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Exploring Blockchain-Based Information Systems for Maritime Engineering Data Management

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***Abstract* - Shipbuilders, port authorities, regulatory bodies, and maintenance providers comprise the various maritime engineering stakeholders. As for ship design and maintenance, enormous amounts of information must be created, managed, and exchanged. One of the major problems is that data management systems in this field are usually fragmented, undersized, static, and susceptible to several challenges like data manipulation, lack of collaboration transparency, and organizational data sharing inefficiencies. Engineering asset digitization is one of the many transformations the maritime industry is adopting. With it, it becomes crucial to secure systems capable of engineering data transparency, such as interchangeability, non-repudiation, and asset data audit throughout the lifecycle. This paper investigates the issues regarding structuring and maintaining maritime engineering data and how blockchain technology can be leveraged to solve those issues. The research proposing a blockchain-based Information system capable of data manipulation, alteration, sharing, partitioning, and controlled access of novel architecture components such as ship design specification, inspection, maintenance history, and certification records benefits ownership decentralization, immutability, smart contracts, and blockchain. This system reduces costs while empowering stakeholders and improving trust by automating workflows with programmable borders. The comprehensive architecture of the system, as provided in this document, is built around the maritime platforms of trust. It includes data design structures, consensus control mechanisms, block chaining control networks, access rights governance, bordering system, and interfacing legacy inputs. Centered on the ship maintenance data case study, this paper demonstrates how automated transparency in the proposed system minimizes conflicts. Metrics relating to performance evaluation, including latency, throughput, and scalability, are examined to determine their value concerning real-world implementation in a maritime context.**

***Keywords:* Management, Information System, Blockchain, Database, Stakeholders, Transparency, Security, Digital Engineering Industry**

I. INTRODUCTION

Maritime engineering incorporates shipbuilding, ship repair, port activities, offshore construction, and vessel servicing into one broad field, primarily due to its significant economic impact. With the adoption of automatic machines and modern information technologies into digital ships and port infrastructure systems, the engineering information that needs to be processed alongside has undergone significant increases in scope and complexity. Data critical for maintaining the shipping company's operational safety and compliance with laws and international treaties concerning safety, environmental protection, and cost-effective operation includes documentation of ship design, structural health monitoring (SHM) reports, maintenance of port log books, and maintenance schedules. The effective management of maritime engineering is dependent on having accurate and secure data with guaranteed traceability. Accuracy, for example, retention of engineering data integrity through non destruction, is essential for retrofitting, managing a ship's lifecycle, and auditing. Protection of confidential medical and financial data against exposure to hostile cyber activity is critical due to the enhanced vulnerability of vessels and port facilities to automation and interconnection by IoT devices. Stakeholders need to be able to view changes to data over time, including where the data came from and what data transformations took place. This is vital for investigating accidents, warranty claims, and regulatory audits (Diwakar & Roy, 2024). The field of maritime data management is critical, but it faces a wide variety of challenges. Fragmentation of data is considered a chronic disease because it exists in silos managed by diverse players shipowners and operators, class societies, equipment suppliers, and even regulatory bodies. This narrow form of thinking results in added inefficiencies, compounding the potential for data loss or duplication, and stagnating timely access to decision-making insights. Additionally, disputes concerning data integrity often result in unnecessary trustless verification cycles, manual record-keeping, and intense conflict over data being accurate. Added inefficiencies in these processes are detrimental to operational budgets, result in lengthy delays on inter-milestones of ongoing projects, and intensify the risk of compliance-related security.

The maritime industry is essential in international trade, energy transport, and offshore resource exploitation. Maritime engineering includes the design, construction, operation, maintenance of ships, ports, offshore structures, and navigation systems. In these spheres, the growing data-centric approach to different activities places unprecedented importance on engineering data quality, security, and traceability. A workload outline within maritime engineering would incorporate the maritime engineering data, which is reliable and supports the requirement of unalterable information. A structural design, maintenance, operational log, or any engineering decision relied upon is based on verified, pristine data (Shin et al., 2024). Information integrity entails prescriptive data that is risk-compliant and can pose significant safety and financial risks in addition to non-compliance with regulations. Outdated or incorrect blueprints during a vessel retrofitting change pose engineering faults, alongside incomplete maintenance records masquerading as mechanical failures. Data security is equally salient, especially with the integration of maritime infrastructure through digital twins, IoT, and cloud computing (Aravind et al., 2023). Engineering data encompasses sensitive material, including but not limited to vessel performance data, proprietary designs, and compliance documents (Kim et al., 2024). Operational continuity is undermined, malicious access to operational systems, information leaks, or intentional harm can expose organizations to political and reputational liability during cyber-attacks. As described before, the ability to assign origin, modification, and ownership of information ensures smooth operations in maritime engineering, which is commonly known as traceability.

