust system for real-time bridge health monitoring and maintenance management. Each tool played a critical role in ensuring the accuracy, security, and reliability of the collected data, ultimately contributing to the project's success.

5.3 Designing the Solution

The design phase involved creating detailed specifications for both the sensor network and the blockchain platform. The sensor network design included selecting appropriate sensors and determining their optimal placement on bridge structures to ensure comprehensive monitoring. Data collection protocols were defined to standardize the process.

For the blockchain platform, the design included defining data structures, consensus mechanisms, and smart contract functionalities. The goal was to ensure

secure and transparent data management, addressing issues of data inconsistency and lack of transparency found in traditional methods.

The integration of these components was designed to facilitate early detection of structural issues, efficient maintenance interventions, and enhanced transparency in maintenance activities.

5.4 Implementation

This section outlines the implementation of the system's smart contract, elaborating its specifications, core algorithms and data handling procedures as a functional enhanced system for bridge health monitoring.

InfraChain is functioned with a logical and optimized smart contract. The smart contract gets activated accepting data. An oracle sends data to the smart contract over the leap of 24 hours. At first it checks for any threshold breach. If any parameter breaches the threshold a request indicating that maintenance is needed takes place. Then meeting logical reasoning, if that specific parameter's reading is found below the threshold, a notation indicating that the issue was resolved takes place. The smart contract consists of few logic operations. Some core principles of the contract with their algorithms are described next.

The contract initializes with the Constructor deployment. Algorithm 1 ensures that an authorized oracle is only allowed to invoke the smart contract and send data. The algorithm shows the authorized deployment of the smart contract with a verified oracle address. This also keeps the flexibility to add any other oracle in case of adverse situations.

After receiving data the smart contract maps the sensor ids (SiD) and their respective parameter value as sensor data, shown Algorithm 2. The odd number sensorIDs are identified as strain gauge sensors and the function maps only strain and displacement parameters' reading. Followingly, the even number sensorIDs are identified as fiber optic sensors and the function maps strain, displacement and temperature parameters' readings. The function further sets thresholds(Th) for each parameter(Pm). For every parameter, the thresholds are set as strain

Algorithm 1 Smart Contract Triggering

Input: Smart Contract Triggering**Result:** Execute a secure Oracle interaction

```
1 Begin
  initiate modifier onlyOracle()
  if msg.sender != oracle then
2 |   Revert with "Only Oracle can call this function"
3 else
4 |   call receiveSensorData()
   |   _get SiD, Pm
5 End
```

=150, temperature =12 and displacement =25. In the next step, the operation proceeds checking if any maintenance request (MR) was made for the parameters and if any parameter breaches its own threshold. If any parameter is not found to make MR and the preset Th for any parameter is breached, it will trigger the *ReportMaintenanceRequested* function for the respective parameter. Then a cool down period(CP) will initiate for that Pm . Within the cool down period, the function will not request maintenance for any breached parameter. It has been done to avoid data redundancy. No event will execute if there is no previous request and threshold breach. If any parameters' reading is below or equal to the threshold and if there a MR exists for the parameter, then it will be logged as resolved executing the *ReportMaintenanceAddressed* function.

Algorithm 3 depicts the logic that an event is specified for every requested maintenance incident. A function labeled *ReportMaintenanceRequested* emits the event. The function requires sensorIDs of the parameters' who have not requested for maintenance recently and have been found to breach the threshold. The function emits the event *ReportMaintenanceRequested* for those parameters, followingly activating the cool down status and setting requestID (RiD)to true. The final execution concludes with creating a block for the incident. The event emits logs such as ID of request, ID of the sensor, name of the parameter, the reading of the parameter, maintenance status as requested and an activated cool down period.

Algorithm 2 Data handling

Input: Si_D, P_m **Output:** Sensor Type and Parameter Reading Validating

```
6  determine Sensor type
   if Parameter is valid for sensor type then
7    determine  $T_h, P_m$ 
      if then
8       |  $\_request = false \text{ AND } P_m > T_h$ 
9       event ReportMaintenanceRequested
      else if
      then
10      |  $\_request = true \text{ AND } P_m > T_h$ 
11      if  $C_p = on$  then
12      | No event emitted
13      else
14      | ReportMaintenanceRequested
15      else if  $request = true \text{ AND } P_m \leq T_h$  then
16      | ReportMaintenanceAddressed
17      else
18      | no event emitted
```

In algorithm 4 the event 'ReportMaintenanceAddressed' executes when the corresponding function gets value meeting initial conditions. The maintenance is addressed when a parameter's reading is found below or equal to threshold after it has been requested for maintenance. The event increases the request count followingly setting the request status to false. A block is created against this event. The event emits data of sensor's ID, request ID, name of the parameter, reading of the parameter, status as addressed and cool down period as off.

For users to view the stored data of blocks , they have to interact with getAll-RequestsForSensorData function and getSensorRequestData function. The prior one needs sensorID as input and outputs all the requestID for that sensorID. Next, if the sensorID and any specific requestID are passed as input into the later function,

Algorithm 3 Event Emit (Maintenance Request)

Input : R_{ID}, S_{ID}, P_m, P_m Reading

Output: Maintenance Request Event is Triggered

Function *ReportMaintenanceRequested*

R_{iD}, S_{iD}, P_m, P_m Reading

log M_R details

request count++

set request[P_m] = true

emit event ReportMaintenanceRequested

Algorithm 4 Event Emit (Maintenance Addressed)

Input : R_{ID}, S_{ID}, P_m, P_m Reading

Output: Maintenance Addressed Event is Triggered

Function *ReportMaintenanceAddressedd*

R_{iD}, S_{iD}, P_m, P_m Reading

log M_R details

request count++

set request[P_m] = false

emit event ReportMaintenanceAddressed

it will display the data the requestID has for that sensorID.

5.5 Web Application View

This section reveals the Infrachain web application view. It shows the operations of the application that has been designed and mentioned in the system application mechanism part.

The application interface starts with a user *log in* action. After a successful login the user can see the home, users, sensor specification, sensor data, monitoring data, maintenance data and the blockchain events.

