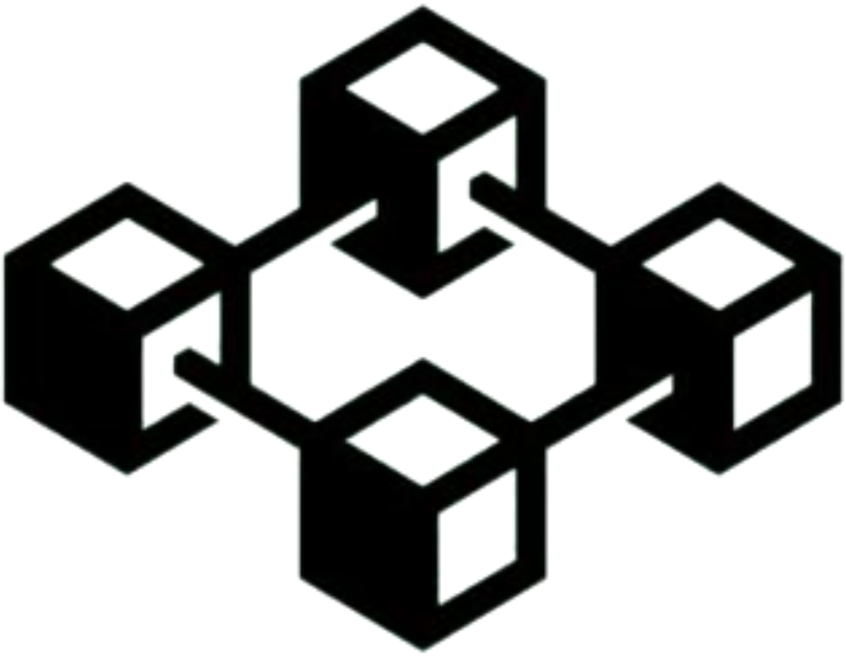

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MSc. Thesis

Integrating Blockchain Technology with Project Management System in the AEC Sector

Haihan Yu

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Integrating Blockchain Technology with Project Management System in the AEC Sector

by

Haihan Yu

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Preface

Reflecting on the journey of my master's thesis at TU Delft, I am filled with a sense of accomplishment and gratitude. The opportunity to delve into the integration of blockchain technology within the Architecture, Engineering, and Construction (AEC) sector was both challenging and exciting. The opportunity to work under advisors who are experts in these niche areas, especially in a department where such specialization is rare, was both a privilege and a driving force in my academic journey. I am particularly grateful to Dr. Eleni, Dr. Daniel, and Dr. Jérémie for their expert advice and guidance throughout this process.

My enthusiasm for blockchain and the AEC sector made this research engaging and enjoyable. However, the journey was not without its challenges. Communicating effectively with my advisors was a significant challenge, given my introverted personality. Despite this, the consistent support and insightful feedback from my advisors, especially Dr. Roel, were crucial in shaping my research. Dr. Roel was a pillar of support throughout the entire course of my master thesis, assisting in setting up the master committee, organizing meetings, and providing advice on the steps necessary to complete my thesis. His approachability, patience in answering my queries, and constructive advice were invaluable.

This thesis was a gateway to numerous new experiences and learning opportunities. I gained a deeper understanding of blockchain technology's nuances and its potential applications in the AEC sector. I explored new areas – learning new programming languages, creating my first webpage, and developing smart contracts. Each of these experiences was a step outside my comfort zone, contributing significantly to my professional growth.

The support and encouragement of my family and girlfriend were the foundation of my journey. Their belief in my abilities provided me with the strength to persist through challenging phases of my research. Lastly, special thanks to Dr. Theo Dounas for connecting me with Dr. Daniel at the start of my master's thesis and for pointing me in the right direction. Without his help, I wouldn't have been able to begin my master's thesis as quickly as I did.

As I conclude this chapter at TU Delft, I am equipped with a wealth of knowledge and skills, ready to embark on new adventures in my career. This thesis has been more than an academic pursuit; it has been an unforgettable experience that has prepared me for future endeavours. I look forward to applying the insights gained from this research in practical, real-world contexts.

Haihan Yu

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Abstract

Since its emergence in 2008, blockchain technology has significantly expanded its scope, impacting various industries beyond its initial cryptocurrency applications. Its potential to enhance established practices is increasingly recognized, yet its application in the Architecture, Engineering, and Construction (AEC) industry has been relatively little researched to date, let alone been applied in practice. This research aims to develop a system facilitating the initiation and management of architectural projects on the blockchain, enabling multi-disciplinary collaboration and participation, by integrating blockchain technology into the AEC ecosystem.

The proposed system is designed to allow architects, engineers, and designers, irrespective of their preferred design software, to contribute, manage and record their designs. By uploading these designs to the InterPlanetary File System (IPFS) and recording the IPFS hashes on the Ethereum blockchain, the system ensures immutable data provenance, transparent ownership representation, and heightened project transparency. Furthermore, this framework automates various aspects of project management, including contractual obligations, payments, and compliance verification through smart contracts.

At the core of this research is a multi-step approach that begins with a literature review to establish the current state of blockchain applications within the AEC sector. The review focuses particularly on the potential of smart contracts, NFTs, and IPFS for improving the management of construction projects. A conceptual framework is then developed, drawing from the literature to designing a prototype system that integrates these technologies. The prototyping phase involves creating a blockchain-based system where architectural project management can be conducted securely and efficiently. Key to this phase is the crafting of smart contracts to automate project workflows and the use of NFTs for clear delineation of design ownership and achievements. The system also incorporates a method for off-chain storage of design files through IPFS, connected to the blockchain, ensuring data integrity and easy retrieval. Systematic testing under certain scenario assesses performance and informs iterative optimization to refine the system's functionality. A performance evaluation strategy is employed to assess the prototype, ensuring its suitability for real-world applications in the AEC sector.

This research develops a blockchain-based system in attempt to restructure project management in the AEC sector. Through iterative development, testing, and optimization, the objective of this study is to contribute to enhanced efficiency, transparency, and collaboration within the industry, exploring the potential benefits of integrating blockchain technology in a structured and measured manner.

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1. Introduction

Contributing to approximately 13% of the global GDP (Oxford Economics, 2021), the Architecture, Engineering, and Construction (AEC) industry has been a major player in worldwide economic development for several decades (McKinsey & Company, 2017). Despite its significance, the industry has been plagued by inefficiencies and escalating costs, often attributed to outdated management practices leading to issues such as delayed payments, project setbacks, and budget overruns. While emerging technologies like Building Information Modeling (BIM), Augmented Reality, and the Internet of Things are making strides in modernizing the AEC landscape, blockchain technology is uniquely poised to address some of the industry's most pressing challenges, thanks to its features of immutability, transparency, and decentralization (Perera et al., 2020).

Originally conceived by Satoshi Nakamoto in 2008 as the backbone for cryptocurrency transactions, blockchain technology operates as a distributed ledger that provides a secure, transparent method for recording transactions among various parties without the need for intermediaries. The technology employs a continually updated shared database that holds transaction records. These records undergo validation by a network of computers and are encrypted through complex algorithms, ensuring data security (Gupta & Jha, 2022). While its initial applications were centered on cryptocurrency, blockchain's versatility has led to its adoption in diverse fields such as finance, supply chain management, healthcare, and logistics (Jaoude & Saadé, 2019). When applied to the AEC industry, blockchain has the potential to greatly enhance operational efficiency, diminish costs, and foster greater transparency and trust among stakeholders.

Nevertheless, the AEC sector has been comparatively slow in adopting new technologies, often due to either an insufficient understanding of technological potential or an overemphasis on short-term returns on investment (Nawari & Ravindran, 2019). Therefore, the focal point of this master thesis is not merely to advocate for the adoption of blockchain technology in the AEC industry but to systematically explore strategies that can overcome the barriers hindering its widespread implementation. Specifically, the research will develop a blockchain-integrated prototype for the storage of large-scale design files using the InterPlanetary File System (IPFS). Additionally, the thesis will delve into the integration of Non-Fungible Tokens (NFTs) for ensuring robust ownership identification and version control, aiming to instate a new layer of assurance and efficiency in design and construction phases.

Building upon these considerations, the thesis proposes a comprehensive blockchain-based platform to streamline the architectural project lifecycle within the AEC sector. This platform introduces a system where architectural projects can be initiated on the blockchain, allowing for decentralized and transparent collaboration across various design disciplines. Utilizing IPFS for the storage of design files and Ethereum blockchain for maintaining immutable records, the system ensures secure data provenance and effective ownership management. The integration of smart contracts will automate critical aspects of project management, encompassing contractual obligations, payments, and compliance checks, thus enhancing overall project efficiency and governance. By establishing a clear workflow for project owners and designers, the system aims to optimize collaboration, reduce redundancies, and foster an environment of trust and accountability, essential for the modernization and future growth of the AEC industry.

Following this introduction, the Theoretical Background section dives deep into specific challenges in the AEC sector, examining issues like collaboration barriers and complexities in responsibility allocation. It then provides a comprehensive exploration of blockchain technology, including network types, cryptographic and consensus algorithms, and smart contracts. The focus then shifts to blockchain platforms like Ethereum and Hyperledger Fabric, concluding with a discussion of blockchain's advantages, limitations, and its varied applications within the AEC sector.

The Research Design section articulates the problem statement and research objectives. This part outlines the research approach and strategy. It also explains the steps taken for encompassing literature review, developing a conceptual framework, crafting a prototype, and evaluating its performance.

