

Article

Enhancing Facility Management with Emerging Technologies: A Study on the Application of Blockchain and NFTs

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Abstract: In recent years, Facility Management has undergone significant technological and methodological advancements, primarily driven by Building Information Modelling (BIM), Computer-Aided Facility Management (CAFM), and Computerized Maintenance Management Systems (CMMS). These innovations have improved process efficiency and risk management. However, challenges remain in asset management, maintenance, traceability, and transparency. This study investigates the potential of blockchain technology and non-fungible tokens (NFTs) to address these challenges. By referencing international (ISO, BOMA) and European (EN) standards, the research develops an asset management process model incorporating blockchain and NFTs. The methodology includes evaluating the technical and practical aspects of this model and strategies for metadata utilization. The model ensures an immutable record of transactions and maintenance activities, reducing errors and fraud. Smart contracts automate sub-phases like progress validation and milestone-based payments, increasing operational efficiency. The study's practical implications are significant, offering advanced solutions for transparent, efficient, and secure Facility Management. It lays the groundwork for future research, emphasizing practical implementations and real-world case studies. Additionally, integrating blockchain with emerging technologies like artificial intelligence and machine learning could further enhance Facility Management processes.

Keywords: non-fungible tokens; smart contracts; blockchain technology; facility management; BIM



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1. Introduction

Facility Management (FM), as defined by ISO 41011:2018, is an “organizational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business” [1].

This definition underscores the multifaceted role of FM in enhancing the lifecycle of a building, primarily by improving the user experience and secondarily by promoting environmental, social, and economic sustainability. The economic significance of the FM sector is evidenced by substantial investments that have driven technological advancements, resulting in sophisticated Computerized Maintenance Management Systems (CMMS), Computer-Aided Facility Management (CAFM) systems, and Integrated Workplace Management Systems (IWMS) [2,3]. These solutions incorporate cloud-based maintenance,

resource management, and data analytics capabilities, reflecting the sector's commitment to leveraging technology for enhanced operational efficiency.

However, these systems can face challenges such as data inaccuracy, lack of interoperability, inaccessible data and high management costs [4,5]. To address these challenges, Building Information Modelling (BIM) has been increasingly integrated into FM [6], coupled with Internet of Things (IoT) sensors and Building Automation Systems (BAS) to develop digital twins (DTs) [7]. This integration is ongoing and presents significant challenges, such as the need for new best practices, contractual paradigms, skills and updated responsibilities. The use of smart devices and sensors for careful monitoring has led to the accumulation of huge amounts of raw data (Big Data), which are difficult to align, annotate and process manually using traditional methods [8].

The Centre for Digital Built Britain emphasized the need for information security, quality, and openness in digital developments for construction in its document entitled "The Gemini Principles" [9]. This document addresses digital development in the construction industry, defining the basic principles to guide the development of the National Digital Twin (NDT) and the related Information Management Framework (IMF). It is therefore necessary to identify the tools in the field of information technology that are able to meet these needs and Blockchain technology promises to be a viable solution, offering significant potential when integrated with DT, IoT and BIM to address issues of trust, transparency and communication throughout the lifecycle of a building [10]. It provides a tamper-proof infrastructure for value and information exchange, ensuring data immutability and uniqueness. This fosters innovation and transparency in managing the lifecycle of manufactured goods, especially in sectors prone to controversy and corruption [11].

Blockchain relies on distributed ledger technology (DLT) to record transaction data securely and immutably using cryptographic techniques [12]. Transactions on the blockchain, including digital document transfers, smart contracts and process stage records, are grouped into blocks, verified by network participants and added to the ledger through consensus mechanisms [13]. Once validated, a block is permanently recorded, creating an unbroken, immutable chain. The validation of a block of information is a crucial aspect of the system, and this can be achieved through various mechanisms (e.g., Proof of Work, Proof of Stake, Proof of Authority). These mechanisms generally rely on a decentralized validation system that is implemented through a network of independent computers (nodes) working together to verify and approve transactions. This ensures the security and reliability of the network [14]. With regard to the transparency of transactions and the accessibility of the data contained in the blocks, blockchain technology facilitates the determination of precisely which data is to be made public to network participants and the registration of only non-sensitive data contained in transactions on the chain, thereby ensuring privacy and confidentiality [15].

In many industries, blockchain applications have attracted research interest such as healthcare [16], energy systems [17], agriculture [18], education [19], supply chain [20], food traceability [21] and also the construction industry [22], where it has the potential to cover all phases of the building life cycle, but has so far had a dominant focus on the construction phase [23]. Different blockchain infrastructures can be developed to meet specific process and environmental needs.

The integration of blockchain technology in building facilities management can enhance the efficiency, transparency, and security of operations [24]. It enables the creation of immutable records for maintenance activities, asset management, and service contracts, ensuring data integrity and reducing the risk of fraud. Smart contracts can automate and enforce agreements between parties, streamlining processes such as lease management, vendor payments, and compliance tracking [25]. Additionally, blockchain can facilitate

real-time tracking of building performance data, improving decision making and predictive maintenance. Overall, blockchain provides a reliable and decentralized platform for managing the complex and dynamic aspects of facility management.

One of the key areas of blockchain technology is that it is characterized by smart contracts. In 1994 Szabo proposed, for the first time, the term “smart contract” as “a computerized transaction protocol that executes the terms of a contract” [26]. But they have been implemented in the Ethereum blockchain only in 2014 with the definition of “systems which automatically move digital assets according to arbitrary prespecified rules” [27]. In this context smart contracts can be seen as autonomous, self-executing protocols that facilitate and enforce contract terms [28]. In FM, smart contracts can be integrated with a digital twin solution in order to automate service contracts with external providers, ensuring payments are only made when specific performance targets are met, reducing disputes and payment delays [29]. Smart contracts also manage process information, facilitating data exchange and verification during operations and maintenance phases, and their decentralized nature minimizes the risk of fraud and manipulation. Moreover, it is precisely through the utilization of Smart Contracts that the integration with IoT systems can be managed in order to automate specific process steps, such as monitoring and control [30], and address problems like interoperability, inefficiency, intractability and democratization in different sector, such as smart cities [31].

A further extension of the potential of smart contracts is the possibility of creating non-fungible tokens (NFTs), defined as a “cryptographic asset on a blockchain containing unique identifying information and codes that separate them from one other” [32]. NFTs are gaining in popularity and are already extensively implemented not only in research but also in real case applications [33]. They are unique cryptographic tokens that certify the ownership and authenticity of assets on the blockchain, showing potential use cases in different sectors [34]. From previous research NFTs have mainly two important research implications: first, at an institutional and economic level, such as NFTs for decentralization and commons management, and second, at an individual level with marketing and consumer psychology perspectives, NFTs for consumer behavior in relation to digital property [35]. However, one of the main features of NFTs is the ability of certify and manage different digital assets, also building ownership [36], assigning management responsibility to specific individuals during process stages [37]. NFTs linked to digital or physical assets can be programmed with smart contracts, enabling limitless functionality [38].

Focusing on blockchain-based data management and sharing infrastructures in Facility Management (FM) processes, this paper explores the state of the art of blockchain technology, its main features and types, and its integration into the FM domain through a comprehensive review of international research applications. From this analysis, the primary research question addressed is as follows: How can the integration of blockchain technology and programmable Non-Fungible Tokens (NFTs) enhance transparency, traceability, and efficiency in the management of cleaning services within Facility Management, and what are the new possible processes and solutions associated with their implementation? Following an evaluation of current practices, a traditional process model for FM services, specifically cleaning services, is outlined. Subsequently, an innovative solution integrating blockchain technology into this model is presented, with a particular emphasis on the use of NFTs and smart contracts for information and contract management. The paper concludes with a critical analysis of the proposed solution, identifying implementation challenges and potential future developments to further optimize blockchain integration in FM and maximize the benefits of these advanced technologies.