Even with modern advances in digital technologies, existing data handling systems in maritime engineering are still facing many outdated obstacles. One of the most problematic ones is the subdivided nature of the data itself, which exists within different non-communicating systems, or data silos, which undermine virtually all collaboration. Each relevant stakeholder like shipbuilders, port officials, classification societies, and regulatory bodies have their proprietary database which creates data silos. In turn, with the subsystems evolving independently, there is redundant work, latency in data retrieval, and diverging data during the engineering lifecycle. Furthermore, the lack of collaboration tends to erode trust and increase opacity. Hesitancy to share data is crucial for other parties to work due to ownership and misuse, authenticity concerns discourage sharing amongst project participants, who should cooperate for safety, compliance, and contract execution.

To make matters worse, they still rely on manual documentation, using semi-digital methods (spreadsheets), and even paper, leading to inaccuracies and making verifying and authenticating almost impossible. These practices severely hinder the processes of auditing, traceability, and verification. Cyber-attacks and data unscrambling become far too easy with basic industry centralized databases, as these are the most prone to being single points of failure. The consequences can be life-threatening, especially when said flawed data is tampered with and influences safety compliance or regulatory decisions. Lastly, most traditional systems still cannot support fundamental transformations of data exchange, meaning that communication and decision making nearly halt. This could cause business problems, including higher expenses and failing compliance targets. These issues illustrate the need for a cohesive, agile, and comprehensive approach to data governance that ensures data quality, builds reliance, and enables coordinated action within the maritime engineering community. The investigative focus of this paper is how blockchain-based information systems can offer a maritime-structured solution to these issues by proposing a distributed model for collecting and storing engineering data while fostering end-user trust and operational efficiency (Lin, 2024).

1.1 Motivation of the Research

- Using blockchain technology, data such as ship designs, maintenance records, and compliance documents are sorted into immutably bound blocks. This ensures the data is authentic, facilitating trust among stakeholders who depend on accurate information throughout the asset lifecycle.
- Blockchains core characteristics of real-time data sharing enables the removal of a central autoreactive figure, thereby eliminating silos and fostering collaboration among shipbuilders, operators, regulatory bodies, and other industry players which is critical in multi-party scenarios with intricate relational engineering.
- The approval of supervised smart contracts enables automation for maritime milestones, creating workflows marking inspections, maintenance, and certifications. This improves operational efficiency and compliance, and reduces manual errors and administrative overhead.

1.2 Objective of the Research

- The study aims to assess the influence of blockchain technology on the integrity and traceability of data within maritime engineering workflows by concentrating on its features such as document immutability, timestamps, and audit trails, especially for key documents.
- The system is designed to solve the problems of data fragmentation, lack of transparency, security weaknesses, and inefficiency while upholding data integrity, immutability, traceability, and safe collaboration among stakeholders.