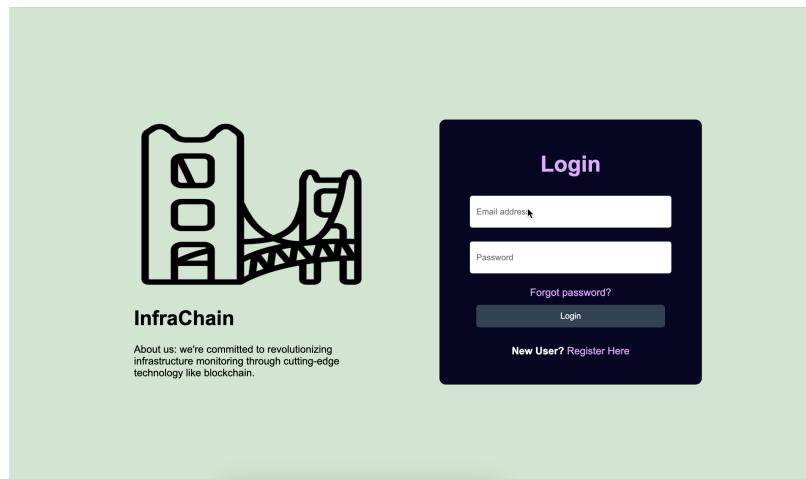


Figure 5.1: Login Interface 01

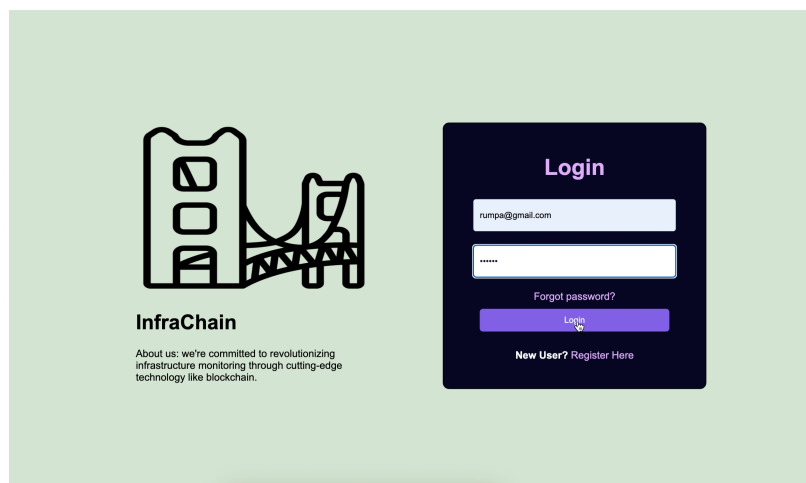


Figure 5.2: Login Interface 02

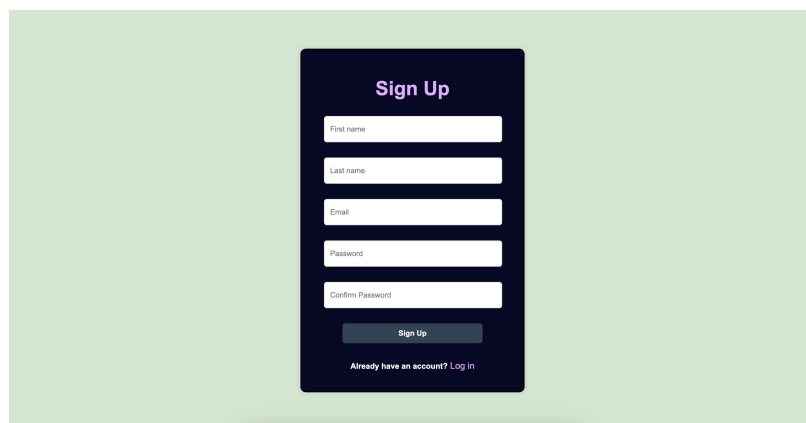


Figure 5.3: Sign up Interface

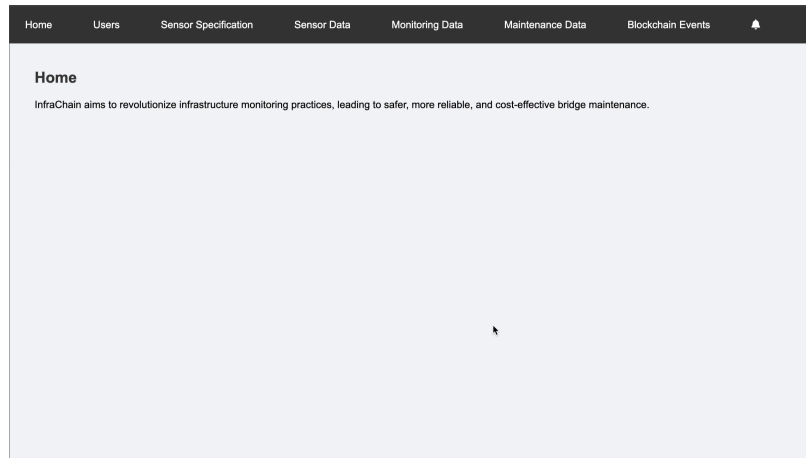


Figure 5.4: Home Page Interface

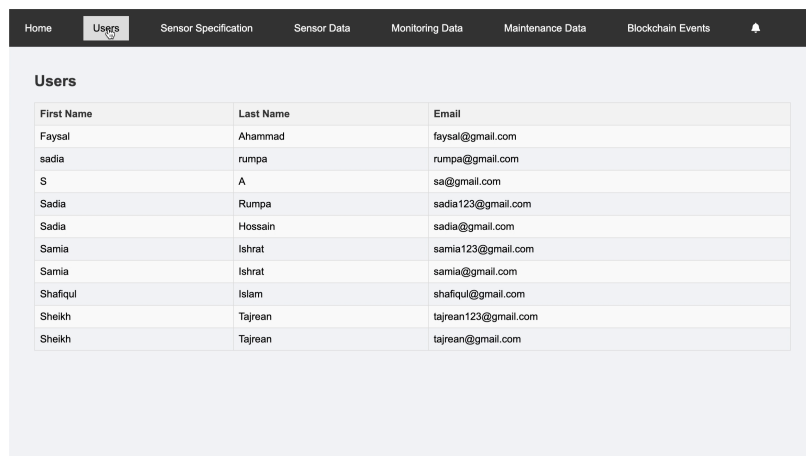


Figure 5.5: Users Details Page Interface

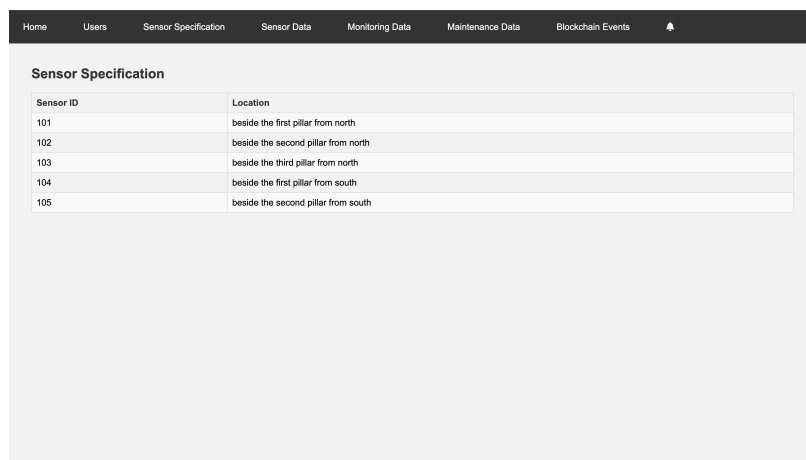


Figure 5.6: Sensor Specification Page Interface

Home	Users	Sensor Specification	Sensor Data	Monitoring Data	Maintenance Data	Blockchain Events	▲
Sensor Data							
Reading ID	Timestamp	Reading	Temperature	Sensor ID			
102	2024-04-01 01:00:00	150.00	13.00	101			
103	2024-04-01 02:00:00	149.00	12.00	101			
104	2024-04-01 03:00:00	150.00	13.00	102			
105	2024-04-01 04:00:00	150.00	13.00	102			
106	2024-04-01 05:00:00	150.00	13.00	102			
107	2024-04-01 06:00:00	149.00	12.00	101			
108	2024-04-01 07:00:00	149.00	12.00	102			
109	2024-04-01 08:00:00	150.00	12.00	101			
110	2024-04-01 09:00:00	151.00	12.00	102			
111	2024-04-01 10:00:00	151.00	12.00	101			
112	2024-04-01 11:00:00	149.00	12.00	101			
113	2024-04-01 12:00:00	149.00	13.00	102			
114	2024-04-01 13:00:00	152.00	13.00	102			
115	2024-04-01 14:00:00	151.00	12.00	101			
116	2024-04-01 15:00:00	150.00	13.00	101			