2. Literature Review

2.1. Blockchain Background

The term “blockchain” refers to an innovative technology that has permeated various sectors since its inception in 2008 [39], initially revolutionizing the financial sector with the advent of Bitcoin, and now extending its influence to other industries such as construction. Blockchain is a type of distributed database, known as Distributed Ledger Technology (DLT), which consists of interconnected blocks of data that store information and transactions occurring within the network. The primary characteristic of this technology is the decentralization of data, facilitated by a peer-to-peer system that replaces the traditional client–server model of storing data in a single central database. In this decentralized framework, each participant (or node) in the network operates at the same hierarchical level as other actors, maintaining its own copy of the data held by other nodes. Blockchain aims to overcome the use of an intermediary in electronic transactions by using asymmetric cryptography. This method involves the use of public and private key digital signature techniques and hashing. Each transaction is then signed by the sender’s private key and sent to the receiver’s public key; in order to carry out the transaction, the sender must be able to prove that he is in possession of the personal private key. The system sorts all these transactions by putting them into groups called blocks, and then links these blocks together through what is called a blockchain. The transactions in a block are considered to have taken place at the same time. These blocks are linked together (like a chain) in a proper linear chronological order, with each block containing the hash of the previous block. This chain is called the ledger, and within it, all the blocks relating to the operations carried out in the network are created and stored. The individual block consists of two main parts: the block header and the block body [40]. The block header includes several components: the block version, which specifies the set of block validation rules to be followed; the Merkle root hash, which is the hash value of all transactions in the block; the timestamp, which records the current time in seconds in Universal Time since 1 January 1970; the nBits, which is the target threshold of a valid block hash; the nonce, which is a 4-byte field usually starting at 0 and increasing for each hash calculation; and the parent block hash, which is a 256-bit hash value pointing to the previous block. The block body consists of a transaction counter and the transactions themselves. The maximum number of transactions a block can contain depends on the size of the block and the size of each transaction. The main characteristics of the blockchain are decentralization, consensus, and security [14].

Decentralization, as already mentioned, no longer relies on a central server that acts as an intermediary and is responsible for monitoring the flow of information between different users [41]. Instead, transactions are carried out and verified by the nodes within the network themselves. This peer-to-peer network typically incorporates a decentralized consensus mechanism that distributes the computational load across multiple nodes in the network, makes it easier for nodes to establish and maintain connections, and ensures that each node in the network receives and transmits data [42].

Consensus is another critical feature, as the agreement of multiple nodes is required to record a transaction. Consensus mechanisms significantly impact the scalability and efficiency of blockchain networks. Different algorithms, such as Proof of Work (PoW) and Proof of Stake (PoS), influence energy usage, throughput, and the ability to handle adversarial conditions. By optimizing how nodes participate based on work, stake, or reputation, developers can enhance performance, leading to improved scalability and energy efficiency [43]. Before any transaction is recorded, a consensus method is agreed upon to create new blocks and hash chains. The nodes responsible for validating transactions are called generally miners, and their role is to prevent irregularities or tampering that may occur within the network. The method used to agree on a new transaction can be chosen from

several options, the most common of which is Proof of Work (PoW). Rather than randomly selecting a node for consensus approval, which could lead to network manipulation, PoW is based on solving a mathematical problem that leverages the computing power of the nodes' hardware. The group of nodes with the most computing power decides whether or not to approve the transaction. Each node in the network calculates a hash of the block header. The block header contains a nonce, and miners frequently change the nonce to obtain different hash values [40]. The consensus is that the calculated value must be equal to or less than a certain value. When a node reaches the target value, it sends the block to other nodes, and all other nodes must mutually confirm the correctness of the hash value. If the block is validated, other miners would add this new block to their blockchain. By working on multiple nodes simultaneously, it is likely that more than one miner will be able to find the correct value, thus forming multiple branches of the same chain. However, this cannot be repeated for multiple blocks, so one longer branch will eventually be identified as the authentic one. This is the method used in the Bitcoin network, where it is called mining [44]. It is a very complex method that requires a huge amount of energy. Another consensus method is Proof of Stake (PoS) [45]. Unlike PoW, which relies on computational power, PoS selects validators based on the number of tokens they hold and are willing to "stake" as collateral. In PoS, the probability of being chosen to validate a new block and earn rewards is proportional to the amount of cryptocurrency the validator holds. This method significantly reduces the energy consumption associated with block validation, as it does not require extensive computational resources. Validators are incentivized to act honestly because they risk losing their staked tokens if they attempt to validate fraudulent transactions. PoS is considered more environmentally friendly and scalable compared to PoW, making it an attractive alternative for many blockchain networks.

Security is another fundamental attribute of blockchain technology [14]. The immutability of the blockchain ensures that once data is recorded, it cannot be deleted or modified without the consensus of the majority of network participants. This feature protects the data from tampering and unauthorized alterations, making blockchain a robust solution for secure data management. It is possible to have different levels of security since each participant is essentially a stakeholder and no single participant has full administrative privileges. Every operation, be it an update or an audit, requires the consent of the peers, ensuring that no single entity can unilaterally alter the data.

In addition to these core features, blockchain technology offers several other advantages. For instance, it enhances traceability by providing a clear and unalterable record of transactions, which is particularly valuable in supply chain management and asset tracking [20]. Blockchain also supports the implementation of smart contracts—self-executing contracts with the terms of the agreement directly written into code [46]. These smart contracts automate and enforce contractual agreements, reducing the need for intermediaries and minimizing the risk of disputes [47]. Moreover, blockchain's decentralized nature reduces the risk of single points of failure, as the data is distributed across multiple nodes. This resilience makes blockchain systems more robust against cyber-attacks and system failures. The technology also promotes data integrity and auditability, as the historical record of transactions is preserved and can be audited at any time.

As a result of the different applications and their needs, there is a main classification of the different types of blockchain in use: public or permissionless blockchains, private blockchains, and consortium blockchains [48]. Public or permissionless blockchains allow any participant to reach consensus via the PoW method and usually use a native cryptocurrency or none to validate transactions, all of which are publicly visible. Having a large number of participants makes it difficult to tamper with the chain, but on the other hand, it takes a long time to perform the necessary transactions, sometimes with latency issues.

Private blockchains, where the actors who can contribute to the creation of consents, as well as those who have permissions to create smart contracts, are limited. It can be considered a centralized network, as it is fully controlled by one organization. Unlike its predecessor, transactions are not visible to anyone, but with fewer nodes, they could be more easily manipulated. Consortium blockchains, consisting of several organizations, are partially decentralized as only a small proportion of nodes are selected to determine consensus.

In summary, blockchain technology represents a transformative approach to data management and transaction processing, characterized by decentralization, consensus, transparency, and security. Its potential applications across different sectors, including construction, highlight its versatility and promise for driving innovation and efficiency in various domains. In particular, the disaggregated structure of the construction industry makes it well suited for the use of blockchain, but the same structure poses challenges for the implementation of innovation and new technologies, especially when large-scale changes are required. This administrative gap hinders the implementation of blockchain technology, despite ongoing digitization efforts through computer-aided design and BIM, highlighting a significant gap between the envisaged framework and the current state of digitization in the industry [49]. In any case, early research has already explored the use of such technology for various applications, including contract management [50], claims management [51], supply chain management [52], stakeholder collaboration [53] and Common Data Environment (CDE) management [54]. By leveraging blockchain, the construction industry can achieve greater efficiency, transparency, and security in its operations, ultimately leading to improved project outcomes and stakeholder satisfaction.

2.2. Integration with FM Processes and Digital Twin Concepts

Facility Management (FM) has emerged as a transformative profession that significantly enhances the value of the built environment. Despite progress, the FM industry remains in its early stages of development, largely due to the slow adoption of digitalization in the construction industry. While the FM procurement process has improved over time, the road toward optimization and full automation in decision making is still in progress, and it remains complex, inefficient and fraught with challenges, mainly due to a lack of digital innovation [55]. In this context, blockchain technology has emerged as a disruptive digital solution under the 'Procurement 4.0' paradigm, and research in this area has demonstrated that the effective use of blockchain technology in the FM procurement process can address existing inefficiencies and encourage greater innovation in the industry [56]. The present study aims to identify integration solutions between Facility Management and Blockchain Technology that have already been experimented with, and to understand their implementation characteristics, the challenges encountered, and the progress made in this direction. Research documentation was sourced from databases such as Scopus, Web of Science and Research Gate using the following keywords: Facility Management, Digital Twin, IoT, Blockchain Technology, Smart Contracts and NFTs. The scientific literature on technologies for Facility Management generally aligns with solutions addressing various facets of sustainability: environmental, social, economic, managerial, and operational. Indeed, facility management integrates aspects concerning people, workplaces, and resources; consequently, sustainability concerns in facility management have received increasing academic attention.