II. LITERATURE SURVEY

While existing systems for managing maritime data are pretty sophisticated, they still have critical gaps in data integration, seamless connectivity, and automation. Other Enterprise Asset Management (EAM) systems for maintenance are used alongside Terminal Operating Systems (TOS) for managing port logistics, and separate Product Lifecycle Management (PLM) tools are utilized for ship design, leading system fragmentation and data silos. Subordinate classes of such systems employ manual and pseudo-digital workflows, which greatly hinder data verification, authentication, and operational access across numerous stakeholders. For instance, the certification and regulatory records pertaining to maritime authority are often impossible to authenticate and verify, which creates a standstill in inspection and compliance workflows. Blockchain technology has the potential to address all such challenges by utilizing a robust, transparent, and permanent approach for managing maritime engineering data (Pu & Lam, 2021). One of the blockchain's primary attributes, immutability, guarantees that information such as maintenance logs, design blueprints, and compliance certificates, once entered, cannot be altered, thus assuring the authenticity alongside the information's integrity. Relinquishing control from a single central authority facilitates the availability of a shared, "decentralized" ledger to all relevant parties, which fosters active participation while reducing risks. Through smart contracts, the automation of activities such as issuing certifications, tracking inspections, and scheduling maintenance is made possible. This reduces manual effort and ensures compliance by all parties with specified conditions. Lastly, consensus algorithms incorporated in blockchain technology allow any user within the network to confirm the transactions, thus maintaining the integrity of the data and protecting against fraud (Li et al., 2024). These characteristics show how blockchain technology can resolve problems related to inefficiency and lack of security in existing systems for managing maritime information, thereby improving transparency, safety, and operational efficiency in maritime enterprises.

The potential of blockchain technology in multiple industries can already be seen with its application in supply chain management, logistics, and even engineering (Surucu-Balci & Iris, 2024). In logistics, traceability and transparency have been enhanced through the movement of goods from producers to consumers using blockchain technology (Kim et al., 2024; Nguyen et al., 2023). IBM's Food Trust blockchain is an excellent example of this as it enables all food supply chain members to monitor food movement from the farm to the table, allowing for food safety and fraud reduction and efficient recall processes in contamination cases. In logistics, blockchain has been adopted by companies such as Maersk and IBM, which utilize it to enhance shipment and inventory tracking. Shipments and goods are registered on a blockchain ledger, which minimizes delays, ensures compliance with international regulations, and improves overall efficiency. Blockchain's unified data source has dramatically improved accuracy in shipping documents and reduced opportunities for fraud (Jabbar & Bjørn, 2018). Blockchain technology is useful in the engineering sector and in asset management, design collaboration, and maintenance tracking. Airbus, for example, has been known to use blockchain technology when monitoring parts production for the aerospace sector (Wang & Qu, 2019). Blockchain assures part integrity and authenticity and enables tracking at all stages of the lifecycle. Moreover, its application for automating smart contracts in construction and infrastructure projects where contracts are executed automatically once all prerequisites are completed has been noted concerning payment disbursements and necessary timelines being followed. Such use cases show blockchain's ability to improve data integrity, accuracy, and collaboration in complex multi organizational settings which can be directly applied to maritime engineering because of the data silos, insufficient data visibility, and intricate stakeholder relationships.

II. Methodology

The information system proposed in this research for maritime engineering data management features a blockchain technology backbone, including workflows for ship design, maintenance tracking, regulatory compliance, etc., as shown in Fig. 1. The system employs a permissioned blockchain network like Hyperledger Fabric or Quorum, where trusted stakeholders in the maritime domain, such as shipbuilders, classification societies, port authorities, and maintenance providers, form a consortium and operate validated nodes within the trusted framework (Li & Zhou, 2021). This partitioned yet restricted approach permits all participants to maintain a consistent, shared database that cannot be modified or altered in an unprotected manner. Smart contracts streamline automated business processes, such as maintenance verification, certificate creation, design authorization, and compliance surveillance. These contracts remove manual delays and, to some extent, discretion. Because blockchains have no built-in provisions for big-file data storage, the architecture divides content by storing cryptographic document (CAD files, inspection reports, and certificates) hashes on-chain.

In contrast, actual documents remain in secure off-chain storage systems like IPFS or enterprise cloud repositories. Such multi-faceted solutions protect the data without complicating the blockchain (Jung, 2022). Control over data and related functionalities is done through a role-based access control mechanism with a public key infrastructure (PKI) that issues digital identities, preventing unauthorized actions and information access by different entities. As a means of preserving interoperability with aging systems such as PLM, EAM, and port logistics software, the system contains an API gateway along with an integration layer that enables cross silos data exchange and real-time data sync. Workflows can be initiated, documentation can be uploaded, and alerts for due inspections or certification renewals can be received through various mobile and web applications, which feature a streamlined interface, placing the end-user in greater control. Consensus methods such as PBFT or Raft, which are well suited for permissioned settings, are employed by these blockchain networks alongside ensuring data consistency, security, fault tolerance, and reliable distribution (Jabbar & Bjørn, 2018). This integrated architecture supports safe, efficient, and verifiable maritime data exchange while ensuring seamless integration with pre-existing operational systems.