Figure 5.7: Sensor Data Page Interface

Home	Users	Sensor Specification	Sensor Data	Monitoring Data	Maintenance Data	Blockchain Events	▲
Monitoring Data							
Monitoring ID	Timestamp	Anomaly	Sensor ID	Reading ID			
8	2024-03-31 18:00:00	151	101	6			
9	2024-03-31 18:00:00	152	102	2			
10	2024-03-31 18:00:00	151	104	14			
11	2024-03-31 18:00:00	151	101	11			
12	2024-03-31 18:00:00	151	102	17			
13	2024-03-31 18:00:00	152	104	18			
14	2024-03-31 18:00:00	151	101	21			
15	2024-03-31 18:00:00	151	102	22			
16	2024-03-31 18:00:00	151	101	11			
17	2024-03-31 18:00:00	152	102	2			
18	2024-03-31 18:00:00	151	104	14			
19	2024-03-31 18:00:00	151	101	6			
20	2024-03-31 18:00:00	152	104	18			
21	2024-03-31 18:00:00	151	102	17			
22	2024-03-31 18:00:00	151	102	22			
23	2024-03-31 18:00:00	152	104	12			
24	2024-03-31 18:00:00	151	101	25			
25	2024-03-31 18:00:00	160	105	101			

Figure 5.8: Monitoring Data Page Interface

The Figure 5.6 ‘Sensor Specification’ shows the sensor Id and their specific location on the infrastructure. This helps to know about any particular part of the damaged infrastructure if the system triggered maintenance requests for the respective sensor.

The interface shown in Figure 5.6 is data of sensors that are displayed wiith time. From this segment, users can easily learn about the parameter reading of any sensor.

The interface in Figure 5.8 shows if any sensor has any anomaly detected. It also displays the Monitoring id with a timestamp. Which helps to evaluate the time of action taken for the identified damages.

Home
Users
Sensor Specification
Sensor Data
Monitoring Data
Maintenance Data
Blockchain Events

Maintenance Data

Maintenance ID:

Date:

Duration:

Maintenance Type:

Sensor ID:

Maintenance ID	Date	Duration	Type	Sensor ID	User
101	2024-05-10	25:19:39.000000	Crack	101	sadia@gmail.com
102	2024-05-17	48:24:00.000000	pothole	102	sadia123@gmail.com
103	2024-05-17	24:30:00.000000	crack	101	sadia123@gmail.com
105	2024-05-14	96:00:00.000000	pothole	104	sadia123@gmail.com
106	2024-05-17	06:00:00.000000	crack	103	sadia123@gmail.com
107	2024-05-28	12:00:30.000000	Pothole	102	sadia123@gmail.com

Figure 5.9: Maintenance Data Page Interface

Home
Users
Sensor Specification
Sensor Data
Monitoring Data
Maintenance Data
Blockchain Events

Blockchain Events

- [Fetch Data Using Sensor ID](#)
- [Fetch Data Using Requested ID](#)

Figure 5.10: Blockchain Events Page Interface

Figure 5.11: Blockchain Events: Data Fetching using Sensor ID 01

Request ID	Sensor ID	Breached Parameter	Parameter Reading	Status	Cool Down Period
7	101	Temperature	153	Maintenance Requested	on
9	101	Stress	158	Maintenance Requested	on
12	101	Displacement	148	Addressed	off
14	101	Displacement	156	Maintenance Requested	on
15	101	Displacement	155	Maintenance Requested	on
19	101	Displacement	153	Maintenance Requested	on
20	101	Temperature	154	Maintenance Requested	on
21	101	Temperature	154	Maintenance Succeeded	on

Figure 5.12: Blockchain Events: Data Fetching using Sensor ID 02

These Figures from 5.10 to 5.15 particularly enables the users to see the data for any particular sensor or any particular reading using *Fetch Data Using Sensor ID* or *Fetch Data Using Reading ID* option. In case of Fetch Data Using Sensor ID, all the data of the input Sensor ID will be displayed in a tabular form as shown in Figure 5.12 and Figure 5.13. On the other hand, when using the Reading ID, data of that particular Reading ID will be displayed as output in a tabular form.

Fetch Data Using Sensor ID

Sensor ID:

Fetch Data

Request ID	Sensor ID	Breached Parameter	Parameter Reading	Status	Cool Down Period
3	103	Displacement	157	Maintenance Requested	on
6	103	Temperature	150	Maintenance Requested	on
29	103	Stress	149	Addressed	off
32	103	Stress	157	Maintenance Requested	on
35	103	Displacement	149	Addressed	off
37	103	Displacement	157	Maintenance Requested	on
38	103	Displacement	148	Addressed	off
40	103	Displacement	146	Addressed	off
50	103	Stress	153	Maintenance Requested	on

Figure 5.13: Blockchain Events: Data Fetching using Sensor ID 03

Fetch Data using Reading ID

Reading ID:

Fetch Data

Figure 5.14: Blockchain Events: Data Fetching using Requested ID 01

Fetch Data using Reading ID

Reading ID:

Fetch Data

Request ID	Sensor ID	Breached Parameter	Parameter Reading	Status	Cool Down Period
9	101	Stress	158	Maintenance Requested	on

Figure 5.15: Blockchain Events: Data Fetching using Requested ID 02

Chapter 6

Performance Analysis

6.1 Performance Analysis and Validation

This section presents the performance analysis of the proposed system based on three key metrics: Transaction Per Second (TPS), latency, and block data fetching time. The results are analyzed to illustrate the efficiency, scalability, and responsiveness of each network under varying loads of transactions and data requests. Through visual representations, an illustration is drawn of how the proposed system is enhanced with the private blockchain network. For comparisons, the system has also been deployed on a public blockchain network (Polygon).