Okoro [57] conducted an exploratory study on this theme, utilizing scientometrics and content analysis based on extant literature from 2012 to 2022 published in the Scopus database. The results showed that current research paths focus on four clusters, including planning and implementation, community-oriented smart facility management, innovation, and corporate environmental and energy management. The prevailing themes within

the field are Building Information Modeling and Digital Twin, whilst Blockchain Technology, Smart Contracts, and non-fungible tokens remain less explored in the FM context. Sadri et al. [8] have highlighted the emergence of research in this field, as well as the need for further practical implementations to discover and demonstrate the true potential of these technologies and their fusion. By developing a comprehensive framework model, Götz et al. [58] provide valuable insights into the role of blockchain-based digital twins in integrating asset life cycle management practices with emerging technologies such as IoT and smart contracts, and demonstrate the potential benefits of adopting a holistic approach to technological innovation in this area. The study by Hasan et al. [59] presents a framework for creating Digital Twins (DTs) using Ethereum blockchain technology, focusing on ensuring data security, traceability, and accessibility. The solution employs Smart Contracts to manage transactions related to DT creation and integrates with the InterPlanetary File System (IPFS) for data storage and sharing. Key components of the framework include stakeholders, software services for participant interaction, an IPFS database for off-chain data, on-chain resources for traceability, and Smart Contracts for managing the creation process. The DT creation involves specific stages controlled by Smart Contracts, which record initiation and approval events on-chain while keeping intermediate changes off-chain to reduce costs. The choice of blockchain type is crucial, as it affects privacy and data security; while the study uses Ethereum, the framework can be adapted to other blockchains with different characteristics.

Rane & Narvel [60] discuss the integration of blockchain and Internet of Things (IoT) technologies to enhance organizational agility in Industry 4.0. They present a case study on the implementation of an IoT system for monitoring and optimizing the operation of industrial oil pumps and its subsequent development through blockchain integration. The research group systematically developed the IoT solution, later highlighting the advantages of blockchain integration for the specific case study. The advantages of blockchain integration for this specific case study revolve around the concept of a 'trustless system,' which ensures proper operation by all process actors through the use of Smart Contracts and immutable data recorded on the blockchain. For IoT systems, which require lightweight, scalable, distributed solutions with a focus on privacy and security, blockchain has the potential to be a significant game-changer. The integration of blockchain into IoT systems has the potential to enhance security and privacy by providing a reliable and traceable sharing service. The combination of these two technologies holds great promise, as blockchain can provide resilience to cyber-attacks and enable reliable, auditable, and trustless interactions with peers, with high process agility. But IoT and blockchain alone are insufficient without BIM for digitalizing project data. Integrating all three technologies optimizes access and organization of digital building information. The "Cup-of-Water" theory illustrates their relationship: BIM as the "cup base" (foundation), IoT as "water" (real-world data), and blockchain as the "cup wall" (secure, transparent environment) [61]. The continuous integration of these technologies is poised to trigger substantial transformations across multiple industries, giving rise to novel business models.

Hellenborn et al. [62] conducted a thorough analysis of Asset Information Requirements (AIRs) essential for developing and maintaining an Asset Information Model (AIM) in the context of blockchain-based digital twins. Their study focuses on data-driven predictive analysis and identifies three main data categories that support this analysis, highlighting their characteristics and influence on AIM development and maintenance. The authors emphasize the importance of an ontology-based data structure and high reliability for creating an AIM that can effectively represent a virtual replica in a blockchain-based digital twin. This structure enables the conversion of data into a knowledge graph, enhancing the digital twin's understanding of asset relationships and facilitating predictive

analyses through AI. Tavakoli et al. [63] discuss the creation of a data provenance model within a blockchain-based digital twin (DT) system aimed at ensuring the reliability and trustworthiness of data used in Predictive Asset Management. While acknowledging the potential of blockchain technology (BCT) to improve data reliability and transparency, they also highlight challenges related to tracing the origin and history of data. In their case study, they developed a Smart Contract with functions for storing and visualizing results, retrieving asset status for informed decision making, and sending alert notifications for predictive maintenance. The study emphasizes the management of large data volumes and suggests a hybrid approach that combines off-chain and on-chain databases to enhance the efficiency of data storage, retrieval, and processing, thereby addressing the challenges of increasing data loads. Li et al. [64] propose a forward-thinking framework utilizing Distributed Ledger Technology (DLT) and smart contracts to enhance traceability and create a digital record platform for semi-automated maintenance and repairs of built assets. The framework includes a National Product Database (NDP) for building component data, a Construction Certification Organization (CCO) for verifying individual competencies, and an e-Marketplace for e-procurement to improve competitiveness and transparency. Central to the framework is a Decentralized Autonomous Organization (DAO) that automates maintenance and repair activities, ensuring data transfer to the blockchain and linking relevant information to the digital record, thus increasing traceability. Putz et al. [65] present EtherTwin, a prototypical implementation of a Decentralized Application (DApp), where a formal access control model, coupled with encrypted off-chain data storage, addresses integrity and confidentiality aspects based on Digital Twin components and lifecycle requirements.

Izumi and Toyoda [66] present the NFT-ization of BIM data through the definition of the IFC Catalog, a JSON-format metadata that structurally expresses the uses of IFC files and the properties required, offering a solution by enabling the publication and distribution of Industry Foundation Classes (IFC) file information within a blockchain-based ecosystem, providing incentives for data creators. The authors developed a minimum viable product for an application that displays NFT information in the IFC Catalog, confirming that the information can be displayed in a structured manner with simple controls. Teisserenc & Sepasgozar [67] addressed key challenges and literature gaps in the construction industry (CI) related to Blockchain-based Digital Twins (BCDTs) by proposing a comprehensive software architecture and smart contract framework. It identifies critical functional and non-functional requirements for BCDT applications, addressing issues such as design data notarization, process automation, supply chain traceability, financial automation, asset management, environmental data management, risk mitigation, and regulatory compliance. The study develops seven industry use cases, refines smart contract designs using NFTs, and conducts a cost analysis of various EVM-compatible public blockchains. The findings highlight that secure and decentralized networks such as Avalanche and Arbitrum are suitable for sensitive projects, while cost-efficient networks like Polygon and Fantom are better suited for smaller projects, ultimately enabling distributed collaboration in CI 4.0 through resilient blockchain networks and smart contract automation.

The research gaps that motivated this study stem from the slow adoption of digitalization within the Facility Management industry, which remains in its early stages despite the transformative potential of technologies like blockchain, Digital Twins, and the Internet of Things (IoT). While existing literature highlights the benefits of these technologies in enhancing data reliability, transparency, and operational efficiency, there is a notable lack of practical implementations and integration solutions that address the complexities and inefficiencies in FM procurement processes. Additionally, current research predominantly focuses on theoretical explorations of blockchain's advantages rather than

its adoption mechanisms, leaving a gap in understanding the factors influencing construction professionals' willingness to embrace these innovations. Furthermore, the integration of blockchain with FM processes and the development of comprehensive frameworks that encompass asset life cycle management and sustainability concerns remain under-explored. Wang et al. [68] have identified factors affecting blockchain adoption in construction, examining technical, organizational, and environmental aspects. They extended the classical Technology Acceptance Model (TAM) framework and found that external factors significantly influence construction professionals' perceptions of blockchain and their willingness to adopt it. Key factors affecting adoption include perceived usefulness and ease of use, with usefulness having a stronger impact. Competitive pressure and technology maturity also enhance perceptions of blockchain's usefulness and ease of use. Contrary to expectations, organizational readiness negatively impacts perceived usefulness. Wang et al. [69] present a causal loop diagram to illustrate the dynamic interactions influencing blockchain technology growth in the AEC industry, highlighting factors such as organizational readiness, top management support, and adoption costs. They emphasize the need for dynamic analysis over static methods and propose a theoretical framework using system dynamics (SD) to model and forecast blockchain trends. The research utilizes the Technology–Organization–Environment (TOE) and TAM frameworks to build a theoretical model for SD research, testing the system simulation model for validity, stability, and sensitivity. Findings indicate that technological, organizational, and environmental factors significantly impact blockchain development, with varying effects at different stages. The study concludes that blockchain technology shows strong potential for the construction industry, following an S-shaped growth trend, and suggests early-stage policies tailored to the industry. Limitations include the exclusion of stakeholders' subjective factors and the impact of disruptive technologies.