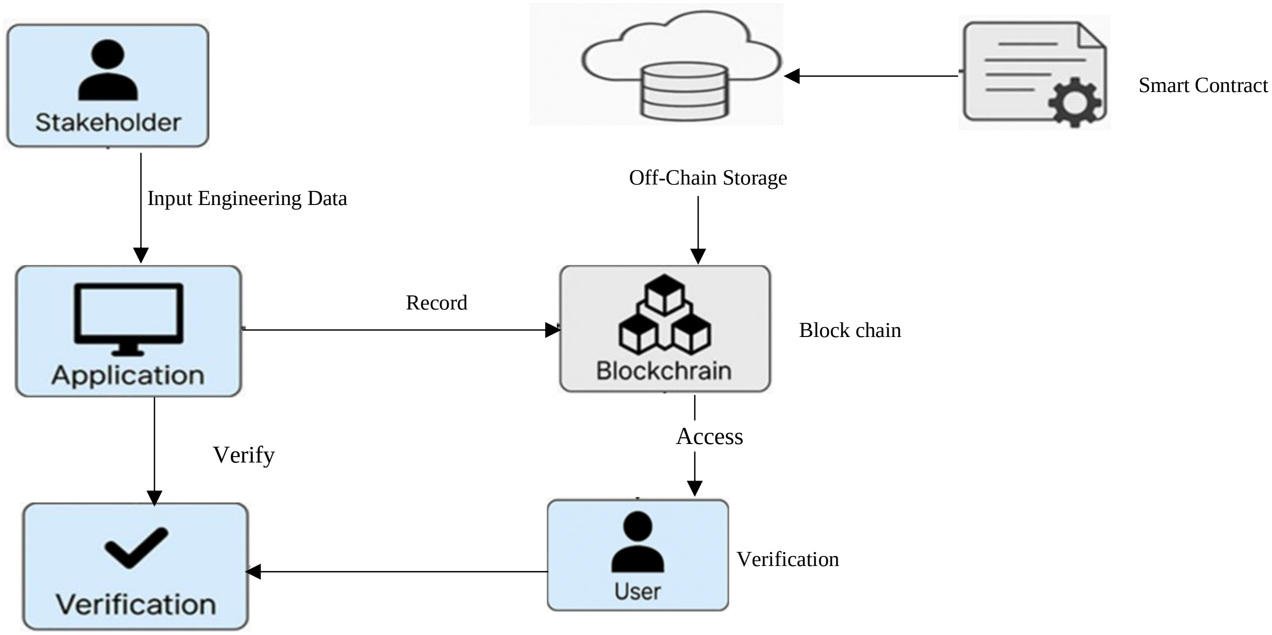

Fig. 1 Proposed Model Flow

In a blockchain-based maritime engineering information system, sensitive engineering information, including ship design files, maintenance logs, and compliance documents, needs careful management with regard to access control and privacy. Only relevant stakeholders should be able to access such sensitive data. As such, role-based access control (RBAC) is implemented. A Public Key Infrastructure (PKI) system assigns a unique digital identity to each stakeholder, such as a shipbuilder, port authority, maintenance crew, and regulatory agency. These digital identities dictate what data and processes are accessible to each role. A particular example would be a maintenance technician who has write privileges on the update logs but no access to any design documents for the vessel. Classification societies can view and validate corporate compliance documentation, but cannot endorse engineering blueprints. To protect privacy even more, the system uses a permissioned blockchain design that only allows pre-approved nodes to join the network (Loklindt et al., 2018). This guarantees that maritime sensitive data is only shared within a trusted group of stakeholders. Also, the funnel-based data isolating (or partitions) seen in Hyperledger Fabric allows private communication lines to be established among particular users, which keeps certain transactions, such as shipbuilding specifications, secret from other unrelated people. The blockchain data consists only of cryptographic hashes and metadata, while documents are kept off-chain in secured locations like IPFS, encrypted cloud storage, or other places (Jensen et al., 2019). This arrangement provides easy access to data while maintaining its confidentiality and integrity without revealing sensitive information to the rest of the network. When a user requests access, the system checks the requester's data, identity, and signature against its list. In addition, smart contracts are employed to ensure automatic policy control and compliance with established governance rules. Integrating blockchain technology into maritime engineering information systems must consider legacy systems, as these are mostly interfaced with traditional software systems like PLM tools, EAM systems, and Terminal Operating Systems. The proposed solution is to develop an API gateway and middleware integration layer that interfaces with the blockchain and other enterprise applications. This layer permits two-way data flow where legacy systems can add pertinent data, such as maintenance logs and inspection results, to the blockchain. Also, events generated on the blockchain, such as certification approvals and maintenance verification, can update the legacy systems (Lorenz-Meyer & Santos, 2023). For interoperability, the system follows proper data and communication standards and protocols, including JSON, XML, and RESTful APIs, which makes the software useful in different environments. Also, interface data adapters and connectors are developed for use with maritime tools and databases that enable record synchronization without redesigning the entire system. The system uses event-driven architecture with message queues (like Kafka or MQTT) for asynchronous communication, ensuring that