The comparison between public and private blockchain networks in terms of Transaction Per Second (TPS) lays a significant difference in performance, with the increment of transaction volumes. In a private blockchain, TPS remains high and efficient across various transaction loads, largely due to its more controlled environment. The figure 6.1 shows, at 600 transactions per proposal, the private network can handle 565 TPS, while the public network only manages 325 TPS. This gap extends as transaction volumes rise, focusing on a key limitation of public blockchains which is scalability. It is seen from the graph 6.1 that the private network has a highest point rise 2100 number of proposals. After that the TPS seems to get lower. So, a number of 2100 transactions are compatible for the proposed system in a private network. The private blockchain's efficiency roots from its lower consensus overhead and smaller number of nodes, which makes it less defenseless to delays caused by network congestion or complex validation processes. These factors allow it to process transactions faster. Such characteristics are a better fit for environments where performance and speed are critical, such as organizational or

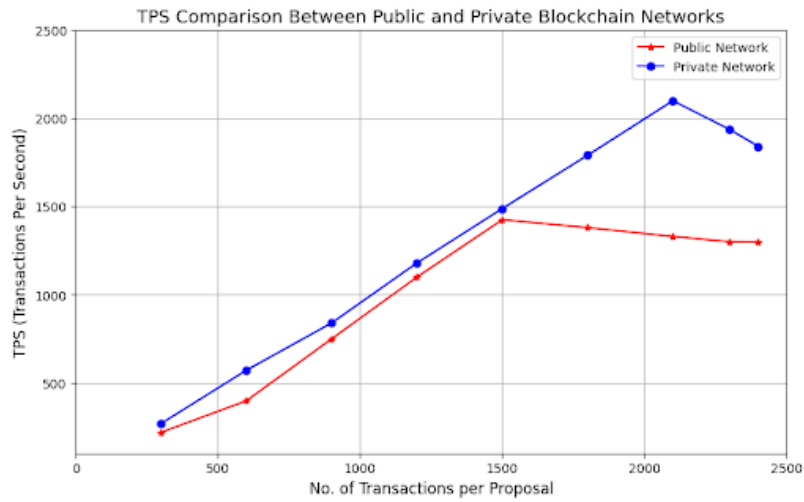


Figure 6.1: TPS Graph Comparison between Public and Private Blockchain Networks

consortium blockchains. On the other hand, the public blockchain, while offering greater decentralization and trust through a large number of participating nodes, struggles with throughput. Its more distributed nature and reliance on more complex consensus mechanisms, like Proof of Work, slow down transaction processing. This results in a performance constraint, when transaction volumes grow, making it less efficient for use cases requiring high throughput or low latency.

The figure 6.2 contrasts latency of public and private blockchain networks. A clear difference is sketched in response times as the transaction rate increases. In the private network, latency remains consistently low, staying below 1.5 seconds even when processing higher volumes of transactions. This stability suggests that the private blockchain is optimized for faster communication, likely due to its smaller number of nodes and efficient consensus mechanisms, which reduce the time spent on transaction validation and block creation. Even as the transaction rate approaches 200 TPS, the private network maintains a responsive and predictable performance. The public network experiences a significant increase in latency. Starting at 0.85 seconds with low transaction rates, it climbs steadily to 3 seconds as the load reaches 200 TPS. This is primarily due to the complex consensus mechanisms like Proof of Work and the larger number of nodes participating in the network. These factors slow down the validation process and introduce network congestion, making the public blockchain less efficient for applications where fast response

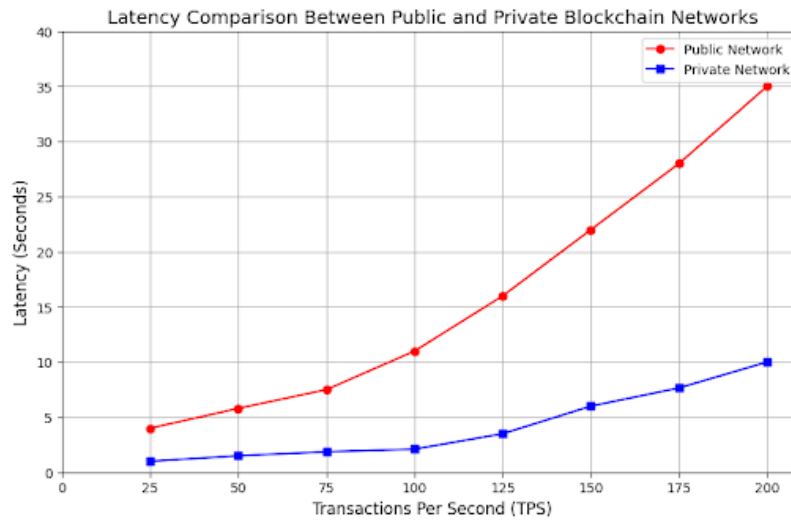


Figure 6.2: Latency Comparison between Public and Private Blockchain Networks

times are critical.

The last indicator, in Figure 6.3 uplifts the difference that the private network requires faster data retrieval times, taking less than 3 seconds to fetch up to 500 units of data. This efficiency is driven by its controlled environment, with fewer nodes and streamlined consensus mechanisms, enabling quicker data access. The stable performance across varying data sizes makes private blockchains ideal for use cases requiring frequent and fast data retrieval, such as in enterprise systems or supply chains. In contrast, the public network shows a dramatic increase in fetching time as the data size grows, reaching up to 28 seconds for the same 500 units of data. This delay is largely due to network congestion, the larger number of nodes, and the more distributed nature of the public blockchain. The need for consensus among many nodes slows down data retrieval, making the public network less suitable for high-frequency data access applications.

In compliance with the objective of putting forward an enhanced bridge health monitoring system, the performance analysis has been done with metrics mentioned in the testing and validation. The bridge health monitoring system is a near real-time data aggregator. Data is logged in the system with every 24 hour leap. The system requires a low latency so that the incoming continuous data can be transacted properly. its ability to maintain low-latency and efficient data retrieval, even under

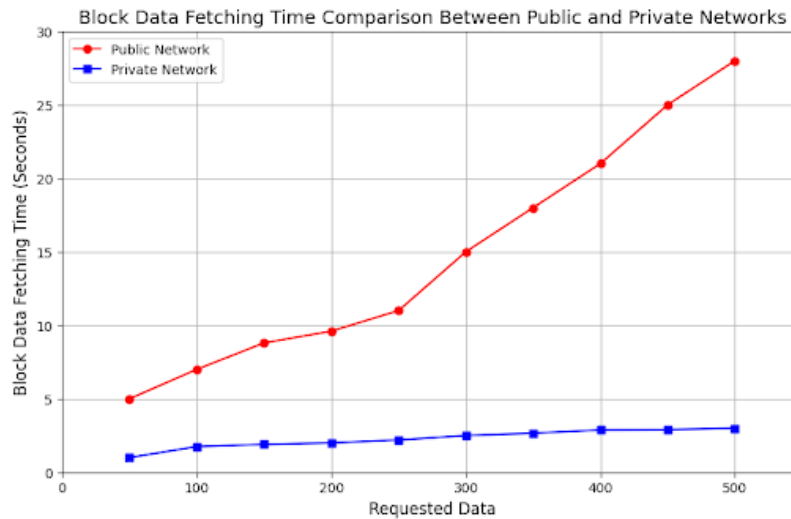


Figure 6.3: Block Data Fetching Time Comparison between Public and Private Blockchain Networks

high transaction volumes, makes it an ideal choice for real-time applications or enterprise environments where speed and performance are critical.