This study aims to bridge these gaps by identifying and analyzing existing integration solutions, implementation challenges, and the progress made in leveraging blockchain technology within the FM context, ultimately contributing to a more robust understanding of its practical applications and potential for driving innovation in the industry.

3. Methodology

This section delineates the methodology employed in the development of the blockchain-based process model, with a particular focus on cleaning services for Facility Management (Figure 1). The following fundamental steps are outlined:

- Identification of a traditional process model structure: This preliminary stage is preparatory for the subsequent integration with Blockchain Technology. The aim of this phase is to highlight the characteristics of the traditional process model and to identify the following components.
- Identification of process-related issues: This phase identifies weaknesses and potential inefficiencies in the traditional process. Specifically, potential critical issues in the following areas are addressed.
- Identification of blockchain-based solutions: This phase involves the exploration of blockchain-based solutions that can be integrated into the process model.
- Development of the blockchain-based process model: This phase proposes a blockchain-based process model. It highlights the necessary technological infrastructure and specifies how to use the identified solutions.
- Conclusions and discussion on the proposed solution: This phase discusses the potential benefits, critical issues related to the proposed process model, and future developments.

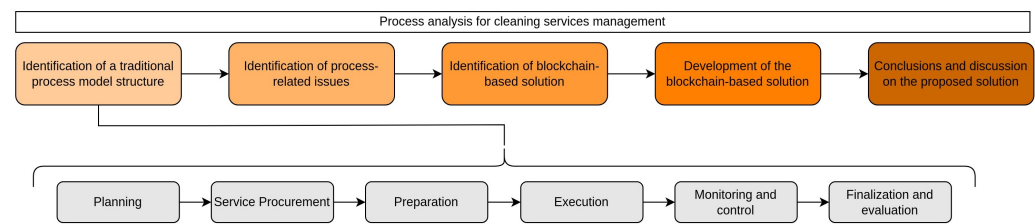


Figure 1. Workflow used to develop the blockchain-based process model for cleaning services.

3.1. Identification of the Traditional Process Model

As illustrated in Table 1, a process model for the management of cleaning services is delineated, comprising six primary phases: Planning, Service Procurement, Preparation, Execution, Monitoring and Control, and Finalization and Evaluation. Each phase is further delineated into specific sub-phases, with the involvement of various key stakeholders.

Table 1. Process model for cleaning services.

Phase A—Planning	Stakeholders
A.1—Requirement analysis	Facility Manager, Client
A.2—Definition of cleaning specifications	Facility Manager, Client
A.3—Activity scheduling	Facility Manager, Client
Phase B—Service Procurement	Stakeholders
B.1—Research and selection	Facility Manager, Client, Service companies
B.2—Offer evaluation	Facility Manager, Client, Service companies
B.3—Contract stipulation	Facility Manager, Client, Selected company
Phase C—Preparation	Stakeholders
C.1—Procurement of materials and equipment	Cleaning supervisor
C.2—Personnel training	Cleaning supervisor, Staff
C.3—Team organization	Cleaning supervisor
Phase D—Execution	Stakeholders
D.1—Routine cleaning	Cleaning staff
D.2—Extraordinary cleaning	Cleaning staff
D.3—Extra services	Cleaning staff
Phase E—Monitoring and Control	Stakeholders
E.1—Periodic inspections	Cleaning supervisor
E.2—Feedback and reports	Facility Manager, Cleaning supervisor
E.3—Compliance verifications	Facility Manager, Cleaning supervisor
Phase F—Finalization and Evaluation	Stakeholders
F.1—Data collection, reporting, and evaluation	Facility Manager, Client
F.2—Client feedback	Facility Manager, Client, Company administration
F.3—Payment management	Facility Manager, Client, Company administration

3.2. Identification of Process-Related Issue

An analysis of the conventional process of managing cleaning services reveals numerous potential issues and inefficiencies that can be effectively addressed through the implementation of advanced technological solutions. Disorganization and a lack of standardization have the potential to emerge as significant problems, especially in the preparation and execution phases of cleaning activities. The coordination of personnel, the procurement of materials, the training of staff, and the organization of teams often result in the overlap or omission of activities, which can compromise service efficiency. The management of personnel, in addition to the coordination of routine, extraordinary, and extra cleaning

activities, is further complicated by the difficulty of monitoring staff productivity and presence. Planning cleaning activities is often inefficient due to inadequate tools, an inability to adapt planning to unforeseen changes, and a lack of centralized visibility. The definition of times, necessary resources, and priorities is often problematic, resulting in inefficiencies and resource wastage. The quality control and service verification processes, which are traditionally dependent on manual checks, are susceptible to errors and lack of objectivity. The situation is further exacerbated by insufficient control frequency and the absence of a structured feedback system. Information flow between different process participants represents another potential critical aspect. In the planning, procurement of services, finalization and evaluation phases, communication issues can cause delays and misalignments, while a lack of transparency and reliance on verbal or written communications can increase the risk of errors. In addressing the initial two phases of the conventional process model, a digital metaproject for restructuring information exchange and contract management is proposed, utilizing innovative technological solutions.

3.3. Blockchain-Based Solutions for FM

The integration of facility management processes with blockchain technology necessitates the delineation of technical and technological solutions, as well as the establishment of information technology infrastructures. To achieve this, it is necessary to identify the network's needs:

- **Data security and privacy:** Ensure that only authorized parties have access to sensitive information. Consequently, the utilization of permissioned blockchain solutions is recommended. Furthermore, it is imperative to implement robust identity management and authentication mechanisms for users accessing the network. Lastly, unauthorized data alteration must be impossible.
- **Moderate decentralization:** In this context, the decentralisation of the network can be utilized for the storage of data, thereby ensuring the maintenance of a centralized control system for access and authorizations. With regard to the network's consensus mechanism, solutions that strike a balance between security and efficiency are required. Furthermore, the selection of consensus mechanisms with limited complexity facilitates low transaction latency, thereby enhancing the user experience.
- **Scalability and performance:** The network must handle a high number of transactions per second to support Facility Management's daily operations.
- **Interoperability and compatibility:** The blockchain solution is intended to be integrated with existing IT systems, including Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), and resource management systems. This will require the use of application programming interfaces (APIs) and interoperability standards.
- **Network governance and management:** Establish a comprehensive delineation of the roles and responsibilities of each network participant. Furthermore, the implementation of access and control policies is essential to regulate the addition, modification, and viewing of information on the blockchain.
- **Smart contracts:** The network must be capable of supporting the implementation of Smart Contracts, in order to facilitate the management of the various process sub-phases. Prior to implementation, it is imperative to verify and audit Smart Contracts to ensure process integrity.
- **Programmable NFTs:** The network must be capable of facilitating the transfer of programmable Non-Fungible Tokens through the utilization of Smart Contracts, thereby enabling the process of asset tokenization and on-chain management.

- Maintenance and updates: In order to maintain optimal levels of security and efficiency, the network must be subject to continuous monitoring and regular updates.