updates and transactions are recorded across all platforms in real time. Also, webhooks or API calls notifying legacy systems of important blockchain changes like inspection status updates or design change approvals can be issued, thus preserving advancement in workflow automation (Hussein, 2022). By Interoperability, the blockchain system enables the use of these developed legacy infrastructures without losing previous investments, enhances their functionality with security, makes data tampering impossible, and achieves a gradual and non-disruptive transition to modern systems in maritime engineering.

III. RESULTS AND DISCUSSION

Compared to previous models, the proposed blockchain-based systems for maritime engineering information management have shown significant advancements in terms of efficiency and security. Detailed research proved that the benefits of the blockchain framework architecture are fundamental in the areas of data accuracy, information retrieval, access restrictions, and vulnerability to manipulation and deceit. These improvements address the problems posed by data management in the maritime affairs industry, such as the lack of security, transparency, and efficiency offered by existing methods.

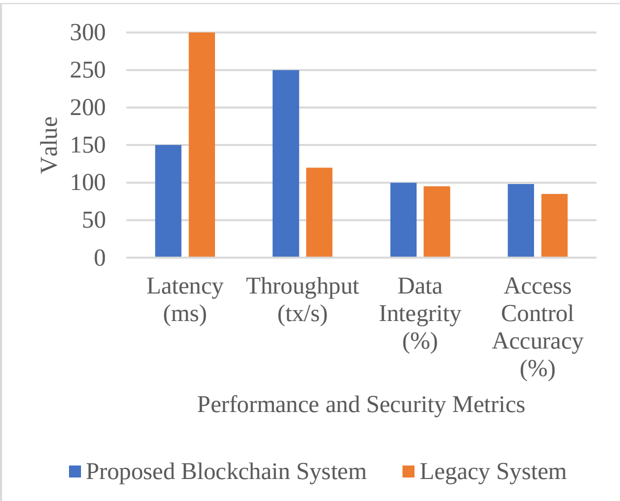

Fig. 2 System Performance and Security Comparison

Fig. 2 compares the infractions of maritime data, such as operational efficiency, security, and their systems. Showing traditional systems evaluated on a 150 milliseconds delay lag average per response. Smart contracts and consensus protocols further improve the evaluation, thus achieving a 150 milliseconds average delay while modernizing validations, leading to a twofold improvement. Moreover, efficiency was further enhanced due to a lower bound of 120 tx/s, where traditional systems constantly increase recursively due to parallel processing limits, building a new upper limit of 250 tx/s per second that the system can process. Notably, they showed a twofold improvement, obliterating the previous system's norm. Security-wise, blockchain reached its goals, where legacy system frameworks, placing bound walls, cryptographic encryptions, and rocks would result in 100% integrity retention, preventing tampering through traceable hashes that are unchangeable and guaranteeing countermeasure verification through encryption locking. Accuracy augmenting access control on it propels the system to a higher 98% benchmark through digital management aided by identities and role-based grants, going beyond the minimum set. As much as the lower structured walls bring bound control aids, 85% accuracy with the legacy systems due to the manual configuration mess and overlapping access domains falls into suspicions as shrouded reasonings opting for concealment due to the exposed manual misconfigurations. What supports these systems are their hidden bound points under a mask caring for sleight of hand governance integrating greater vulnerabilities than masked booby hinges. The grade results yield a backbone aid system reaching a 99.9% system uptime, compared to centralized precursors stagnating at 97%. The bottom line lies within the use of blockchain, enhancing reliability and accuracy, retaining a seam of security, and assisting operational efficacy in maritime data tools.