The private blockchain's streamlined architecture, fewer nodes, and efficient consensus mechanisms ensure quick transaction processing and reduced delays, aligning well with the performance needs of the system. While the public blockchain offers greater decentralization and trust, its slower data retrieval and higher latency, particularly as transaction volumes and data requests increase, make it less suitable for this system. The public network's focus on decentralization over speed introduces performance bottlenecks that could impede the system's responsiveness. Therefore, the private blockchain is better equipped to meet the system's demand for low-latency and high-throughput, ensuring smooth operation in high-transaction environments.

Chapter 7

Business Model

7.1 Customer Segmentation

InfraChain is an overall solution that will be implemented in different forms for the customers involved in the management of road infrastructure. Such stakeholders include government agencies such as municipal, city, state, and even national transport authorities, private infrastructure developers such as civil construction and engineering firms, business concern that invests in and operate infrastructure such as building government or private payback road bridges, or even transport services providers such as freight, bus companies, and logistics also insurance firms for infrastructure development and smart cities such as urban planning divisions.

These stakeholders derive benefits from the system in the following kinds: collection and integration of up-to-date information in finding solutions towards construction and maintenance of roads and bridges both in the present and in years to come, management frameworks and monitoring of repair budgets and programs of works on repairs as of now, assessment of building activities within and after completion of the building works and all advanced analysis and strategizing for the future, safeguarding of the asset and the investment at this time, cut down maintenance costs at this particular moment, ensure the safety of the route and efficient movement of goods at present, guarantee effective and secure transport services to her people at present. InfraChain is a valuable tool that contributes positively to the mobility and safety of cities.

7.2 Value Proposition

The system utilizes the integration of evolving sensing systems and blockchain to enhance the assessment of road and bridge structures. The benefits include pinpoint early signs of wear and tear, meaning that road surfaces can be maintained before the onset of serious problems resulting in increased durability. This ensures that the surfaces are repaired before serious issues arise, thus enhancing their lifespan. Maintenance strategies could be incorporated, given the information presented in InfraChain. Hence, savings will be made. In this manner, it is managed as a maintenance undertaking and, simultaneously, a blockchain-based system that records the different types of maintenance. It also aims to use the technology to maintain roads for safety where roads are controlled for any possible risks, as explained in the case of InfraChain. InfraChain can also deliver various infrastructure projects, from large-scale works to intricate lower-scale projects, thanks to its adaptable nature, which is premised on a simple-to-assemble modular sensor system and plug-and-play parts. InfraChain cuts the need to spend a lot of time doing physical inspection handling, making more economical work. InfraChain uses a collection of various social infrastructure states to yield an overall understanding of the structural condition of the critical assets.

7.3 Revenue Sources

Even though it can generate revenues through different ventures, InfraChain has minimal income from various sources. It offers a cost-effective subscription service with primary and enhanced features for tracking purposes at different levels. Free plans are provided for all interested users, who can also pay for the plan monthly or annually. InfraChain requests its customers to pay a one-off charge, which involves providing the users with the chain's sensors and system. To ensure everything is working as it is supposed to, they also decided to sell maintenance and support packages, and an extended warranty can also be offered. Besides, there are some billable services that InfraChain makes available, such as analytical data and advisory services. They also have different types of subscriptions, which companies pay to access their services through their various apps, and pay-as-you-use subscriptions, whereby clients pay to improve their systems with the company's systems.

7.4 Principal Activities

InfraChain focuses on the development, implementation, and optimization of the fabrication of an advanced infrastructure monitoring system. This refers to the expansion of their research and development segment, where they are working on enhancing the precision and sturdiness of their sensors in all circumstances. They are also constantly improving how their systems handle blockchain technology for security and more transparency in data storage. InfraChain outlines how everything from the sensors, data acquisition units, and blockchain technology is integrated into the system. They also value usability and foster user-friendly structures of interfaces that allow customers to use and interpret the gathered information easily.

After this, they set the system according to each client to fit all their requirements so there is no possibility of having wrong data at the initial stages. Real-time data analysis is also used at InfraChain to keep track of the health status of the infrastructure and pinpoint the early stages of the problem. In that way, they set certain thresholds, and once unusual data is observed, they generate alerts for necessary maintenance or repair. InfraChain provides detailed aftercare providing constant technical support so that the system can run smoothly and identify any problems. They also frequently service the sensors, data acquisition units, and software to ensure all elements work optimally.

Other strategies include doing market surveys that help InfraChain identify potential customers and their unique needs to help the firm provide customized solutions. They also develop good relations with provincial and local governments, institutions, private enterprises, and clients to capture a larger market. To assist customers, they also contribute to various counterparts by installing and demonstrating the benefits of the system as well as its potential in planning workshops.

7.5 Important Partnerships

InfraChain has established strategic alliances to enhance its technology, market, and system solutions and capabilities. This way, they get the best, leading manufacturers' sensors and the best, safest blockchain intact. Working with reliable cloud

correspondents to accommodate vast amounts of data for real-time analytics and safe storage. Collaborating with these firms can achieve adequate placement and correct arrangement of the sensors. This assists the government bodies in getting in line with the regulations on attaining BIG wins in their operations. They also rely on funding agencies to help them grow financially.

Partnerships with universities also help them remain among the leading institutions in innovation since they continuously conduct research and test the efficiency of the technologies being used. These pairings enable InfraChain to integrate with network existing networks and their product's interoperability. Current membership in industry groups is an indication that they are alert to trends in the market, and this enables them to join forces and lobby. Outsourcing with consulting firms in infrastructure management helps gain ideas and adds to the potential services.

7.6 Cost Structure

7.6.1 Prototype Development Cost

This section describes the total expenditures for Research and Development, testing and simulation, equipment and materials, and miscellaneous expenditures. The proposed spending for research and development is BDT 2,000,000. The general estimate for the cost of creating a technology prototype with varying difficulty is BDT 935,000 to BDT 4,675,000. Tk20,00,000 grant takes into consideration the requirement for specialized blockchain integration.

The testing and simulation budget allocated is BDT 1,500,000. The testing and simulation software frequency can set a price range of BDT 467,500 to BDT 1,870,000. The testing cost is 1500000 BDT, which encompasses software and affiliate facilities for extensive tests.

The money set aside for acquiring the equipment and materials is BDT 3,000,000. The cost of procuring necessary sensors and other instruments associated with this project's scope varied barely between BDT 1,402,500 and BDT 2,805,000 per prototype. Setting BDT 3,000,000 aside to purchase raw materials and components

ensures the firm procures quality.

The budget for miscellaneous expenses is BDT 500000. This budget covers unforeseen costs and follows the standard practice of allocating 10 to 15 percent of the total project cost as a contingency fund.

7.6.2 Full Scale Business Costs

The venture's operational cost has been set at BDT 5,000,000. Other fixed costs the startup has to incur are salaries and office rent with utility bills, which cost between BDT 5,610,000 and BDT 11,220,000. BDT 5,000,000 is reasonable for these figures based on our current scale of operation. BDT 6,000,000 is earmarked for manufacturing and deploying products for the target population. The cost foundations of the drones and their implementation indicate the general cost spectrum, which ranges from BDT 4,675,000 up to BDT 18,700,000, depending on the series manufacturing and development of technologies. BDT 6,000,000 was projected merely for the initial manufacturing and deployment costs.