In order to assess the actual capability of existing blockchain solutions to meet these requirements, a study was conducted in which seven systems with different technologies were examined. The blockchain solutions analyzed are Hyperledger Fabric, Quorum, Corda, Multichain, Polygon CDK, Polkadot and Cosmos. Hyperledger Fabric [70] is a permissioned blockchain framework developed by the Linux Foundation as part of the Hyperledger project. Designed for enterprise use, it provides a modular architecture that enables plug-and-play components such as consensus and membership services. Among the key features of Hyperledger Fabric is its support for smart contracts, known as ‘chaincode’, written in popular programming languages such as Go, Java and Node.js. The framework emphasizes privacy and confidentiality through its channel architecture, which enables private transactions and data sharing between specific network members. In addition, Hyperledger Fabric supports a pluggable consensus mechanism, allowing organizations to choose the consensus protocol that best suits their needs. Quorum [71] is an enterprise-focused version of the Ethereum blockchain, developed by J.P. Morgan. It is designed to meet the specific needs of financial institutions and other businesses that require high-speed, high-throughput processing of private transactions [72]. Quorum’s key features include its permissioned network, which restricts access to authorized participants, and its support for private transactions, which ensures that transaction details are only visible to the parties involved. Quorum also incorporates a modified Istanbul Byzantine Fault Tolerance (IBFT) consensus mechanism, which improves transaction finality and network performance. In addition, Quorum maintains compatibility with the Ethereum ecosystem, allowing the use of existing Ethereum tools and smart contracts. Corda [73], developed by R3, is a distributed ledger technology (DLT) platform designed specifically for the financial services industry. Unlike traditional blockchains, Corda does not block transactions, but records them directly between parties, ensuring privacy and scalability. Corda’s key features include its unique consensus mechanism, where transactions are only validated by the parties involved, reducing computational overhead. The platform also supports smart contracts written in Kotlin and Java, allowing complex business logic to be executed on the ledger. Corda’s architecture is designed to interoperate with existing financial systems, making it a suitable choice for institutions looking to integrate DLT into their operations. Multichain [74] is an open source blockchain platform designed to facilitate the creation and deployment of private blockchains for enterprise use. It offers a high degree of customization, allowing organizations to configure various aspects of the blockchain, such as permissions, asset issuance and data streams. Key features of Multichain include its permissioned network model, which ensures that only authorized participants can join the network and access data. The platform also supports multi-asset issuance, enabling the creation and transfer of multiple types of digital assets on a single blockchain [75]. In addition, Multichain provides robust data management capabilities, including the ability to efficiently store and retrieve large amounts of data [76]. Polygon CDK (Custom Development Kit) [77] is a framework designed to facilitate the development of scalable and interoperable blockchain networks within the Polygon ecosystem. It leverages the Ethereum blockchain’s security while providing enhanced scalability through its Layer 2 solutions, such as Plasma, Optimistic Rollups, and zk-Rollups [78]. Key features of Polygon CDK include its modular architecture, which allows developers to customize and extend the framework to meet specific requirements [79]. The platform also supports cross-chain communication, enabling seamless interaction between different blockchain networks. Polygon CDK aims to provide a comprehensive solution for building decentralized applications (dApps) with high performance and low transaction costs [80].

Polkadot [81] is a multi-chain blockchain platform developed by the Web3 Foundation, designed to enable interoperability between different blockchains. Its architecture consists of a central relay chain that coordinates consensus and communication between multiple parallel blockchains, known as parachains. Polkadot's main features include its shared security model, where all connected parachains benefit from the security of the relay chain, and its ability to facilitate cross-chain transfers of any type of data or asset. The platform also supports on-chain governance, allowing stakeholders to participate in decision-making processes. Polkadot's scalability is achieved through its sharding mechanism, which distributes the processing load across multiple parachains [82]. Cosmos [83] is a decentralized network of independent, scalable, and interoperable blockchains, known as Zones, connected through the Cosmos Hub. Developed by the Interchain Foundation, Cosmos aims to create an "Internet of Blockchains" by enabling seamless communication and data transfer between different blockchains [84]. Key features of Cosmos include its Tendermint consensus algorithm, which provides fast finality and high throughput, and its Inter-Blockchain Communication (IBC) protocol [85], which facilitates interoperability between zones. The Cosmos SDK (Software Development Kit) allows developers to build custom blockchains with ease, leveraging modular components and a flexible architecture [86]. Cosmos focuses on scalability, usability, and interoperability, making it a robust solution for building interconnected blockchain networks. In summary, these blockchain solutions offer different features and capabilities tailored to different business and industry needs. Their unique architectures and consensus mechanisms provide varying levels of scalability, security and interoperability, making them suitable for a wide range of applications in the evolving blockchain landscape. Table 2 shows the rating assigned by the authors to each system; it is based on the existing technical documentation for these systems, and expressed on a scale from 1 (poor compatibility) to 5 (perfect compatibility).

The results of the analysis demonstrate that Polygon CDK is the most promising solution in the specific case when compared with the other solutions under consideration. This is attributable to several key factors. Firstly, Polygon CDK is designed to handle a high volume of transactions thanks to technologies like rollups and sidechains, which allow the workload to be distributed and maintain efficiency even in data-intensive scenarios typical of Facility Management and IoT systems. Additionally, Polygon CDK's native compatibility with the Ethereum ecosystem provides immediate access to a wide range of existing decentralized tools and applications. This reduces development costs and time, allowing for easier integration of functionalities related to the use of programmable NFTs. Another crucial aspect that distinguishes Polygon CDK is its robust interoperability with existing enterprise management systems, such as ERP and CRM. The platform supports standardized APIs and middleware, enabling seamless communication between the blockchain and legacy systems, facilitating a gradual transition, and minimizing disruptions to current operations. Polygon CDK also offers data management tools through frameworks compatible with the Ethereum ecosystem, allowing the creation of customized smart contracts that can interact directly with ERP and CRM modules. This facilitates not only the automation of transactions and contractual procedures but also the real-time synchronization of information between the blockchain and enterprise systems, enhancing data consistency and transparency. A notable benefit of this platform is its adaptability, which facilitates the customization of blockchain modules to suit specific identity management requirements and consensus mechanisms. Additionally, Polygon CDK's scalable and interoperable architecture is known to result in lower operational and maintenance costs when compared to alternative solutions. In terms of data management and privacy, the platform supports the implementation of a permissioned blockchain, thereby restricting access, viewing, and participation in the network to authorized users. Achieving a fully

private network is possible, and it is compatible with the Ethereum ecosystem, being able to leverage all its advanced functionalities. Depending on requirements, additional tools and measures for managing sensitive data can be utilized with Polygon CDK, such as multi-factor authentication, sensitive data hashing, permission management, and smart contracts programmed to limit the visibility of transaction-related data exclusively to the involved parties. The combination of these features renders Polygon CDK the most promising blockchain solution, among those considered, for the development of the research.

Table 2. Analysis of available blockchain solutions based on network's needs.

Requirements	Hyperledger Fabric	Quorum	Corda	Multichain	Polygon CDK	Polkadot	Cosmos
Data Security and Privacy							
Confidentiality	5	4	5	4	4	4	4
Integrity	5	5	5	4	4	5	5
Authenticity	5	4	5	4	4	4	4
Moderate Decentralization							
Distributed Storage	4	4	4	4	4	4	4
Consensus	4	4	4	3	4	4	4
Scalability and Performance							
Transaction Capacity	4	4	4	3	5	5	5
Latency	4	4	4	3	5	5	5
Interoperability							
System Integration	4	5	3	3	5	5	5
Compatibility	4	5	3	3	5	5	5
Network Governance and Management							
Roles and Responsibilities	5	4	4	4	5	5	5
Access Policies	5	4	4	4	5	5	5
Smart Contracts							
Process Automation	5	5	4	3	5	4	4
Verification and Audit	5	5	4	3	5	4	4
Programmable NFTs with Smart Contracts							
Programmable NFTs	3	4	2	2	5	4	4
Maintenance and Updates							
Continuous Monitoring	4	4	3	4	5	4	4
System Updates	4	4	3	4	5	4	4
Total	70/80	69/80	61/80	55/80	75/80	71/80	71/80

4. Blockchain Technology Applied to Cleaning Services

4.1. Overview of the IT Architecture

The IT infrastructure for blockchain-based processes represents a sophisticated and multifaceted ecosystem that integrates a diverse array of hardware, software, and security components (Table 3). This infrastructure is essential for facilitating secure, efficient, and scalable operations within decentralized networks, thereby enabling organizations to leverage the transformative potential of blockchain technology. As blockchain continues to gain traction across various sectors, understanding the underlying IT infrastructure becomes increasingly critical for researchers, practitioners, and policymakers.