In the State-of-the-art chapter, the report conducts a critical analysis and comparison of existing blockchain frameworks in the AEC sector. It synthesizes these findings to integrate them into the proposed system, highlighting the gaps in current methodologies and the novel aspects of the proposed system.

The Framework Development chapter details the construction of the blockchain-based platform. It includes development plans, system requirements, and the development of key components such as smart contracts, frontend, and backend, providing a comprehensive view of the technical aspects of the system.

The report then presents a Scenario chapter using the MEGA project at TU Delft as a case study. This section illustrates the practical application of the blockchain system, addressing various AEC sector challenges, and outlining workflows for project owners and designers within the context of the system.

In System Evaluation, the report analyses the blockchain-based platform's performance, examining transparency, data provenance, design ownership, and project management efficiency. This evaluation provides insights into the system's strengths and potential areas for improvement.

The Discussion chapter reflects on the system evaluation results, the research contributions, and limitations. It analyzes the strengths, weaknesses, and future potential of the system, providing a review of the research outcomes.

Finally, the Conclusion & Recommendations section summarizes the findings, offering a final synthesis of the research and suggesting directions for future work. This section is followed by a comprehensive reference list and an appendix showcasing the webpages developed for the project.

The structure of the report is designed to guide readers through a journey from understanding the problem context, exploring theoretical foundations, practical application, and critical evaluation, to reflective discussion and final insights.

2. Theoretical Background

2.1. Challenges in AEC Sector

In the Architecture, Engineering, and Construction (AEC) sector, collaboration, ownership, and identity management pose significant challenges, often impeding project efficiency and success. The multifaceted nature of construction projects necessitates effective collaboration among diverse stakeholders, including designers, contractors, and clients. However, issues like misaligned objectives, communication barriers, and fragmented processes frequently obstruct collaborative efforts. Additionally, the intricacies of Building Information Modeling (BIM) and project resource management raise complex questions regarding data ownership and responsibility. These challenges are further compounded by the evolving need for robust identity verification mechanisms, underscoring the sector's struggle with securing and managing digital and physical assets effectively. This section succinctly summarizes the primary challenges in the AEC sector as collaboration difficulties, ownership and responsibility disputes, and identity management complexities.

2.1.1. Collaboration in Construction Networks

In the multifaceted environment of construction, collaboration becomes a key for success. Typically, stakeholders in construction projects include the project owner, the architect responsible for the design, an engineer for technical oversight, a general contractor for coordinating the workflow, as well as a plethora of specialized subcontractors for plumbing, HVAC, electrical work, and framing, among others. Fabricators, who supply materials or pre-constructed elements, also play a crucial role (Taylor & Levitt, 2005).

Collaboration emerges when an assembly of autonomous stakeholders involved in a specific problem space actively engage in a mutual process. This interactive process is guided by collectively accepted rules, norms, and organizational frameworks and is aimed at making decisions or taking actions that address issues pertinent to that domain (Wood & Gray, 1991). In the context of construction networks, collaboration is considered a pivotal component for achieving success throughout various stages of the construction project lifecycle (Suprapto et al., 2015).

In the complex and multidisciplinary environment of construction, team members often originate from diverse fields, each bringing unique expertise to the table. Decisions or actions taken within one professional relationship can have significant ripple effects on other collaborating firms (Grilo et al., 2013). For instance, the selection of specific construction materials or methodologies can impact not just one component but multiple relationships and the overall trajectory of the project.

The concept of collaboration within construction networks extends beyond mere agreement among team members. It encapsulates the willingness among specialists to pool their resources, including data, information, and knowledge, toward the accomplishment of broader project goals. These goals are generally set by clients or stakeholders and aim at achieving synergies that individual entities cannot achieve in isolation (Hughes et al., 2012; Matthews et al., 2018).

In short, collaboration in construction networks is not merely a desirable attribute but a necessity. It involves multi-layered interactions among diverse stakeholders, guided by a set of shared rules and objectives. This complexity underscores the importance of effective management and the meaningful interaction of various collaboration antecedents for the successful completion of construction projects.

2.1.2. Collaboration Barriers in Project Design Phase

Maintaining collaboration among participants from diverse specializations and establishments has been identified as a significant challenge (Matthews et al., 2018). Problematic collaboration is often a result of various interconnected antecedents that impede effective teamwork. Building upon Patel et al.'s CoSpaces Collaborative Working Model (2012) and Poirier et al.'s concept of collaboration (2016), Oraee et al. (2017) formulated a framework called the "Collaboration Pentagon." This model synthesizes five principal antecedents: Task, Process, Team, Actor, and Context, which all engage in reciprocal interactions.

Within this pentagon, the 'Task' component pertains to the specific attributes of activities related to BIM. The 'Process' variable is concerned with technological interventions to transform available resources into deliverables. The 'Team' category focuses on the relational architecture within the network of building and construction participants. The 'Actor' element highlights the interplay of social and communicative skills among team members. Lastly, the 'Context' parameter describes the environmental settings where these antecedents operate (Oraee et al., 2017).

A further elaboration of these categories identifies common barriers to collaboration. As Oraee et al. (2019) highlighted, process-related barriers emanate from inadequate tools, insufficient guidance resources, and lack of educational training. Contextual obstacles are attributable to a fragmented environment and discrepancies in organizational culture. Actor-related barriers essentially pertain to the knowledge, skills, and abilities of team members. Issues within the 'Team' category often involve inefficient team structures, poor relationship between teams, and insufficient knowledge-sharing mechanisms. Lastly, task-related barriers are associated with the complex nature of tasks and the unavailability of necessary information (Oraee et al., 2019).

The Collaboration Pentagon serves as a valuable framework for understanding the intricate nature of collaboration barriers in construction networks. Recognizing these barriers is the first step in devising strategies to improve collaboration efficiency, thereby enhancing the overall success of construction projects.

2.1.3. Ownership and Responsibility

In the construction industry, Building Information Modeling (BIM) serves as a collaborative tool that necessitates open access to data and information. However, this collaborative nature brings forth complicated challenges related to ownership (Oraee et al., 2019; Rezgui et al., 2013). Specifically, the primary obstacle often lies not in the technology but in the behaviour and attitudes of practitioners towards data ownership (Zhang et al., 2017).

The collaborative essence of BIM makes it arduous to distinguish individual contributions for copyright matters. In the absence of explicit contractual clauses, design professionals are exposed to the risk of their work being reused in subsequent projects without due compensation. Furthermore, the integrated framework of BIM exacerbates the challenge of identifying responsibility for any errors or discrepancies, leading to further complications in ownership and responsibility (Rosenberg, 2007). Given the complexity of construction projects, no simple answer exists for data ownership issues. Each project mandates a distinct solution based on the requirements and expectations of the involved stakeholders (Azhar, 2011).

The issues of data ownership and responsibility in construction networks are multifaceted. To circumvent potential conflicts arising from copyright or ownership, Rosenberg (2007) advocates the allocation of ownership rights and responsibilities explicitly within contract documentation before initiating any work. Custom-tailored approaches and explicit contractual terms is required to resolve the potential disagreements and to fairly attribute ownership and responsibility.

Blockchain technology offers a viable solution to the responsibility issue highlighted in BIM's collaborative environment. Its ability to create a detailed and immutable record of each transaction ensures transparent tracking of individual contributions and changes. For instance, when a structural engineer finalizes a calculation, this action is recorded on the blockchain, clearly assigning responsibility. This clarity extends to contractors and manufacturers, with each modification or decision being logged and timestamped. Such a system minimizes disputes and enhances accountability, as every action is traceable and verifiable. By integrating blockchain, the AEC sector can achieve a more precise and fair allocation of responsibilities, aligning with the complex nature of construction projects.

2.1.4. Ownership and Identity on Blockchain

The evolution of blockchain technology offers possible solutions for managing both identity and ownership in various industries, including the AEC sector. The challenges in these domains, such as the authentication of user identities and transparent ownership of resources, can find solutions in the capabilities of blockchain technology.

Blockchain allows the scalable management of user identities through unique identifiers like addresses or tokens (Hunhevicz et al., 2022). Unlike traditional identity management systems, which can be prone to security breaches, blockchain ensures a decentralized and secure environment for identity verification. Another major application of blockchain is the tokenization of resources. The concept of tokenization refers to the digital representation of ownership, which in the context of AEC can relate to project resources like digital budgets or even physical assets like building materials (Hunhevicz et al., 2022). The advantage of tokenizing project resources lies in the clear definition of ownership, thereby eliminating ambiguities and enabling efficient resource monitoring. Tokens act as digital certificates, thereby ensuring the integrity and ownership of the resource they represent.

Blockchain technology presents an opportunity to address certain challenges in identity and ownership management within the AEC industry. As digital practices become more prevalent in the industry, incorporating blockchain might offer useful solutions to enhance operational efficiency. The characteristics of blockchain, such as immutability and transparency, could potentially aid in improving processes related to identity verification, ownership allocation, and project management, contributing to improved accountability and efficiency in the sector.

2.1.5. Identity Verification on Blockchain

Blockchain technology introduces methods for identity verification and access control, crucial for secure data handling and transaction management. These mechanisms, pivotal in a blockchain network, ensure that only verified individuals or entities access specific information or functionalities. This is particularly significant in the AEC industry, where maintaining the integrity and security of project data and operational processes is essential.

Address-based and token-based systems are two primary approaches within blockchain for implementing these security measures, each offering distinct methods of controlling access and verifying identities in the context of complex construction projects. Address-based access control operates on unique user addresses within the blockchain network. Although straightforward to implement, this method presents challenges. In an address-based control system, the authorized user must frequently update the smart contract to add or remove individual addresses whenever change occurs, making it less scalable over time (Hunhevicz et al., 2023).