Another important expenditure is the cost of marketing and sales, which has been determined to be BDT 4,000,000. The expected marketing expense of new tech startups is BDT 935000 to BDT 4675000 a year. BDT 4,000,000 will be used for massive marketing to cover the market with advertisements and promotions.

The required money for support and maintenance is BDT 2,500,000. Annual maintenance costs include spare parts and employee time, which hover at roughly BDT 935000 to BDT 4675000 per fleet. Since this is the starting year, BDT 2,500,000 will fund the initial fleet maintenance.

BDT 2,500,000 has been set for research and development activities to persist so that the company can identify new additions in the market. The likely annual capital requirement for continuous RD is USD 28,000-USD 141,400 (BDT 2,610,000-BDT 13,150,000), while operational cost varies between USD 24,000 and USD 118,000 (BDT 1,870,000-BDT 9,350,000). BDT 2,500,000 ensures constant additions and enhancements to the current services.

It is estimated that BDT 1,000,000 will be required to host the organization. Costs related to hosting cloud services, servers, and data storage are calculated at an approximate rate of BDT 935,000 to BDT 2,805,000 per annum and are based on the prevailing industry average. Stating our desired level of funds, BDT 1,000,000 lies in this range.

The budget for the Ethereum platform expenditure is \$20000, or the equivalent of BDT 1,500,000. The general expenses in executing the Ethereum network comprise the smart contract development cost and the gas fee, which range from 1,402,500 to 4,675,000 BDT. BDT 1,500,000 is required to be spent on these expenses.

The budget in question is assigned to the DApp development costs, which sum up to BDT 2,000,000. Creating an app from scratch costs between 27783 and 145,250, which equals BDT 1,870,000 and BDT 9,350,000, respectively, for a decentralized app. BDT 2,000,000 will look ahead at establishing a sound foundation for managing operations in a robust DApp.

7.6.3 Revenue and Break Even Point

Subscription fees will be another additional source of revenue, and the projected amount from subscription fees is BDT 10,000,000 only. Many technology-related services revenues are achieved through subscription-based systems, where the income from such sales can be dramatic and could be between 30 and 50 percent of the total revenues. According to this projection of the same group, BDT 10,000,000 is reasonable.

The overall revenue expected to be generated through the service fees is BDT 7,000,000. Distribution services' fees from on-demand delivery may also be high, and they generally account for between 20% and 30% of the overall revenue. BDT 7,000,000 is expected to be generated from this source.

Another additional source of revenue will be the Subscription fees. BDT 50000 is the only projected subscription fee for the selected travel agency. Several initiatives sell revenues of technology-related services through subscription-based systems, and revenues from such undertakings could be dramatic, ranging from 30

to 50 percent of total revenues. As per this kind of projection of the same group, it has been found that the BDT 10,000,000 is rational.

The projected sales amount receivable from performance contracts is BDT 7000000. This can comprise 20-30% of revenues in companies that engage in performance-based arrangements, particularly with their government and big-business customers. BDT 7,000,000 has been estimated from these contracts. NB: these are rough estimates and the actual figures could vary based on various factors.

Chapter 8

Conclusion

The procedures tackle the challenges posed by the social, legal, ethical, and environmental elements of traditional monitoring infrastructures. It assists in dealing with problems like divergent information from different sources and unresolved facts about certain activities or maintenance work, which often affects the safety and quality of bridges. The response makes bridge health data indisputable, transactive, and trackable by employing blockchain technology, which lowers the chances of information sabotage and boosts the user's confidence in the whole monitoring exercise. Also, a healthy bridge monitoring system enables transactions to be carried out quickly, and it facilitates maintenance decisions for the structures in a more efficient and effective manner, promoting the safety of people. Advanced technology also helps to care for the environment by reducing the need to print out plenty of documents for administrative purposes along with filing.

8.1 Societal, Health, Safety, Legal, and Cultural Aspects

The introduction and use of InfraChain, a sensor-based bridge maintenance system incorporating a few elements of blockchain, positively different sectors of society including health, safety, legal, and even cultural practices. InfraChain avails itself to society by improving the safety and reliability of the transport infrastructure. Since the system facilitates the constant assessment of certain structural health parameters, it greatly helps prevent problems that can arise that can lead to the collapse of the infrastructure. This strategy not only increases the safety of the

public but also enhances the quality of the transportation services provided.

There is much more to the safety concerns of InfraChain than meets the eye. Thanks to continual sensor monitoring, road damage and structural deficiencies can be recognized much earlier to avoid loss of lives and traffic disruption. By ensuring that bridges do not fall into the wrong hands or that any damage happens to them, the InfraChain system lessens the impact posed by the decaying infrastructure on people and their health.

Since its components are largely based on mobile apps, legalism will keep every element of the service offered by InfraChain in check. The built-in features of blockchain provide everyone, including the regulators, with non-changeable – permanent records of what maintenance has been done and when. Such clarity helps avoid misunderstanding and increases responsibility for the infrastructure resources.

8.2 Impact on Environment and Sustainability

The role of InfraChain in environmental protection and sustainability is quite extensive. It employs state-of-the-art technologies to reduce its environmental impact and at the same time offer maximum efficiency of the infrastructure.

InfraChain lessens the environmental factors related to infrastructure upkeep by increasing the interval of effective maintenance tasks. This detailed scheduling reduces the unnecessary energy consumption directed to maintenance and also unnecessary interventions. In addition, the sustainable aspects of InfraChain are enormous. It is thanks to the system that infrastructure failures do not result in universal skidding of equipment and material resources, as extensive repairs and replacements of damaged infrastructure are not needed. Furthermore, because of InfraChain, the wear of the infrastructure assets is reduced, and as such, it helps fulfill the sustainable development goals by increasing the bridge's life while lessening the use of materials. In addition, the proper use of these resources is embedded in the work of InfraChain. The proposed system assists in cutting down costs and enhancing operational efficiency since maintenance tasks are well scheduled using

sensor and agricultural blockchain data. This efficiency improves the sustainability of the infrastructure management system.

8.3 Ethical and Professional Principles

In the course of putting up and running InfraChain, there is a basic respect for values and practices that guide the profession. Data protection and safeguarding of individual privacy is paramount in InfraChain. Because of the use of Blockchain technology, sensitive information about the infrastructure's condition, including how the infrastructure is maintained, will be kept in a backend system that only a few designated persons are allowed to access. This protects the identity of the users, thus eliminating the chance of data exposure. One important value that InfraChain upholds is the value of Transparency. The system makes use of a blockchain ledger to record all the maintenance activities so that all the participants have access to the records, which cannot be changed. This way, stakeholders instill trust in each other regarding the management of the income-generating infrastructures and hence the need for accountability.

On the contrary, InfraChain incorporates a professional approach in its operations. Professional integrity is one of the guiding principles in the design and usage of the system together with regulatory requirements, which makes sure that all maintenance practices are performed within the law and moral obligations. This integrity guarantees added value to the system and its operations.