- **Hardware Components:** The hardware layer comprises critical elements such as servers, networking devices, and Internet of Things (IoT) sensors. Validation servers and backup servers are pivotal for maintaining the integrity and availability of blockchain networks, while data centers provide the necessary physical environment for these servers. Networking components, including switches, routers, firewalls, and Virtual Private Networks (VPNs), are integral for establishing secure and reliable communication channels. Additionally, IoT sensors, such as environmental, motion, and asset status sensors, play a crucial role in data collection and real-time monitoring, enhancing the blockchain's ability to interact with the physical world.
- **Computing Services:** The computing layer is characterized by the adoption of cloud-based services, specifically Infrastructure as a Service (IaaS) and Platform as a Service (PaaS). These services enable organizations to leverage scalable computing resources and development platforms, facilitating the deployment and management of blockchain applications without the need for extensive on-premises infrastructure.
- **Software Frameworks:** The software layer encompasses operating systems, middleware, and development tools that support blockchain applications. Operating systems provide the foundational software environment, while middleware and frameworks facilitate the integration of various components, enabling seamless communication and data exchange across the blockchain ecosystem.
- **Security Measures:** Security is a paramount concern in blockchain infrastructure, necessitating robust measures to protect data integrity and user privacy. This includes data encryption techniques, authentication protocols, and authorization mechanisms. Identity management systems and Multi-Factor Authentication (MFA) further enhance security by ensuring that only authorized users can access sensitive information and perform critical operations.
- **Monitoring and Logging:** Effective monitoring and logging are essential for maintaining the health and security of blockchain systems. Security Information and Event Management (SIEM) solutions provide real-time analysis of security alerts generated by applications and network hardware. Logging mechanisms capture detailed records of system activities, enabling organizations to conduct audits and forensic investigations when necessary.
- **Management and Maintenance:** The management and maintenance of blockchain infrastructure are facilitated through DevOps practices and Continuous Integration/Continuous Deployment (CI/CD) pipelines. These methodologies promote automation and collaboration between development and operations teams, ensuring that blockchain applications are consistently updated and maintained in alignment with evolving business requirements.
- **Integration of On-Chain and Off-Chain Components:** The integration of on-chain and off-chain components is critical for enhancing the functionality of blockchain systems. Techniques such as hashing and the use of on-chain metadata facilitate the secure linking of off-chain data, ensuring that the integrity of the blockchain is preserved while allowing for the efficient handling of large datasets.

The IT infrastructure for blockchain-based processes is a complex and dynamic framework that encompasses a wide range of hardware, software, and security components. This infrastructure not only supports the operational needs of blockchain applications but also addresses the critical challenges of security, scalability, and interoperability, thereby enabling organizations to harness the full potential of blockchain technology.

Table 3. IT infrastructure for a blockchain-based process.

Hardware	Computing
Servers e data center	Infrastructure as a service
- Validation servers	Platform as a service
- Backup servers	Software
- Data centers	Operating systems
Networking	Middleware and Tools
- Switches and routers	Frameworks and libraries
- Firewalls and VPNs	Security
IoT Sensors	Data encryption
- Environmental sensors	Authentication and authorization
- Motion and presence sensors	- Identity management
- Asset status sensors	- Multi-Factor Authentication
Off-chain storage	Monitoring and Logging
Off-chain databases	Security Information and Event Management (SIEM)
- SQL Databases	Logging
- NoSQL Databases	Management and Maintenance
Distributed file storage systems	DevOps and CI/CD
- InterPlanetary File System (IPFS) for decentralized file storage	- CI/CD pipelines
- Cloud storage	- Infrastructure as code
On-chain and off-chain integration	Monitoring Tools
- Hashing	- Performance monitoring
- On-chain metadata	- Log management

As illustrated in Figure 2, the technological infrastructure, applied to this use case, can be represented by the following components:

- **IoT Building System:** Defined as the set of intelligent devices and sensors distributed throughout the building or assigned to specific physical assets. The necessity of these devices is predicated on their ability to collect real-time data, which is instrumental in the management of cleaning services. These sensors include motion and presence sensors, which provide data for the optimization of cleaning operations based on occupancy and area use; asset status sensors, which facilitate routine cleaning; and machinery status sensors, which monitor functionality, plan routine and extraordinary maintenance. The IoT system is designed to transmit raw data to off-chain storage and the DAPP server via an IoT Gateway.
- **Off-chain storage:** System that manages the large volumes of data from the IoT system that do not require permanent blockchain recording. However, it is essential that this data is accessible, secure, and integrable with the blockchain system. The implementation of this approach involves the utilization of both SQL and NoSQL databases, in conjunction with the InterPlanetary File System [87], a decentralized file storage solution that is compatible with Blockchain Technology. The off-chain storage interacts with other components by:
 - receiving and storing data from the IoT system;
 - receiving data and files from the DAPP and storing them;
 - interacting with the DAPP to allow data and information access;
 - interacting with the blockchain through hashing mechanisms. In the context of blockchain technology, a distinction is drawn between data stored off-chain

and data stored on-chain. In the former case, a cryptographic hash of the data is generated and recorded on the blockchain. This hash functions as a unique and immutable reference to off-chain data, thereby ensuring that any modification to the original data can be readily detected. Interacting with the blockchain through Smart Contracts, for instance, facilitates the verification of off-chain data integrity through on-chain hash verification.

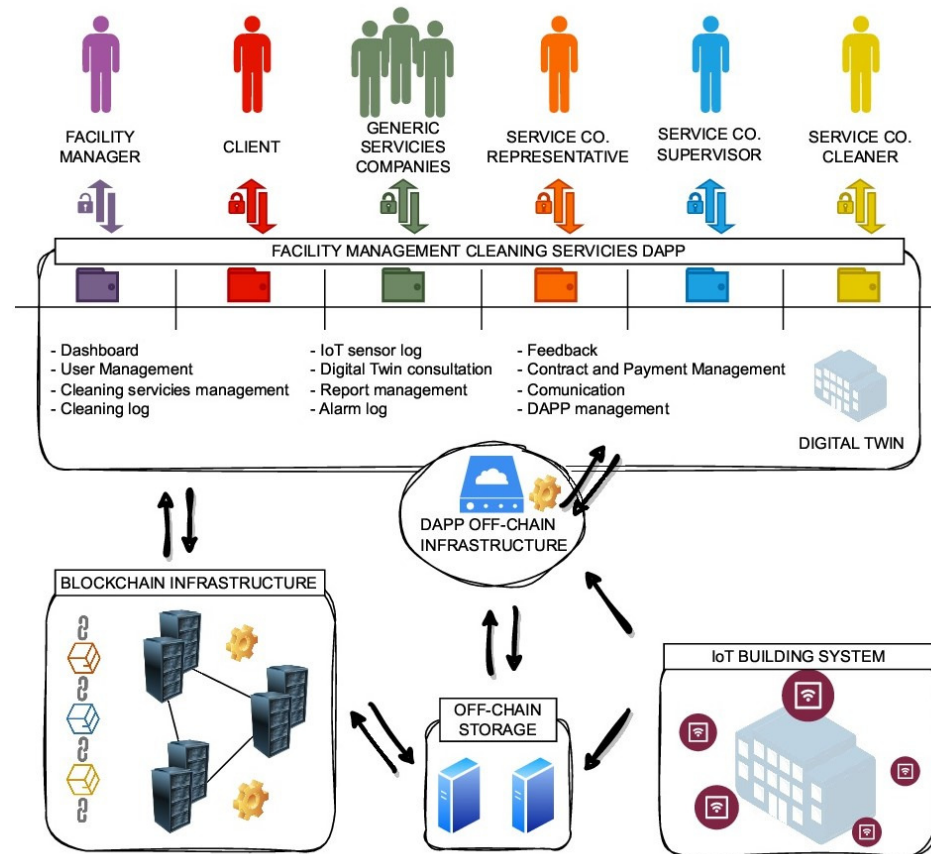


Figure 2. Infrastructure supporting the process model, specifically composed of the following components.