On the other hand, token-based access control involves the issuance and transfer of digital tokens. The ownership of digital tokens grants access control to the token owners. However, as removing a token from an address is impossible, revoking access from certain address can be challenging (Hunhevicz et al., 2023). While both access control systems have their merits and drawbacks, token-based access control outperforms address-based systems in the following ways.

Granular Permissions – Token-based systems can allow for more granular control over permissions. Tokens can represent various types and levels of permissions, which makes it simple to assign or alter specific permissions without having to modify the core contract governing the access.

Transferability – Token-based access control permits the easy transfer of permissions. If an individual or entity no longer requires access or needs to transfer it to another party, tokens make this process straightforward. In an address-based system, such changes would likely require administrative adjustments to the smart contract, which can be cumbersome and error-prone.

Revocability and Expiration – Tokens can be designed to expire or be revoked, providing additional layers of security. In contrast, an address remains constant and generally cannot have its access easily revoked without manual adjustments to the contract.

Adaptability to Changing Conditions – Token-based systems are agile and can quickly adapt to new requirements or changing conditions in the project or organization. As new roles or functionalities are created, new tokens can be minted to accommodate these without a major overhaul of the system.

Reduced Administrative Overhead – In address-based systems, especially as they scale, a significant amount of manual effort may be needed to manage countless addresses and their level of access. Token-based systems can automate much of this process, making it more efficient.

Compatibility with Decentralized Systems – In fragmented industries like construction, where multiple stakeholders are involved, token-based access is beneficial because it allows for decentralized control. Stakeholders can be given tokens representing their level of access, which can be easily adjusted as their role in the project evolves.

These advantages make token-based access control particularly useful for complex, evolving, and multi-stakeholder environments, offering a level of flexibility and scalability that is often lacking in address-based systems.

2.2. Technological Background of Blockchain

Blockchain technology stores committed transactions in a chronological order using an advanced version of distributed ledger technology (Zheng et al., 2017). The stored transactions, protected by a decentralized peer-to-peer network against hacking and tampering, are visible and accessible to all the network users in real-time (Guegan, 2017). As the name suggests, blockchain is a chain of blocks linked to each other, with each block contains numerous transaction data. When a new block is generated and linked to the previous block, cryptographic hash algorithm is utilized to generate unique hash values (Luo et al., 2019). In addition, a consensus mechanism is used to verify the authentication of the transaction data stored in the blocks. Finally, smart contracts are created and deployed to the blockchain to facilitate instantaneous coordination of activities and transactions (Gupta & Jha, 2022). It is evident that blockchain technology is a complex system which is comprised of a number of distinct mechanisms. Each concept that supports the fundamentals of blockchain is introduced in the following section.

2.2.1. Decentralized Network

In comparison with the traditional centralized network where all the nodes are linked to the central server, blockchain is known for its decentralized network which uses peer-to-peer protocols where nodes in the network are inter-connected to each other without the existence of the central authority. A centralized network always has a single point of control which holds the decision-making power. On the other hand, in a decentralized network, all the nodes are linked on a flat topology without the central server, making all nodes share the same duty and responsibility of delivering the required network services (Kaushik et al., 2017). Every time a new block is generated and recorded on the ledger, a copy of the updated ledger appears on the entire blockchain network. All nodes participating in the network have right to view and access the data (Guegan, 2017).

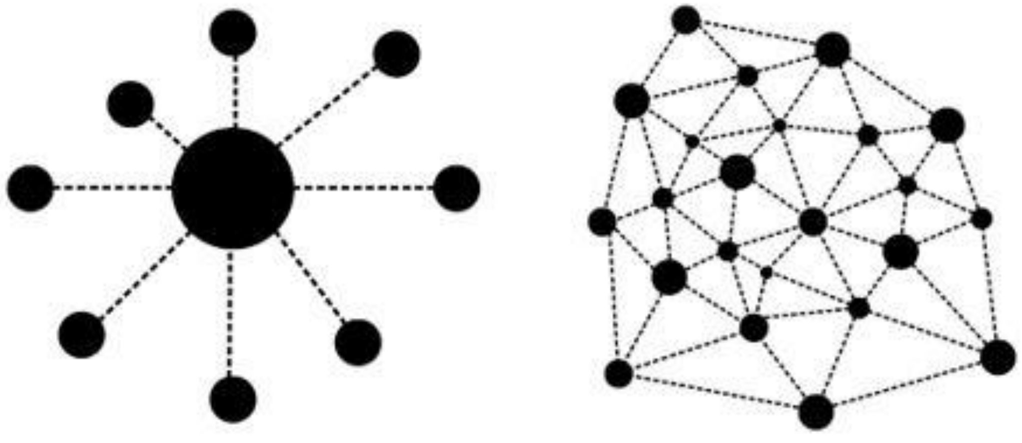


Figure 1 - Centralized Network (left) vs Decentralized Network (right)

2.2.2. Permissionless vs Permissioned Network

Depending on the level of control over who can join the network, the blockchain network can be categorized into two classes: permissioned and permissionless network.

A permissionless network is an open network where anyone can join and participate in the network at any time. These networks are open and often decentralized, meaning that there is no central authority holding the right to control the network, and every node in the network has equal access to the blockchain data (Wüst & Gervais, 2018). The two most known permissionless blockchains are Bitcoin and Ethereum.

As one of the key features of the permissionless network, anyone can become a node and interact with the network by making transactions or creating new blocks, without sacrificing the security of network (Politou et al., 2020). To prevent malicious users from gaining control of the network, consensus algorithm is designed and used by different blockchains. For example, in the case of Bitcoin, miners compete to solve complex mathematical problems to validate transactions and create new blocks. As a reward, the miner who added new blocks to the blockchain receive certain amount of Bitcoin (Nakamoto, 2008). Since anyone can become a miner and participate in the network, this ensures that no single entity can control the network.

A permissioned network is a closed network where only authorized participants can join and participate in the network. In contrast to permissionless networks, central entities exist in permissioned network. They can determine and assign the roles of the participants, allowing certain members to write or read operations on the blockchain (Wüst & Gervais, 2018). Although the existence of central authority partially undermines the decentralization nature of the blockchain, a permissioned blockchain often maintains higher privacy and is more suitable for business governance (Liu & Xu, 2019). Hyperledger Fabric is an example of a permissioned network.

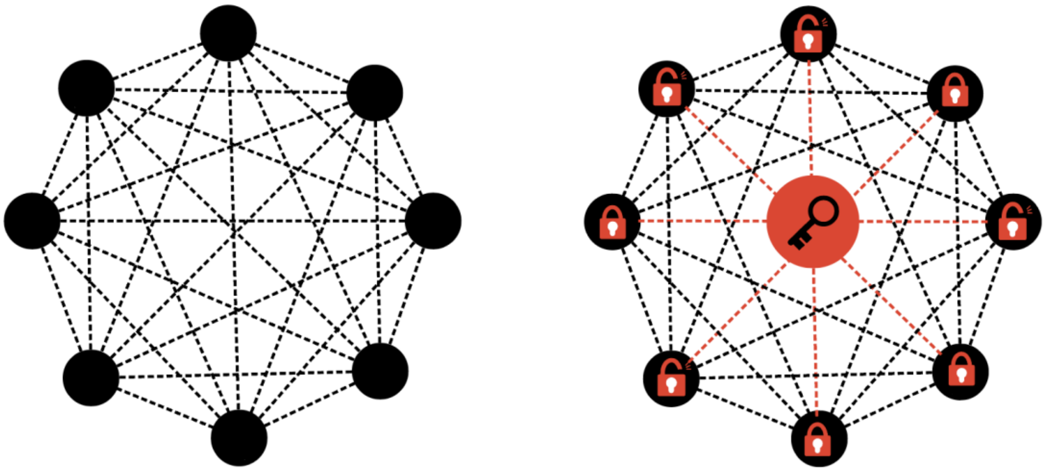


Figure 2 – Permissionless Network (left) vs Permissioned Network (right)

2.2.3. Cryptographic Hash Algorithm

Cryptographic hashing is a technique of utilizing mathematical hash function to convert certain input data of any size to a unique, fixed-size output called hash or digest (Imteaj et al., 2021). Merkle (1989) suggests that a hash function should have the following definitions:

- The hash function should accept any argument of any size.
- The hash function should produce a fixed-size output.
- The same input should always generate the same output.
- If the input is given, it should be easy to compute the resulting hash (output).
- Even if the output is given, it should be infeasible to compute the input.

One of the most famous cryptographic hash algorithms nowadays is SHA-256 by bitcoin blockchain, which satisfies all the above requirements defined by Merkle.