8.4 Future Work

While InfraChain currently utilizes strain gauge to monitor structural strain, future work could explore the integration of additional sensor types. These could include 'Advanced Imaging Sensors', to capture visual data that can be analyzed using machine learning algorithms for detecting surface cracks or other visible signs of deterioration and 'Acoustic Emission Sensors' for detecting stress waves generated by the sudden release of energy within the material, indicative of crack formation or growth. Combining sensor data with geographic data to visualize bridge health in the context of its surrounding environment.

As the number of monitored bridges and the amount of data collected grows, it will be crucial to address scalability and network optimization. Implementing distributed computing techniques to handle large volumes of data and ensure timely processing and analysis. Besides, using edge computing to process data closer to the source (i.e., on-site at the bridge) to reduce latency and bandwidth usage. By pursuing these future work directions, InfraChain can continue to evolve, addressing emerging challenges and leveraging new technological advancements to further enhance bridge maintenance and safety.

Bibliography

- Alharbi, F., Zakariah, M., Alshahrani, R., Albakri, A., Viriyasitavat, W., & Alghamdi, A. A. (2023). Intelligent transportation using wireless sensor networks blockchain and license plate recognition. *Sensors*, 23(5), 2670.
- Al Omar, A., Jamil, A. K., Khandakar, A., Uzzal, A. R., Bosri, R., Mansoor, N., & Rahman, M. S. (2021). A transparent and privacy-preserving healthcare platform with novel smart contract for smart cities. *IEEE Access*, 9, 90738–90749.
- Al-Radaideh, A., Al-Ali, A. R., Bheiry, S., & Alawnah, S. (2015). A wireless sensor network monitoring system for highway bridges. In *2015 international conference on electrical and information technologies (iceit)* (pp. 119–124).
- Alzahrani, R. A., Herko, S. J., & Easton, J. M. (2020). Blockchain application in remote condition monitoring. In *2020 IEEE International Conference on Big Data (Big Data)* (pp. 2385–2394).
- Arachchige, K. G., Branch, P., & But, J. (2024). An analysis of blockchain-based IoT sensor network distributed denial of service attacks. *Sensors*, 24(10), 3083.
- Catbas, N., & Avci, O. (2022, September). A review of latest trends in bridge health monitoring. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering* (Vol. 176, pp. 76–91).
- Celik, Y., Petri, I., & Barati, M. (2023). Blockchain supported BIM data provenance for construction projects. *Computers in Industry*, 144, 103768.
- Chen, Y., & Volz, U. (2022). Scaling up sustainable investment through blockchain-based project bonds. *Development Policy Review*, 40(3).
- Denis, J., & Florentin, D. (2024). Urban infrastructures' maturity and the age (s) of maintenance. In *Handbook of infrastructures and cities* (pp. 119–132). Edward Elgar Publishing.
- Efanov, D., & Roschin, P. (2018). The all-pervasiveness of the blockchain technology. *Procedia Computer Science*, 123, 116–121.

- Feng, W., Chen, B., Tang, Y., Wei, W., He, W., & Yang, Y. (2022). Structural effects and real strain-rate effects on compressive strength of sustainable concrete with crumb rubber in split hopkinson pressure bar tests. *Archives of Civil and Mechanical Engineering*, 22(3), 136.
- Gabbar, H. A., Chahid, A., Isham, M. U., Grover, S., Singh, K. P., Elgazzar, K., & Ouda, H. (2023). Hais: Highways automated-inspection system. *Technologies*, 11(2), 51.
- Gadiraju, D. S., McMaster, R., Azam, S. E., & Khazanchi, D. (2024). Bionib: Blockchain-based iot using novelty index in bridge health monitoring. *arXiv preprint arXiv:2402.14902*.
- Galdelli, A., D'Imperio, M., Marchello, G., Mancini, A., Scaccia, M., Sasso, M., & Cannella, F. (2022). A novel remote visual inspection system for bridge predictive maintenance. *Remote Sensing*, 14(9), 2248.
- Gomez-Cabrera, A., & Escamilla-Ambrosio, P. J. (2022). Review of machine-learning techniques applied to structural health monitoring systems for building and bridge structures. *Applied Sciences*, 12(21), 10754.
- Guerrero-Sanchez, A. E., Rivas-Araiza, E. A., Gonzalez-Cordoba, J. L., Toledano-Ayala, M., & Takacs, A. (2020). Blockchain mechanism and symmetric encryption in a wireless sensor network. *Sensors*, 20(10), 2798.
- Gupta, P., & Jha, K. N. (2023). A decentralized and automated contracting system using a blockchain-enabled network of stakeholders in construction megaprojects. *Journal of Management in Engineering*, 39(4), 04023021.
- Han, D., Hosamo, H., Ying, C., & Nie, R. (2023). A comprehensive review and analysis of nanosensors for structural health monitoring in bridge maintenance: innovations, challenges, and future perspectives. *Applied Sciences*, 13(20), 11149.
- Hassani, S., & Dackermann, U. (2023). A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring. *Sensors*, 23(4), 2204.
- Hu, Z. (2024). Research on bridge structural health monitoring system based on sensor data. *Highlights in Science, Engineering and Technology*, 106, 501–506.
- Huang, S., Wang, G., Yan, Y., & Fang, X. (2020). Blockchain-based data management for digital twin of product. *Journal of Manufacturing Systems*, 54, 361–371.
- Hwang, S., Blay, K., Osmani, M., & Wang, M. (2024). The role of blockchain in enhancing trust: A construction project governance approach. In *Ec3 conference 2024* (Vol. 5, pp. 0–0).

- Jiang, L., Tang, Q., Jiang, Y., Cao, H., & Xu, Z. (2023). Bridge condition deterioration prediction using the whale optimization algorithm and extreme learning machine. *Buildings*, 13(11), 2730.
- Jo, B. W., Khan, R. M. A., & Lee, Y. S. (2018). Hybrid blockchain and internet-of-things network for underground structure health monitoring. *Sensors*, 18(12), 4268.
- Lanciano, C., & Salvini, R. (2020). Monitoring of strain and temperature in an open pit using brillouin distributed optical fiber sensors. *Sensors*, 20(7), 1924.
- Le, T. V., & Hsu, C. L. (2021). A systematic literature review of blockchain technology: Security properties, applications and challenges. *Journal of Internet Technology*, 22(4), 789–802.
- Li, H., Zhang, J., Chen, J., Luo, Z., Zhang, J., Alhandarish, Y., & Wang, L. (2020). A supersensitive, multidimensional flexible strain gauge sensor based on ag/pdms for human activities monitoring. *Scientific Reports*, 10(1), 4639.
- Li, J., & Kassem, M. (2021). Applications of distributed ledger technology (dlt) and blockchain-enabled smart contracts in construction. *Automation in Construction*, 132, 103955.
- Liu, J., Yuan, S., Luo, B., Biondi, B., & Noh, H. Y. (2022). Vibration-based bridge health monitoring using telecommunication cables. *arXiv preprint arXiv:2205.05114*.
- Ma, W., Zhu, H., Zhang, S., Meng, X., Lu, Y., & Tan, W. (2023). A drone-based data management and optimization using metaheuristic algorithms and blockchain smart contracts in road infrastructure projects. *Buildings*, 13(10), 2578.
- Mahmudnia, D., Arashpour, M., & Yang, R. (2022). Blockchain in construction management: Applications, advantages and limitations. *Automation in Construction*, 140, 104379.
- Marchang, J., Ibbotson, G., & Wheway, P. (2019). Will blockchain technology become a reality in sensor networks? In *2019 wireless days (wd)* (pp. 1–4).
- Mbandi, J., & Kisangari, M. (2020). Data collection using wireless sensor networks and online visualization for kitui kenya. In *African handbook of climate change adaptation* (pp. 1–13).
- Mi, F., Zhao, C., Wang, Z., Halim, S., Li, X., Wu, Z., & Thuraisingham, B. (2023). An automated vulnerability detection framework for smart contracts. *arXiv preprint arXiv:2301.08824*.