- **Blockchain Infrastructure:** Represents the core of the decentralized management system, ensuring data and transaction integrity, transparency, and traceability. The private blockchain on Polygon CDK is utilized for the recording of critical transactions and the minting of reports as NFTs. The interaction of the aforementioned actors with the blockchain is facilitated through the DApp, employing transactions, Smart Contracts, and NFTs. Furthermore, the blockchain is configured to communicate with the off-chain storage system whenever hashing operations or data integrity verification is required.
- **Decentralized Application:** The user interface facilitates interaction with the IoT system, blockchain infrastructure, and off-chain archives by system actors (administrators, supervisors, cleaning operators, clients). In addition to Frontend, Backend, and API components for infrastructure communication, it integrates digital wallets assigned to each user for managing private keys and transactions. Depending on their role in the process, users accessing the DApp utilize the user interface functionalities to manage cleaning activities, monitor IoT sensors, generate and view reports, mint reports as NFTs, and sign transactions. The DApp communicates with the backend to perform these operations, and the backend interacts with the blockchain and off-chain archives to execute transactions and manage data.

4.2. Operational Description of the Blockchain-Based Process Model

This section delineates the initial two phases of the process, encompassing the planning and procurement of cleaning services up to the stipulations of the contract. The subsequent phases, which are to be the subject of future work development, are not described herein. The subsequent pictures delineate the initial and secondary process phases, pertaining to planning (Figure 3) and service procurement (Figure 4), respectively.

The key stakeholders involved in these phases include the client, the facility manager, and the service providers, all of whom play a critical role in ensuring a seamless transition from planning to execution. An important aspect to highlight is the nature of communication during these phases. While certain interactions and information exchanges take place through traditional methods—without the use of decentralized applications (DApps) and blockchain technology—critical information that solidifies the subphases, as well as relevant documentation, is transmitted through the DApp. This approach is used to ensure a comprehensive record of all correspondence, thereby increasing transparency and accountability.

The facility manager is responsible for securing key documents, which are stored off-chain and then registered on the blockchain using a hashing mechanism. This dual storage method ensures both accessibility and security of essential information. Contracts between parties are also stored off-chain and registered on the blockchain through a hashing process. Once an agreement has been reached, the contract is represented by a Non-Fungible Token (NFT) that encapsulates various details of the agreement, some of which are partially visible on the blockchain. The NFT, which represents the contract, is designed with a modular architecture that allows different functionalities to be implemented through separate Smart Contracts. These Smart Contracts interact with the NFT through function calls or events, providing a dynamic and flexible framework for managing the contract. The specifics of these functionalities are detailed in Table 4, which serves as a reference for understanding the operational mechanics of this component.

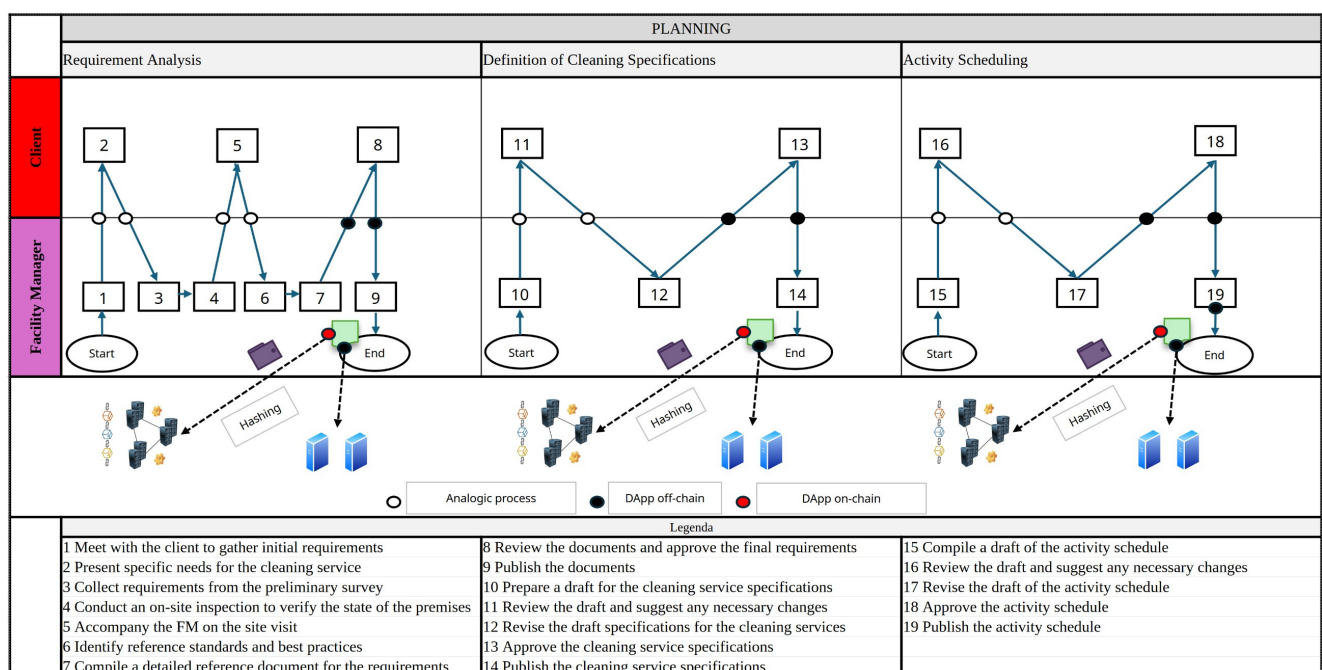


Figure 3. Phase A—Blockchain-based process model for planning.

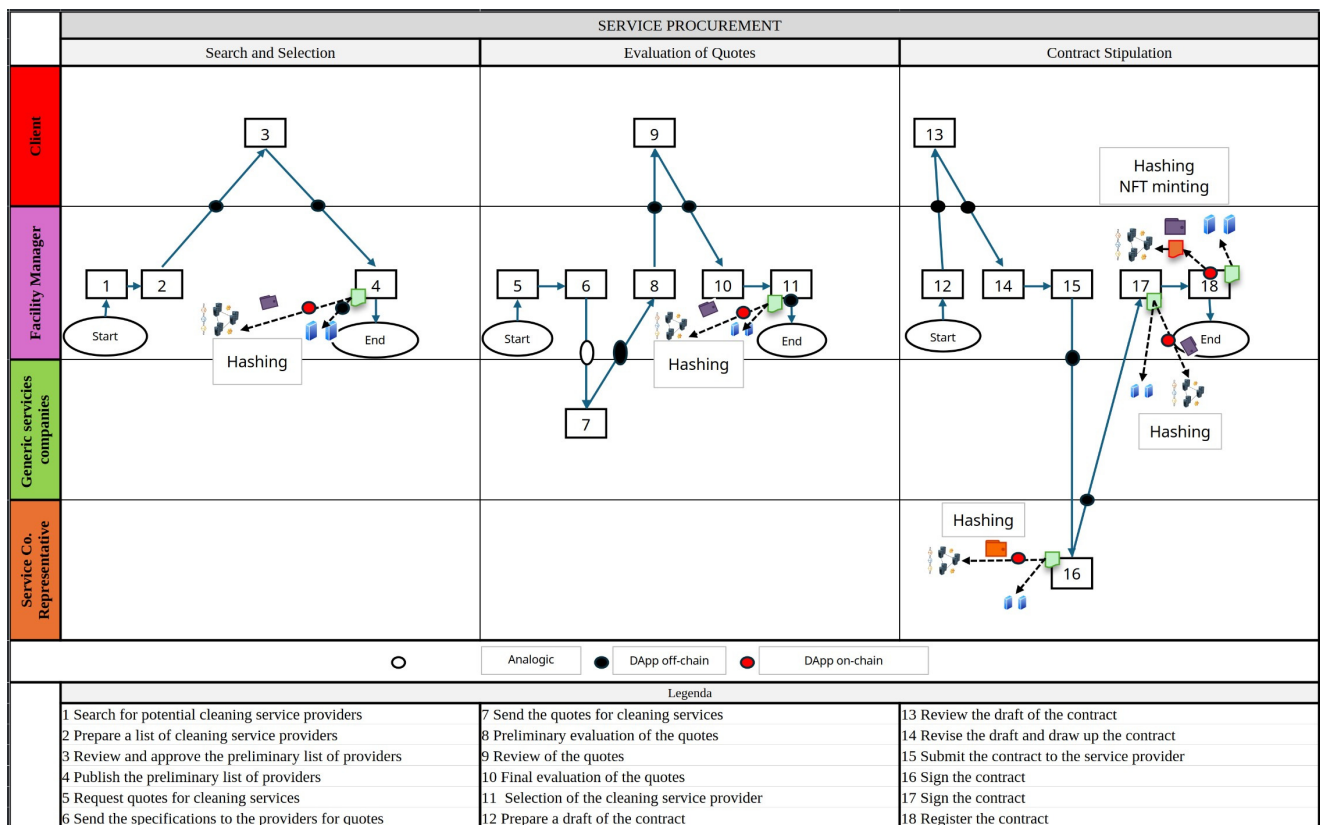


Figure 4. Phase B—Blockchain-based process model for procurement.