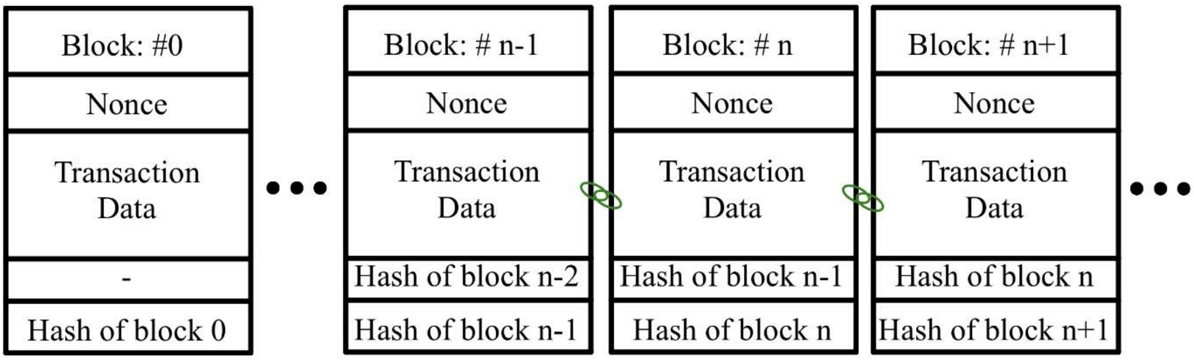


Figure 3 - Blockchain Illustration

A simple illustration of the blockchain is shown in figure 3. As shown in the figure, a series of blocks are linked to each other to form a chain of blocks. Each block typically contains the block index, cryptographic nonce, transaction data, hash of the previous block and the current block. Nonce which stands for "number only used once", is a random number added to a block. When a nonce is combined with the data stored in the block, a unique digest (or hash) will be generated. The purpose of cryptographic nonce is to modify the block's hash value in a specific way so that the resulting hash meets certain criteria set by the consensus algorithm of the blockchain network (Yaga et al., 2018).

Except for the genesis block which is the first block of the blockchain, every block contains the hash of the previous block in addition to its own hash, enforcing all the blocks tied to each other by hash values. This means if any change is made to any block in the chain, the hash in that block will be altered, leading to change of hash values of the following blocks (Nofer et al., 2017). If the hacker wants to attack the blockchain network by tampering the data stored in a block, they must alter the hashes between the tampered block and the latest block. However, tampering a blockchain in one node does not result in a successful attack. In a peer-to-peer, decentralized network, the attacker needs to tamper the blockchain of more than 50% of nodes within a short period of time (also known as 51% attack) in order to hack the entire blockchain (Perera et al., 2020). Considering the 51% attack is almost impossible without a quantum computer, the cryptographic hash algorism is one of the most critical elements for the security of blockchain technology.

2.2.4. Consensus Algorithm

In the applications of blockchain technology, double spending problem and Byzantine Generals Problem cannot be neglected. These two problems frequently occur in a distributed system like blockchain network. Double spending problem refers to using the same cryptocurrency in two transactions at the same time (Mingxiao et al., 2017), while Byzantine Generals Problem is triggered when some attacked nodes attempt to alter the authentic data and send false information (Lamport et al.,1982). These problems can be solved by verifying the transactions by verifying the transaction data by many peers together.

A consensus algorithm is a set of pre-determined rules that allows all the peers in the blockchain network to reach an agreement about the current state of the blockchain without the involvement of central authority (Imteaj et al., 2021). In other words, a consensus algorithm makes sure that all the participants of the blockchain network can come to a consensus about which transaction is valid so that the new verified block can be added to the blockchain. This prevents malicious network users from intentionally changing the information stored in the blocks and taking advantages. The consensus algorithm in blockchain network has been studied for many years. Some of the most used consensus algorithms are introduced below.

Proof of Work (PoW)

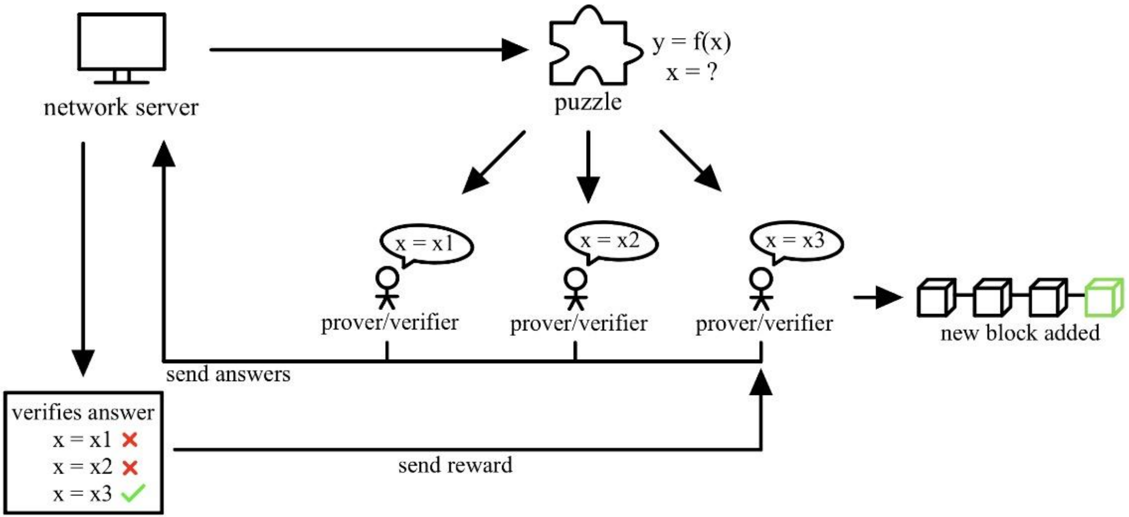


Figure 4 - PoW Illustration

According to Ferdous et al. (2021), there are two different parties involved in PoW mechanism, namely prover and verifier. The prover first needs to solve a complex mathematical puzzle, then the answer is broadcasted to the network to be validated by the verifiers. In this situation, every network participant can be either a prover or a verifier. There is a competition between the provers because the first one to solve the puzzle gets rewarded. Asymmetry is the key in this mechanism, as it requires intensive computing power to reach the answer, but it is fairly easy to verify the correctness of the answer. Once the answer is proven right by the verifiers, all peers reach a mutual agreement, and a new block is added to the blockchain. An illustration of PoW can be viewed in figure 4.

PoW has been being used by bitcoin network since its appearance. The provers compete to find a nonce that, once paired with previous hash and the transaction data in the block, generates a hash starting with certain number of zero bits (Bach et al., 2018). The prover who can find the correct answer first is rewarded with bitcoin. However, due to the demand for energy-intensive computation, PoW is notorious for its enormous energy consumption. Bondarev (2020) estimated that in 2019, the power used for bitcoin mining reached 55.27 TWh, which accounts for 0.24% of the world electricity consumption, making bitcoin network the most energy-consuming blockchain in the world.

Proof of Stake (PoS)

As a more energy-efficient alternative for PoW, Proof of Stake was first implemented by a cryptocurrency PeerCoin in 2012 (King & Nadal, 2012). In a PoS mechanism, instead of miners (provers) competing to solve the puzzle, validators who can create new blocks are chosen based on the amount of cryptocurrency they hold and stake. More cryptocurrency held and staked in the network leads to higher chance of getting elected as a validator (Bamakan et al., 2020).

As stated by Mingxiao et al., the cryptocurrency that adopts PoS typically has the concept of coin age, which can be calculated by multiplying the value of the holding coins by the time period held. For example, holding 5 coins for 10 days equals 50 coin age. When staking cryptocurrency, the larger coin age gives the staker higher opportunity to be chosen as a validator. Nonetheless, even though the validators are qualified to create the new block, they must act honestly and follow the rules of the network, as acting maliciously results in losing their staked cryptocurrency. A simple illustration of PoS mechanism is shown in figure 5.

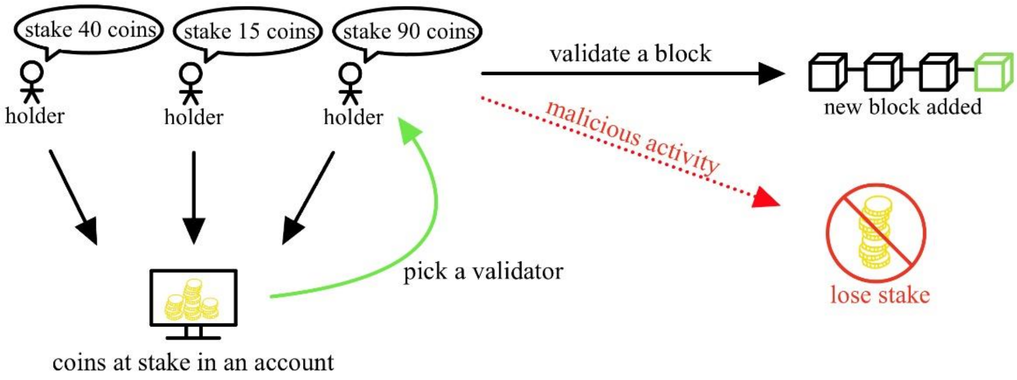


Figure 5 - PoS Illustration

In a blockchain network, PoS is usually used along with PoW, where PoW is merely partially used for coin minting and PoS is used for the network security (Bach et al., 2018). This hybrid system provides a higher energy-efficiency to the blockchain network without sacrificing the security. Moreover, the coin age mechanism encourages the participants to hold the coin for a longer period, thus potentially enhances the value of the cryptocurrency. Ethereum, the cryptocurrency with the second largest market cap, upgraded its consensus mechanism from PoW to PoS in September 15, 2022. This resulted in reduction in Ethereum's energy consumption by 99.95% (Ethereum, 2023).

Delegated Proof of Stake (DPOS)

DPOS was first proposed and applied by BitShares in 2014. Similar to PoS, DPOS implements the coin-age-based-stake system. However, the coin holders stake their cryptocurrency for the purpose of electing their delegates, instead of becoming a block verifier themselves. The elected delegates hold the responsibility to validate and generate new blocks (Larimer, 2014). DPOS uses the shareholders' votes to reach a mutual agreement in a democratic way. This further eliminates the number of nodes participating in block creation, thus reducing the computational power and energy consumption (Zhang & Lee, 2020).