- Nawari, N. O., & Ravindran, S. (2019). Blockchain technology and bim process: review and potential applications. *Journal of Information Technology in Construction*, 24.
- Neves, A. C. (2020). *Structural health monitoring of bridges: data-based damage detection method using machine learning* (Doctoral dissertation). KTH Royal Institute of Technology.
- Ogungbemi, O. S. (2024). Smart contracts management: The interplay of data privacy and blockchain for secure and efficient real estate transactions. *Journal of Engineering Research and Reports*, 26(8), 10–9734.
- Pallante, L., Meriggi, P., D’Amico, F., Gagliardi, V., Napolitano, A., Paolacci, F., & de Felice, G. (2024). An integrated data-driven system for digital bridge management. *Buildings*, 14(1), 253.
- Poli, F., Bado, M. F., Verzobio, A., & Zonta, D. (2023). Bridge structural safety assessment: a novel solution to uncertainty in the inspection practice. *Structure and Infrastructure Engineering*, 1–15.
- Ponzo, F. C., Ditommaso, R., Auletta, G., Lamarucciola, N., & Ielpo, P. (2023). Structural health monitoring of transport infrastructures: preliminary experimental calibration of the numerical model of “ponte della musica–armando trovajoli”. *Procedia Structural Integrity*, 44, 854–861.
- Qi, J. (2024). Bridge safety assessment and management strategies under long-term operating conditions. *Highlights in Science, Engineering and Technology*, 106, 558–564.
- Quinci, G., Gagliardi, V., Pallante, L., Manalo, D. R. J., Napolitano, A., Bertolini, L., & Paolacci, F. (2022, October). A novel bridge monitoring system implementing ground-based, structural and remote sensing information into a gis-based catalogue. In *Earth resources and environmental remote sensing/gis applications xiii* (Vol. 12268, pp. 101–111).
- Rahman, S. (2024). Smart contracts: The blockchain revolution in contract law. *International Journal For Multidisciplinary Research*, 6(3), 10–36948.
- Ramasamy, L. K., KP, F. K., Imoize, A. L., Ogbebor, J. O., Kadry, S., & Rho, S. (2021). Blockchain-based wireless sensor networks for malicious node detection: A survey. *IEEE Access*, 9, 128765–128785.
- Scott, D. J., Broyd, T., & Ma, L. (2021). Exploratory literature review of blockchain in the construction industry. *Automation in construction*, 132, 103914.

- Sigalov, K., Ye, X., König, M., Hagedorn, P., Blum, F., Severin, B., & Groß, D. (2021). Automated payment and contract management in the construction industry by integrating building information modeling and blockchain-based smart contracts. *Applied Sciences*, 11(16), 7653.
- Singh, A. K., Kumar, V. P., Irfan, M., Mohandes, S. R., & Awan, U. (2023). Revealing the barriers of blockchain technology for supply chain transparency and sustainability in the construction industry: an application of pythagorean fahp methods. *Sustainability*, 15(13), 10681.
- Sobecki, A., Barański, S., & Szymański, J. (2022). Privacy-preserving, scalable blockchain-based solution for monitoring industrial infrastructure in the near real-time. *Applied Sciences*, 12(14), 7143.
- Sánchez-Silva, M., & Baker, J. W. (2024). Dynamic infrastructure systems: advancing sustainable urbanization and climate change. *Environment Systems and Decisions*, 1–11.
- Taflanidis, A., & Gidaris, I. (2011). Bayesian updating of deteriorating bridge infrastructures through monitoring data. In *Asme international mechanical engineering congress and exposition* (Vol. 54952, pp. 753–763).
- Tian, Y., Minchin, R. E., Petersen, C., Moayed, E., & Adriaens, P. (2022). Financing public-private partnership infrastructure projects through tokenization-enabled project finance on blockchain. In *Iop conference series: Materials science and engineering* (Vol. 1218, p. 012027).
- Wahab, A., Wang, J., Shojaei, A., & Ma, J. (2022). A model-based smart contracts system via blockchain technology to reduce delays and conflicts in construction management processes. *Engineering, Construction and Architectural Management*. ((ahead-of-print))
- Wang, H., Barone, G., & Smith, A. (2023). Current and future role of data fusion and machine learning in infrastructure health monitoring. *Structure and Infrastructure Engineering*, 1–30.
- Wang, Z., & Guan, S. (2023). A blockchain-based traceable and secure data-sharing scheme. *PeerJ Computer Science*, 9, e1337.
- Wu, C., Wu, P., Wang, J., Jiang, R., Chen, M., & Wang, X. (2021). Critical review of data-driven decision-making in bridge operation and maintenance. *Structure and Infrastructure Engineering*, 18(1), 47–70.
- Xu, J., Liu, H., & Han, Q. (2021). Blockchain technology and smart contract for civil structural health monitoring system. *Computer-Aided Civil and Infrastructure Engineering*, 36(10), 1288–1305.

- Ye, C., Kuok, S. C., Butler, L. J., & Middleton, C. R. (2022). Implementing bridge model updating for operation and maintenance purposes: Examination based on uk practitioners' views. *Structure and Infrastructure Engineering*, 18(12), 1638–1657.
- Zadeh, E. K., & Safaei, M. (2023). Utilizing blockchain technology for enhancing transparency and efficiency in construction project management. *International Journal of Industrial Engineering and Construction Management (IJIECM)*, 1(1), 1–8.
- Zarate Garnica, G. I., Lantsoght, E. O. L., & Yang, Y. (2022). Monitoring structural responses during load testing of reinforced concrete bridges: A review. *Structure and Infrastructure Engineering*, 18(10-11), 1558–1580.
- Zheng, Z., Xie, S., Dai, H. N., Chen, W., Chen, X., Weng, J., & Imran, M. (2020). An overview on smart contracts: Challenges, advances and platforms. *Future Generation Computer Systems*, 105, 475–491.
- Zorbas, D., & O'Flynn, B. (2018). Collision-free sensor data collection using lorawan and drones. In *2018 global information infrastructure and networking symposium (giis)* (pp. 1–5).
- Zou, W., Lo, D., Kochhar, P. S., Le, X. B. D., Xia, X., Feng, Y., & Xu, B. (2019). Smart contract development: Challenges and opportunities. *IEEE Transactions on Software Engineering*, 47(10), 2084–2106.