Table 4. Non-Fungible Token functionalities representing the contract.

Smart Contract—Functionalities	Description
Creation	This smart contract manages the creation of the ERC721 NFT token and the registration of the initial contract metadata.
Validation	This separate contract interacts with the NFT contract to manage the validation of service phases.
Payment	This contract automates payments based on the completion of service phases, subject to validation.
Audit and review	This separate contract manages the audit and review of contractual operations.
Notification	This contract handles notifications for specific events.
Dispute management	This contract allows dispute management, blocking payments for specific and proven events, and activating a dispute resolution process.
Voting system	This contract enables implementing a decentralized voting system for approving contractual changes or critical decisions affecting all parties. Voting may or may not be unanimous, depending on the type of change or decision.
State management	This contract manages contract states, providing functions to update and track the contract's state.

The ERC-721 [88] standard is a foundational framework for creating and managing non-fungible tokens (NFTs) on the Ethereum blockchain, and offers several key benefits. It emphasizes uniqueness, ensuring that each token is unique and cannot be replicated, while allowing for detailed metadata that provides context such as provenance and ownership history. The standard guarantees immutability, meaning that token details cannot be altered, promoting trust and reliability. It also uses robust security protocols to protect transactions

and ensures interoperability, allowing NFTs to be integrated across platforms. In addition, ERC-721 facilitates clear ownership and efficient transferability, streamlining transactions and increasing transparency. Overall, ERC-721 is essential for the effective management of NFTs, focusing on uniqueness, security and usability in the digital asset landscape.

To implement a pilot project, organizations should start by defining their objectives and engaging key stakeholders in the planning process. Selecting an appropriate DApp platform and collaborating with developers to create the necessary Smart Contracts is the most important step. Comprehensive testing and training for stakeholders will prepare them for the new system. After launching the pilot with a select group, monitoring and evaluating its success will provide valuable insights for adjustments and potential scaling. By following these steps, organizations can effectively leverage DApps and blockchain technology to enhance operational outcomes in facility management and service provision.

5. Conclusions and Recommendations

This study examined the integration of blockchain technology into the cleaning services management process within Facility Management, with particular reference to the use of programmable Non-Fungible Tokens (NFTs) and smart contracts to enhance transparency, traceability, and efficiency. The decision to focus on cleaning services as the initial area for applying blockchain technology in Facility Management is based on several considerations. Primarily, cleaning services are distinguished by their relatively standardized and repeatable processes, rendering them an optimal environment for the experimental deployment and application of novel technologies in a meticulous and controlled manner. However, the management of cleaning services is characterized by a high degree of complexity, encompassing factors such as contracts, resource coordination, personnel management, equipment, verification and control mechanisms, and payment management. The necessity to optimize these operations renders the automation and traceability offered by blockchain particularly valuable tools. Consequently, the integration of blockchain in cleaning services signifies a strategically and methodically justified preliminary step towards the extensive implementation of these technologies in Facility Management processes.

The article's novelty is encapsulated in its innovative approach to integrating blockchain technology into Facility Management, specifically through the use of programmable NFTs and smart contracts. By focusing on cleaning services, the study provides a controlled environment to demonstrate the practical benefits of blockchain, such as enhanced transparency, traceability, and operational efficiency. The proposed blockchain-based process model and the comprehensive analysis of implementation challenges and solutions offer a pioneering roadmap for future research and development in the FM sector.

The research demonstrated that programmable NFTs, supported by an immutable blockchain, offer a permanent record of all transactions and contract states, ensuring that all operations are easily traceable and verifiable. This significantly increases the transparency of the process and allows all involved parties to access a shared, incorruptible version of the data. Additionally, the integration of smart contracts within the NFTs facilitates the automation of various sub-phases of the process, such as progress validation, milestone-based conditional payments, and feedback collection and analysis. This automation has been shown to reduce the risk of errors and increase operational efficiency. The reason for this is that smart contracts execute predefined actions based on specified conditions, thereby eliminating the need for intervention and ensuring that operations are performed exactly as programmed. The blockchain infrastructure guarantees the immutability and security of contract-related data, thereby mitigating the risk of fraud and manipulation. The employment of suitable consensus mechanisms and identity management further safeguards the integrity of the information, with each transaction being cryptographically

verified and recorded, making it practically impossible to alter the data without the consent of the involved parties.

The study also highlighted several challenges associated with the implementation of programmable NFTs and smart contracts. The technological intricacy necessitates a comprehensive comprehension of blockchain technology and a substantial investment in personnel training. The management of numerous tokens and transactions can pose scalability challenges for the network, particularly when intending to channel the considerable volume of data generated by IoT systems on-chain. This article puts forward the notion that off-chain management of Big Data should be considered the optimal solution. Nevertheless, as the number and intricacy of processes managed on-chain by the DApp escalate during the developmental process, a range of requirements may emerge. In such cases, solutions such as Layer 2 and sidechains can be utilized to manage the data load on the Polygon CDK blockchain, effectively fragmenting and replicating the functionality of sharing. The integration of Non-Fungible Tokens (NFTs) and smart contracts with existing IT systems, such as Enterprise Resource Planning (ERP) and Customer Relationship Management (CRM), can be complex and necessitates the development of APIs and interoperability standards. This issue can be mitigated by carefully selecting a blockchain system that can facilitate interoperability with existing legacy systems. The initial costs associated with implementing programmable NFTs and smart contracts, and subsequently integrating them into business processes, can be substantial. However, these costs may be justified by the long-term benefits in terms of enhanced operational efficiency and risk mitigation. Another significant challenge pertains to privacy management. Achieving an equilibrium between the transparency afforded by NFTs and smart contracts, on the one hand, and the necessity to protect sensitive information, on the other, is a delicate issue. The article proposes the implementation of a permissioned blockchain on Polygon CDK, allowing access, viewing, and participation in the network only for authorized users, effectively creating a private network. The article further calls for the consideration of additional tools and measures for managing roles and responsibilities, privacy protection, and sensitive data, with particular reference to multi-factor authentication, sensitive data hashing, permission management, and smart contracts programmed with functionalities to limit the visibility of transaction-related data exclusively to the involved parties.

5.1. Limitations of the Study

Despite the promising findings, this study has several limitations. First, the technological complexity of blockchain and NFTs necessitates a substantial investment in personnel training, which may not be feasible for all organizations. Second, the scalability of managing numerous tokens and transactions, especially with the considerable volume of data generated by IoT systems, poses significant challenges. Third, the integration of blockchain technology with existing IT systems, such as ERP and CRM, requires the development of APIs and interoperability standards, which can be complex and resource-intensive. Fourth, the initial costs associated with implementing programmable NFTs and smart contracts are substantial, and while they may be justified by long-term benefits, they could be a barrier for some organizations. Lastly, privacy management remains a delicate issue, as achieving a balance between transparency and the protection of sensitive information is challenging.

5.2. Future Research Directions

Future research should focus on practical implementations and real-world case studies to fully evaluate the potential and effectiveness of the proposed solutions. Additionally, exploring the integration of blockchain technology with other emerging technologies, such as artificial intelligence and machine learning, could further enhance the capabilities and

benefits of Facility Management processes. Research should also investigate strategies to overcome the identified challenges, such as developing more efficient training programs, improving scalability solutions, and creating standardized APIs for better interoperability. Furthermore, studies should examine the impact of privacy management tools and measures to ensure a balance between transparency and data protection. Finally, future research could categorize drivers into high-impact and low-impact items to help business leaders and government agencies focus on key adoption challenges, ultimately promoting blockchain technology growth in the Facility Management sector.

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