Practical Byzantine Fault Tolerance (PBFT)

In 1999, Castro and Liskov proposed PBFT system to solve the Byzantine Generals Problem. PBFT is primarily adopted by permissioned networks because of its high energy efficiency, throughput and security level. Permissioned network only allow access and participation to authorized entities, making them ideal for enterprise settings where data control, privacy, and confidentiality are essential (Liu & Xu, 2019). The PBFT algorithm consists of five stages, which are explained below (Mingxiao et al., 2017) and illustrated in figure 6:

1. Request: The client sends a request to the master server node, in return the node assigns a timestamp to the request.
2. Pre-prepare: the master node forwards the pre-prepare message to the other server nodes, which decide whether to accept the request.
3. Prepare: Each server node that chooses to accept the request broadcast a prepare message to all other server nodes, and wait to receive messages from others. If more than 2/3 of the nodes accepts the request, the commit state takes place.
4. Commit: Each server node who has entered the commit state sends a commit message to all the nodes in the network. If a server node receives commit messages from more than 2/3 of the nodes, it is assumed that a consensus has been reached, so that the request sent by the client can now be executed.
5. Reply: the server nodes send a reply to the client. In some cases, network delays may hinder successful delivery of the reply, in which case the server nodes may need to resend the reply message multiple times until the client receives it.

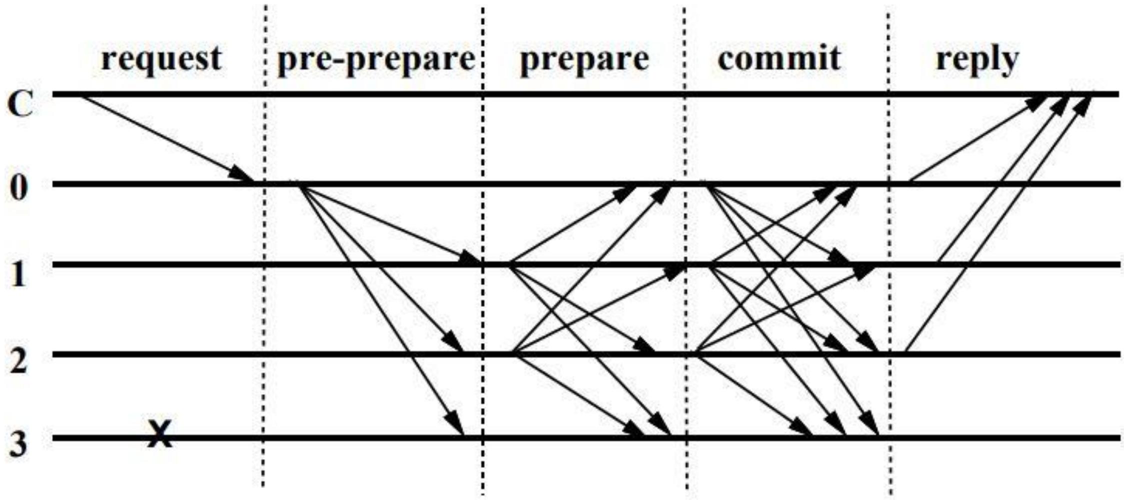


Figure 6 - PBFT flowchart (Castro & Liskov, 1999)

Note that in figure 6, C stands for the client, 0 stands for the master node, and 1, 2, 3 represents all the nodes in the server, while 3 also represents 1/3 of the nodes that act maliciously. As shown, even if 3 has shown malicious behavior, as long as the other 2/3 of the nodes behave accordingly, the entire system is still secure.

Ripple Protocol Consensus (RPCA)

As the name suggests, RPCA is a consensus algorithm used by the Ripple cryptocurrency network to validate transactions and ensure agreement among the network participants. RPCA mechanism was created with the aim of resolving problems related to network delays (Bach et al., 2018). A brief overview according to Ripple whitepaper published by Schwartz et al. (2014) is introduced as followings:

1. Transaction submission: A client initiates a transaction. The transaction is broadcast to all nodes in the Ripple network.
2. Node validation: Each node in the network validates the transaction independently by checking the syntax, verifying if the sender has sufficient funds, and ensuring there is no double spending problem.
3. Node propagation: Validated transactions are broadcast to all nodes in the server. Each node creates a candidate set of transactions it considers valid.
4. Proposal generation: Each node picks a group of transactions to propose as the next transaction set, waiting for the whole network to approve.
5. Vote initiation: Each node broadcasts its proposal to the network. A voting process starts and all the nodes vote on the proposals, indicating their agreement or disagreement.
6. Consensus: If 80% of the nodes agree on the proposed transaction set, the consensus is reached, and the transactions are committed to the ledger. If a consensus isn't reached, the process starts over with a new proposal.
7. Ledger update: The validated transaction set is added to the ledger and is considered part of the Ripple payment network's official transaction history.

Short summary

A short summary of the basic properties of the consensus algorithms is indicated in table 1. Each algorithm has its unique mechanisms and properties. Though not shown, properties like scalability, possible transaction per second (TBS), verification speed also differs between these algorithms. Besides the ones introduced in this section, there exists many other algorithms such as Proof of Importance (PoI), Proof of Burn (PoB), Stellar Consensus Protocol (SCP), with each owning distinct advantages or disadvantages. With further advancement in blockchain technology, more types of consensus algorithms will be invented and applied in the future.

	PoW	**PoS**	**DPOS**	**PBFT**	**RPCA**
Application	Public	Public	Public	Permissioned	Permissioned
Energy Usage	Very high	Low	Low	Minimal	Minimal
Fault Tolerance	50%	50%	50%	33%	20%

Table 1 - Consensus Algorithm Basic Properties

2.2.5. Smart Contracts

The concept of smart contracts was first introduced by computer scientist Szabo in 1997. As theorized by Szabo (1997), the terms of the contract can be executed by smart contracts using the combination of computerized protocol and user interface. However, this concept had remained merely theoretical until the advent of blockchain technology in recent years.

Nowadays, a smart contract is known as a self-executing contract that contains encoded rules or regulations. The terms of the contract are coded into a computer program, which can be executed across a decentralized blockchain network (Peters & Panayi, 2016). By using blockchain technology, a smart contract can verify and enforce the terms of the agreement automatically without the involvement of third parties like banks or lawyers. Once the condition on the contract is fulfilled, the smart contract executes the transaction and releases the agreed-upon assets or funds to the parties involved (Macrinici et al., 2018). For example, a person wants to sell a digital art he drew. This person can create a smart contract and deploy it on an existing blockchain like Ethereum. The information about the art is stored on-chain so that every participant in the same network has access to the information. Whoever wants the art can purchase it by simply fulfilling the conditions written on the contract. In such way, a deal can be made without any intermediacies.

As made apparent from the example, smart contracts provide more security, transparency, automation and efficiency than traditional contracts. Due to these indispensable benefits, smart contracts have found wide-ranging applications in various fields, such as supply chain management, Internet of Things, healthcare systems, and digital rights management. The use of smart contracts in these areas can help to address existing issues like trust, security, and accountability, while also improving the overall efficacy and performance of these systems (Mohanta et al., 2018). As such, smart contracts have emerged as a promising technology that holds significant potential for transforming various industries.

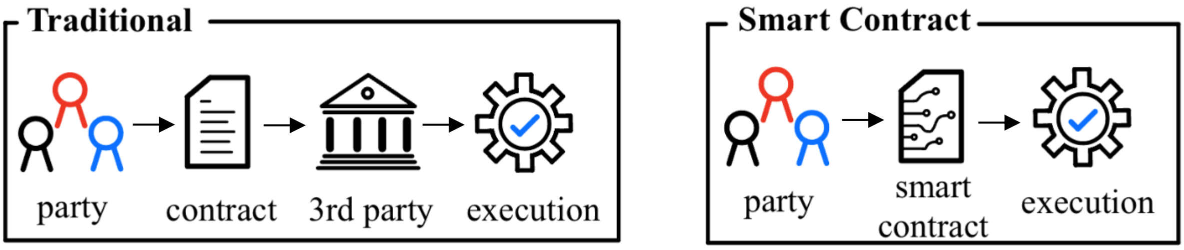


Figure 7 – Traditional Contract vs Smart Contract

2.3. Blockchain Platforms

Delving deeper into the applications of blockchain technology requires a discussion on the diverse platforms that underpin this transformative technology. This section introduces three key blockchain platforms: Ethereum, Hyperledger Fabric, and InterPlanetary File System (IPFS). Each platform possesses unique features, capabilities, and purposes, making them suitable for different use cases. A comprehensive understanding of these platforms will aid in understanding the various possibilities, complexities, and strategic decisions involved in the development and deployment of blockchain-based applications. Therefore, the merits, limitations, and applications of these distinct platforms will be examined.

2.3.1. Ethereum

The following information is largely based on the comprehensive information provided by ethereum.org (2023).

Ethereum is a groundbreaking, open-source platform based on blockchain technology that enables the development and deployment of decentralized applications (dApps). The concept was introduced by Vitalik Buterin, a cryptocurrency researcher, in late 2013, and was brought to life by an online crowdfunding campaign in 2014. The platform officially launched on July 30, 2015.

A cornerstone of Ethereum's innovation is the Ethereum Virtual Machine (EVM), a software that can execute programs by utilizing the Ethereum network, regardless of the programming language. The EVM serves as the environment where all Ethereum accounts and smart contracts exist. The EVM establishes the guidelines for determining a new valid state from one block to the next, thus ensuring the continuous, unbroken, and unalterable operation of this unique state machine.

In conjunction with the use of smart contracts, which are self-enforcing contracts with the agreement terms written directly into code (refer to section 2.1.5 for more details), the EVM makes Ethereum a perfect platform for a broad range of decentralized applications. These smart contracts are coded by developers and become autonomous once deployed on the Ethereum network, predominantly using a programming language called Solidity.