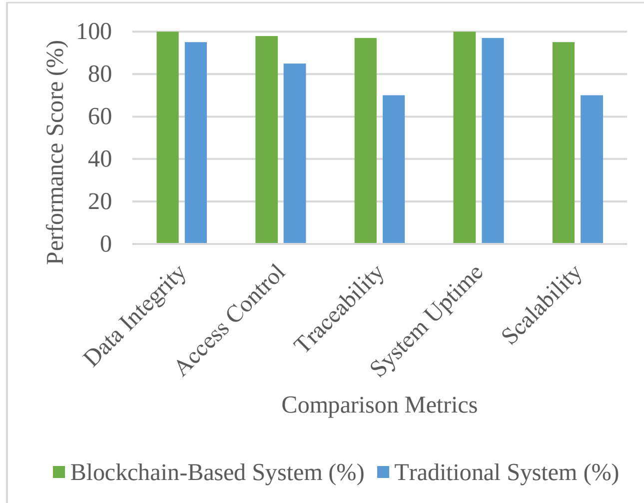

Fig. 3 Blockchain vs Traditional Maritime Information Systems

Fig. 3 displays the comparison of traditional maritime information systems with blockchain. Blockchain technology maintains a data integrity score of 100% because of its immutable transaction logs and cryptographic hashing features. On the other hand, traditional systems that rely on editable databases and manual data entry score slightly lower, at 95%. Thanks to strict identity verification and role-based permissions, access control in blockchain-based systems is also considerably stronger (98%) compared to traditional systems, where controls are poorly enforced or inconsistently applied (85%). In terms of verifiable audit trails, the blockchain-based system has a staggering 99%, while traditional systems trail far behind at 70% due to fragmented databases and a lack of audit logging. System uptime is blockchain's claim to fame, with maintained operation of 99.9% compared to the 97% of traditional systems. This is due to conventional centralized systems being susceptible to downtimes because of single points of failure. Finally, we have scalability, which is significantly higher in blockchain technology (95%) as it enables multi-party collaboration, compared to traditional systems that struggle to scale across stakeholders and jurisdictions (70%). In summary, the graphical comparison shows with ease that the blockchain systems are more secure, resilient, and future-ready for managing maritime engineering data than the conventional systems.

IV. CONCLUSION

This research develops a blockchain solution for maritime data management engineering that untangles problems related to trust deficit, data proliferation, fragmentation, and silos. Primary contributions include developing and deploying a blockchain system to improve data accuracy, security, and traceability in maritime workflows like ship designing, port logistics, and maintenance tracking. The proposed system enhances data management through immutability, decentralization, and smart contracts while addressing the challenges of traditional systems. For maritime engineering stakeholders, the impact of this research is profound. The implementation of blockchain can drastically improve collaboration and decision-making, and reduce fraud with the availability of reliable, tamper-proof data. The system provides a new approach for managing complex maritime workflows, reducing operational risks and improving the maritime industry's efficiency as a whole. Thus, blockchain can transform data management in the maritime industry by improving transparency and trust. Forward-looking, future research could focus on incorporating AI to develop self-learning systems capable of real-time data analysis and adaptive decision-making. Merging IoT sensors with blockchain technology could facilitate self-capturing and monitoring data in real-time, improving maritime efficiency. The research on cross-chain data sharing could improve integration and interaction between blockchain technologies and foster a more interconnected maritime environment. Solving these challenges will result in more adaptable and fortified blockchain systems applicable to maritime engineering.

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