At the heart of Ethereum's operation is Ether (ETH), its native cryptocurrency. ETH serves as the fuel for the Ethereum ecosystem, covering transaction fees and computational services rendered on the Ethereum network. However, Ethereum's function extends beyond just ETH. The platform supports the creation and exchange of a wide range of assets, commonly referred to as 'tokens'. This flexibility has inspired individuals and organizations to tokenize everything from traditional currencies to real estate, artwork, and even their personal attributes. Today, Ethereum hosts a multitude of tokens, each varying in utility and value. The continuous development of new tokens not only opens fresh markets but also unlocks unique possibilities. For more information, please refer to the next section: Tokens on Ethereum.

Notably, Ethereum has undergone significant transformations since its inception. A pivotal upgrade known as "The Merge" took place on September 15, 2022. This event marked the fusion of the original Ethereum Mainnet with the Beacon Chain, a separate proof-of-stake blockchain, resulting in a singular chain. This transition from the original proof-of-work consensus mechanism to proof-of-stake was a landmark moment for Ethereum, slashing its energy consumption by an impressive ~99.95%. The Merge thus underlines Ethereum's commitment to sustainability without compromising on its capabilities as a robust platform for decentralized applications and tokens.

Ethereum underscores its adaptability, resilience, and commitment to harnessing the potential of blockchain technology for creating a decentralized future. Its forward-thinking nature, evidenced by significant milestones like "The Merge", emphasizes its ongoing evolution to meet the emerging needs of a rapidly digitalizing world. Looking ahead, as Ethereum continues to refine its platform and respond to changing global conditions, it will undoubtedly remain an influential player in shaping the blockchain landscape, setting new standards for decentralized solutions, and creating limitless possibilities for global community of developers.

2.3.2. Tokens on Ethereum

Tokens on the Ethereum blockchain serve as digital assets that reside on the blockchain's network. They can represent a multitude of values and utilities, varying from in-game items, digital art, to ownership of real-world assets, all leveraging the blockchain's infrastructure for transactions, smart contracts, and secure, transparent record-keeping.

The token standards on Ethereum, each identified by a unique Ethereum Request for Comment (ERC) number, are protocols that outline a specific set of rules for token interactions. These rules dictate how tokens can be transferred, how transactions are approved, how users can access data about a token, and other important features. These standards ensure interoperability, allowing different tokens to interface seamlessly with various wallets, exchanges, and smart contracts. There are currently hundreds of token standards available on the Ethereum blockchain, with erc-20, erc-721, and erc-1155 being the most popular amongst other. This section will delve into a comprehensive exploration of these varied token standards on Ethereum.

ERC-20

Established in November 2015 by Fabian Vogelsteller, the ERC-20 standard has become a fundamental backbone for tokens within Ethereum's smart contracts. Essentially, ERC-20 token standard provides a set of rules that all Ethereum-based tokens must follow, thus fostering a seamless interaction among various tokens on the Ethereum blockchain (ethereum.org, 2023). The code in figure 8 demonstrates a simplified example of creation of ERC-20 token using token standard.

```
// contracts/Token.sol
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

import "@openzeppelin/contracts/token/ERC20/ERC20.sol";

contract TestToken is ERC20 {
    constructor(uint256 initialSupply) ERC20("TestToken", "TTK") {
        _mint(msg.sender, initialSupply);
    }
}
```

Figure 8 – Simple Example of ERC-20 token Smart Contract

ERC-20 tokens possess a defining characteristic of fungibility. In other words, each token is homogeneous, identically matching every other token in its type and value, mirroring the behavior of Ethereum's native cryptocurrency, Ether (ETH). Therefore, one ERC-20 token is invariably equal to all the others, maintaining consistency across the blockchain ecosystem.

This fungibility extends to various types of tokens. For instance, "stable coins" like Tether (USDT), which are pegged to traditional fiat currencies (USD) for stability, and even the more volatile and often humorously termed "shitcoins." ERC-20's interoperability and standardized approach have paved the way for a multitude of uses ranging from initial coin offerings (ICOs) to decentralized finance (DeFi). The protocol's impact, however, is not just limited to fungible tokens, leading to further token standards that cater to non-fungible tokens (NFTs) and beyond.

ERC-721

The emergence of the ERC-721 token standard on the Ethereum blockchain has enabled the creation and transaction of unique digital assets known as non-fungible tokens (NFTs). Inspired by the ERC-20 token standard, ERC-721 addresses its predecessor's limitations by allowing for the tokenization of distinctly unique assets (Entriken et al., 2018). Like ERC-20, creating ERC-721 token smart contract can be simple by utilizing the predefined token standard (figure 9). However, by incorporating sophisticated logic into the code, the contract's complexity can be elevated, resulting in versatile tokens adaptable to diverse conditions and use cases.

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

import "@openzeppelin/contracts/token/ERC721/ERC721.sol";
import "@openzeppelin/contracts/access/Ownable.sol";

contract MyNFT is ERC721, Ownable {
    constructor() ERC721("MyNFT", "NFT") {}

    function mint(address to, uint256 tokenId) public onlyOwner {
        _mint(to, tokenId);
    }
}
```

Figure 9 – Simple Example of ERC-721 token Smart Contract

As suggested by the name, ‘non-fungible tokens’, ERC-721 tokens are unique and can have differing values even if they are generated by the same smart contract. This standard provides a suite of functionalities: enabling the transfer of tokens from one account to another, determining an account's current token balance, identifying the owner of a specific token, and calculating the total supply of tokens available on the network (ethereum.org, 2023).

This characteristic of uniqueness makes ERC-721 tokens particularly suited for representing unique digital assets and values. As Teisserenc & Sepasgozar (2022) highlighted, ERC-721 tokens can tokenize various forms of value, including datasets, intellectual property, ownership rights to data, or even physical assets. These values are linked to the NFT metadata, transforming them into unique digital assets that can be securely transferred and tracked on the Ethereum blockchain in a decentralized manner.

ERC-1155

ERC-1155 presents an innovative and simple concept, designed to manage any number of fungible and non-fungible tokens within a single contract. It essentially combines the functionalities of both ERC-20 and ERC-721 tokens, offering the ability to handle a wide variety of token types simultaneously (ethereum.org, 2023).

A prominent advantage of ERC-1155 over its predecessors is its efficiency in deploying contracts. Traditional token standards like ERC-20 and ERC-721 necessitate a separate contract for each token type or collection. This not only leads to a surplus of redundant bytecode on the Ethereum blockchain, but it also restricts certain functionalities due to the segregation of each token contract into its own permissioned address (Radomski et al., 2018).

The ERC-1155 standard mitigates these inefficiencies by facilitating multiple token types within a single contract, resulting in reduced redundancy and enhanced functionality. This makes it a versatile tool for developers, enabling them to implement a comprehensive range of assets and value types in a single contract, which could streamline operations and foster a more cohesive ecosystem.

ERC-6551

Recently developed by Windle et al. (2023), ERC-6551 proposes to equip every ERC-721 token, known as a Non-Fungible Token (NFT), with its unique smart contract account. This enhancement expands NFT's abilities, enabling them to own assets and interact with various applications while preserving compatibility with existing ERC-721 contracts and infrastructure.

Currently, NFTs, despite their unique identifiers, can't associate with other on-chain assets or perform any actions by itself. ERC-6551 seeks to circumvent this limitation by introducing a token bound account (TBA), controlled by the NFT's owner, that can interact with the blockchain, or own on-chain assets. Frankly speaking, the main functionality of ERC-6551 standard is to associate an ordinary NFT (ERC-721) with an account that can hold other tokens, without losing the NFT's original functionality. As shown in the figure below, by utilizing a registry contract that links the token with a unique TBA, the token has the capability to possess various types of tokens, as well as interacting with other smart contracts. Moreover, since the NFT now functions as an account, transferring this NFT also transfers any assets bound to it. Notably, this system maintains backward compatibility, allowing it to work seamlessly with existing Ethereum-supporting infrastructures and extend to future asset types. Hence, ERC-6551 presents a promising evolution in the functionality and flexibility of NFTs in the blockchain ecosystem (Windle et al., 2023).

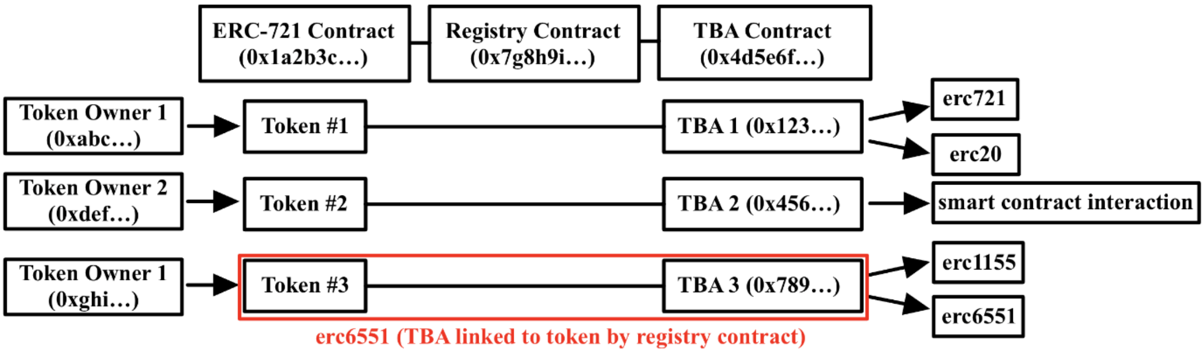


Figure 10 – Scheme of ERC-6551 token standard

ERC-4671

ERC-4671, proposed by Aflak et al. (2022), is a unique token standard in the Ethereum ecosystem that introduces Non-Tradable Tokens (NTTs). Unlike typical tokens, NTTs are fundamentally personal, embodying inherently personal possessions and achievements, and, as their name suggests, are not intended for trade or transfer. They serve as "soulbound" proofs of possession or accomplishment, ranging from educational certificates, government-issued documents like national IDs and driving licenses, to personal milestones such as weddings. The inherent value of these tokens lies not in their monetary worth but in their symbolic representation of personal attainment or recognition by an authority.

Moreover, this standard accommodates the ability for the issuing authority to revoke a certificate. Yet, while the token can be revoked, the record of its once ownership remains indelible on the blockchain. Third parties can validate the existence of a valid token within a given contract, enabling authentication and verification processes. ERC-4671 ushers in an era of personal significance, verifiable history, and immutable recognition in the blockchain space.

2.3.3. Hyperledger Fabric

The following information is mainly based on the comprehensive information provided by Hyperledger Fabric Whitepaper (Linux Foundation, n.d.).

Hyperledger Fabric is a groundbreaking open-source platform engineered explicitly for enterprise use. Established under the umbrella of the Hyperledger project by the Linux Foundation, Fabric is a modular and versatile distributed ledger technology (DLT) suitable for numerous industry use cases.

Fabric's innovative design is renowned for its "network of networks" feature, allowing for distinct transactional relationships within a larger network. This quality enables organizations to maintain confidentiality when needed, by isolating transactions through "channels" or sharing private data merely with relevant parties. This unique design that enables solutions developed with Fabric to be tailored for any industry, leading to a new era of trust, transparency, and accountability for businesses.

The strength of Hyperledger Fabric lies in its modular architecture, allowing plug and play components such as consensus, privacy, and membership services. It supports multiple programming languages such as Go, Java, Javascript, for the development of smart contracts (explicitly called chaincode), coupled with the flexibility to implement any desired solution model. In terms of tokenization, Fabric offers the flexibility for developers to define assets and the rules for transacting them within the chaincode. Additionally, Fabric supports Ethereum Virtual Machine (EVM) and Solidity, bridging the gap between enterprise blockchain application and public blockchain ecosystems. The platform is designed for continuous operations, including continuing upgrades and asymmetric version support.

Hyperledger Fabric has seen extensive adoption among Cloud Service Providers, including industry giants like AWS, Azure, IBM, Google, and Oracle. The breadth of this adoption is unparalleled by any other DLT frameworks to date, demonstrating its commercial feasibility and robustness.

A vibrant open-source community drives Fabric's ongoing development. Contributors range from technology providers to individual developers, fostering an environment of innovation and rapid advancement. The contribution of these diverse community members is crucial for the continuous improvement of Fabric, ensuring that it remains at the forefront of blockchain technology.

Hyperledger Fabric has proven itself as a transformative solution in the blockchain industry. Its modular architecture, coupled with its ability to accommodate private transactions and its rich open-source community, makes it an ideal choice for enterprises looking for a blockchain solution. Its practical applications extend beyond the hype of blockchain technology, with numerous successful deployments, making it a technology that continues to innovate and evolve.

2.3.4. Ethereum VS Hyperledger Fabric

Among the various platforms available, Ethereum and Hyperledger Fabric are two prominent contenders. This section aims to provide a comprehensive comparison between these two platforms, considering diverse aspects such as purpose, programming languages, performance, consensus mechanisms, privacy, and more. The goal is to highlight their unique strengths to identify the most suitable blockchain platform for implementing a parametric design-blockchain integration prototype.

	Hyperledger Fabric	**Ethereum**
Network Type	Permissioned	Permissionless
Main Operating System	Linux/MacOS	Any
Consensus Mechanism	Pluggable (Raft, Solo, Kafka, SBFT)	Proof-of-Stake
Purpose	Enterprise-focused, business application	Decentralized applications, Smart Contract
Privacy	High degree of privacy	Transparent
Transaction Costs	No gas fee	Fluctuating Gas fee based on network demand
Programming languages for smart contract development	Go, JavaScript, Java	Solidity, Vyper
Tokenization	Tokenization is possible but needs custom chaincode	Native support for tokenization through smart contract
Transaction Speed	Can be near-instantaneous, depending on network setup	12s/block
Scalability	High	Low
Throughput	3000 – 20000 tps, depending on network setup	15-45 tps, depending on congestion
Data Storage	Expensive	Expensive
Ecosystem	Growing ecosystem focused on enterprise applications	Vast ecosystem of developers, application, and tokens

Table 2 – Hyperledger Fabric Ethereum Comparison

2.3.5. InterPlanetary File System (IPFS)

The InterPlanetary File System (IPFS) is a technology designed to make the web more efficient and resilient. It represents a peer-to-peer (P2P) method for storing and sharing data, allowing for decentralized communication and collaboration. IPFS addresses multiple challenges within modern data distribution and technology. The challenges include hosting and distributing petabyte datasets, computing large data across organizations, handling high-volume high-definition on-demand or real-time media streams, versioning and linking massive datasets, and preventing the accidental loss of crucial files (Benet, 2014). These intricate challenges are managed and mitigated by the robust structure and forward-thinking approach of the IPFS system.

IPFS allows users to store and share files in a decentralized way, providing improved censorship resistance to the stored contents (Daniel & Tschorsch, 2022). Unlike traditional centrally located servers, IPFS operates on a decentralized model where various user-operators maintain parts of the total data, forming a sturdy system for file storage and sharing. Within this network, any user can provide access to a file using its content identifier, while others can locate and request that specific content from any node possessing it (Krishnan, 2020). This architecture enhances the robustness and effectiveness of data retrieval and sharing.

Content addressability is at the core of IPFS's functionality. This critical aspect signifies that the information is referenced by what it is, known as the content, rather than where it is located (Hamledari & Fischer, 2021). Such an innovation leads to a more flexible and efficient system where data is not bound to a specific location but identified and accessed through its unique content value.

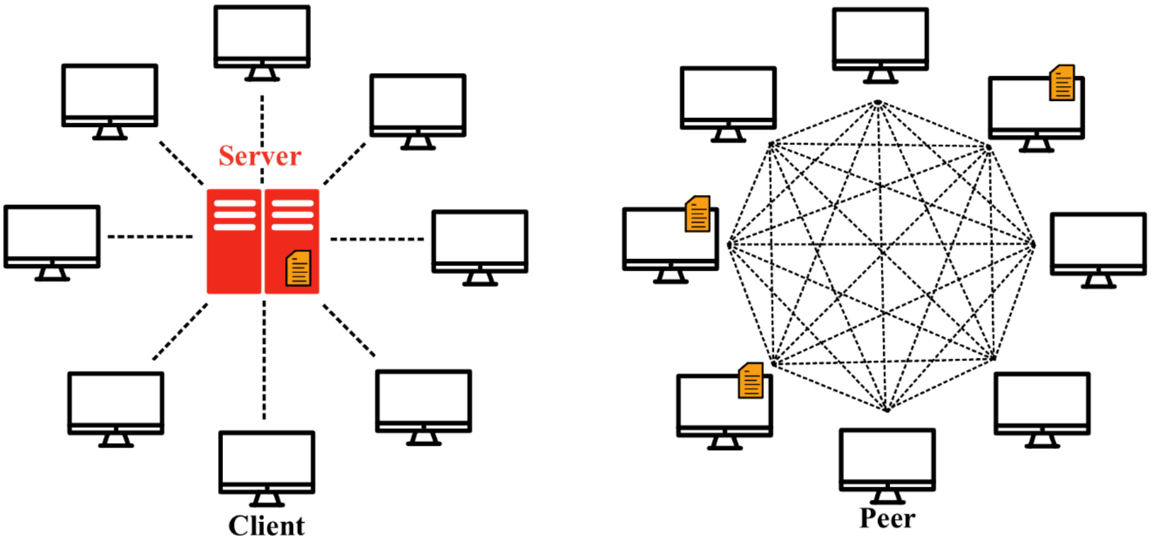


Figure 11 – traditional client-server model (left) vs IPFS peer-to-peer model (right)

Furthermore, IPFS has been heralded as a fresh platform for authoring and implementing applications. It has introduced a novel way of distributing and versioning vast amounts of data, providing new dimensions for data management (Benet, 2014). With IPFS, applications are not only facilitated in their creation but have a robust infrastructure for handling substantial data with greater ease and control.

IPFS is a pioneering system, promoting innovations such as content addressability, new platforms for application development, and offering decentralized storage and sharing. By doing so, it fosters greater resilience, efficiency, and trust in data management and dissemination, reflecting a significant advancement in modern web technology. Its profound impact can be traced across various sectors, providing a framework that aligns with the evolving needs of a digitalized world.

2.4. Advantages and Limitations of Blockchain

As with any emerging technology, blockchain technology also has both advantages and limitation that requires special attention. On the one hand, blockchain offers unprecedented levels of security, transparency and decentralization which have the potential to transform a wide range of industries. On the other hand, technical and practical limitations still exist which may prevent blockchain from widely getting adopted. In this section, some of the most pivotal advantages and limitations of blockchain technology are explored in a greater detail. By understanding these factors, the potential of the technology can be better assessed from a objective viewpoint.

2.4.1. Advantages

Decentralization – Blockchain network is comprised of many inter-connected nodes. The decentralized peer-to-peer blockchain architecture does not require the existence of any central agency, so a transaction can be executed between two parties without the authentication from intermediaries (Monrat et al., 2019). Also, by using all nodes in the network, blockchain can eliminate many-to-one traffic flows, thus avoiding transaction delays and single point of failure (Dorri et al., 2016).

Anonymity – In a blockchain network, users do not need to disclose their identity to a third party. Rather, blockchain users possess one or more addresses to engage with other users and conduct transactions or sign smart contracts. To protect and maintain privacy and prevent identity disclosure, personal information of the users is not revealed (Imteaj et al., 2021).

Security – Blockchain utilizes cryptography to provide integrity and security to every transaction executed on-chain (Bashir, 2017). The use of Asymmetric cryptography enables a trustworthy relationship between users, ensuring the accuracy and privacy of transactions while maintaining their public accessibility (Yaga et al., 2019).

Transparency – In a public blockchain, all transactions are visible and accessible by anyone participating the network, whereas the level of transparency can be controlled if needed (Perera et al., 2020).

Trust – The transparency, high level of security, as well as other aspects of the blockchain provide trust to its users.

Disintermediation – Blockchain negates intermediation. The elimination of third party and associated fees enhances efficiency and cost performance of the transactions (Hamida et al., 2017).

Immutability – Data stored on the blockchain network is considered almost immutable, because altering the data that has already been written to the blockchain is extremely difficult and nearly impossible (Bashir, 2017).

Auditability – According to Zheng et al. (2018), the blockchain records transactions with timestamps and stores the data on the distributed network. With timestamps, users can easily track previous records by accessing any node in the network.

Non-repudiation – Using asymmetric encryption like digital signatures, blockchain can ensure non-repudiation, which refers to the inability of any party involved in a transaction to deny the occurrence and authenticity of the transaction (Imteaj et al., 2021). For instance, A sends B a bitcoin. Once the transaction is made, A cannot undo the action, while B cannot deny that they did not receive the bitcoin. This feature is particularly important in construction industries where disputes and legal issues often occur.

Smart Contract – Many of the modern blockchain networks like Bitcoin, Ethereum, Hyperledger Fabric support smart contracts. Smart contracts eliminate the need for intermediaries, increase efficiency, reduce costs, and lower the likelihood of fraud or error, thus they can be applied in various fields such as supply chain management, real estate and finance (Mohanta et al., 2018).

2.4.2. Limitations

Data Privacy – Blockchain technology is well-known for its transparency, whereas data privacy can become a problem sometimes. In a public blockchain, all information is shared and accessible to every network participant (Lu & Xu, 2017). To address this issue, researchers have proposed and implemented alternative solutions such as use of private blockchain, data encryptions, membership management and private channel (Perera et al., 2020). Additionally, Lo et al. (2017) suggests that while utilizing public blockchain, store confidential and sensitive data off-chain to prevent unauthorized access and misuse of data by malicious nodes.

Data Redundancy – In a blockchain network, all data is duplicated and stored on every node participating the network. Though this mechanism is the core of decentralization, numerous nodes storing a full copy of the distributed ledger, at the same time, creates massive information redundancy (Xue & Lu, 2020).

Data Storage – Public blockchains have certain limitations on data storage capacity (Lu & Xu, 2017). In comparison, consortium blockchains, which involve a limited number of participants in the consensus process, generally have better performance. Another possible solution to the data storage problem is storing unessential information off-chain to reduce the amount of data piled on-chain (Perera et al., 2020). Nevertheless, many researchers question the utilization of blockchain for data storage.

Scalability – A big challenge to the widespread adoption of blockchain technology in practical business settings is the scalability issue (Xie et al., 2019). Blockchain network is notorious for its low transaction throughput and transaction confirmation latency. Compared to electronic payment giant Visa, which can verify approximately 1670 transactions per second (TPS), Ethereum can verify about 20 TPS, and Bitcoin can only verify 7 TPS (Chauhan et al., 2018). As for transaction confirmation speed, due to the large number of transactions occurring on the network, the nodes need considerable time for verifying transactions. On bitcoin network, when the network gets busy, it can take up to 29 minutes to confirm a transaction (Chauhan et al., 2018). Currently, more advanced consensus algorithms are developed to solve this problem.

Energy Consumption – The largest blockchain network, bitcoin, consumes 91.25 TWh of electricity per year, which is comparable to the annual power consumption of Philippines (Digiconomist, 2022). The use of PoW consensus algorithm is the first to blame. New emerging consensus algorithms can reduce the energy consumption significantly.

Private Key Security – Private key serves as a means to authenticate the users' credentials, so it is crucial for transaction verification. Yet, if unauthorized individuals obtain the private key, they can gain access to the wallet of the key owner. Due to the anonymity and non-repudiation aspects of blockchain network, it is difficult to track down the criminals or undo the already-confirmed transactions, making it almost impossible to recover the stolen funds and assets (Li et al., 2017).

Criminal Activity – Because the real-life identity is not tied to the blockchain network users, many illegal activities take place on major networks like Bitcoin or Ethereum. Currently, ransomware generation, underground market for trading illegal items, and money laundering have become some of the most frequent criminal activities on Bitcoin network (Li et al., 2017).

2.5. Applications in the AEC sector

Blockchain technology has gathered significant attention across various fields due to its unique benefits. The AEC sector could also potentially benefit from integrating this technology into its existing ecosystem, as blockchain has the potential to enhance the digitization of the industry and improve various aspects of the AEC sector. Some of the possible applications of blockchain technology are proposed in this section.

2.5.1. BIM Integration

Blockchain technology has the potential to greatly enhance the use of BIM in the design, construction, and delivery phases of a construction project. With blockchain, every change made to the BIM model is recorded and cannot be altered. This attribute allows for the tracking of changes made to the BIM model throughout the design phase, helping to establish intellectual property rights and accountability (Turk & Klinc, 2017). Since the records stored on blockchain network are traceable, these records can function as "visible evidence of trust", encouraging better communication and collaboration between stakeholders in the construction project (Mathews et al., 2017). In other words, by providing a transparent environment for sharing BIM data, blockchain can improve trust and collaboration between involved parties, leading to fewer errors and delays.

Researchers have been looking into solutions to merge BIM and blockchain technology together. For instance, Celik et al. (2023) proposed a practical blockchain-integrated framework to enhance BIM data provenance. The framework records all activities and exchanges in a construction project, which helps project managers and decision-makers to oversee activities across design, construction, and documentation stages. Similarly, Tao et al. (2022) developed the Confidentiality-minded Framework (CMF) for integrating blockchain technology with Building Information Modeling (BIM). This framework effectively segregates and encrypts sensitive BIM data before on-chain storage, ensuring secure access and collaboration within a distributed blockchain environment. Furthermore, Hunhevicz et al. (2020) outlined a crypto-economic system using blockchain technology to encourage the sharing of complete, high-quality datasets at construction project handovers. Their innovative strategy uses smart contracts and digital tokens to keep a trustworthy record of data submissions, automate the flow of information, and incentivize everyone involved in the construction process to share high-quality datasets.

As such, the integration of blockchain technology with BIM has the potential to radically change the AEC sector by enhancing accountability, collaboration, and transparency between stakeholders. This offers a promising means of establishing a more efficient design, construction, and delivery process, which leads to a better outcome for all parties involved.

2.5.2 Supply Chain Management

The construction industry relies heavily on complex supply chains which involves numerous suppliers, manufacturers, contractors, and other stakeholders. The use of traditional supply chain management systems can be cumbersome and time-consuming, causing delays, errors, and inefficiencies. Blockchain technology can effectively address the current problems faced by supply chains.

A study conducted by Wang et al. (2020) shows that the implementation of blockchain into precast supply chain management can optimize information traceability and data sharing among stakeholders. With blockchain, each material can be assigned a unique digital identity and tracked throughout its lifecycle, from the manufacturer to the final installation. Since the details of the construction materials are stored on-chain, any updates are synchronized automatically in real time, providing all stakeholders the information on the material's location, condition, and other relevant data. Likewise, Elghaish et al. (2023) proposed a blockchain-integrated framework that enables secure sharing of building component information, tracking hazardous material treatment history, and creating a repository of reusable BIM families to encourage designers to use these items in their building design. Moreover, the tamper-proof nature of the blockchain makes it nearly impossible to falsify the data stored on the network (Qian & Papadonikolaki, 2020), so the use of counterfeit or substandard materials can be prevented. This leads to improved on-site material, equipment, and labor streamlining, as construction companies can ensure that the materials used in a project have the required quality and comply with all relevant regulations. Overall, the use of decentralized network to store data can help to improve the transparency and traceability of the supply chain.

In addition, blockchain technology can enable a faster and more transparent procurement operation without the involvement of intermediaries. The use of smart contracts enables automatic payments once a pre-agreed conditions are met (Guo & Liang, 2016). By implementing smart contracts, construction companies can automate the purchase and delivery of required materials, ensuring that all parties are paid fairly and on time. This can potentially reduce the risk of disputes, while also improving the overall efficiency of the supply chain.

Overall, the use of blockchain technology in supply chain management can significantly improve the traceability, transparency, and efficiency of the AEC sector's complex supply chains. By implementing blockchain-powered material provenance and smart contracts, construction companies can streamline their procurement processes, reduce the risk of fraud and disputes, and improve the overall quality of their projects.

However, it is important to acknowledge a significant challenge that remains unexplored: the alignment of the digital records on the blockchain with the physical reality of construction materials and processes. Currently, there is a gap in ensuring that the digital "truth" recorded in the blockchain accurately corresponds with the physical state of materials and activities on construction sites. This aspect represents a crucial area for further study and development. Future research is needed to explore effective methods for verifying physical realities and synchronizing these with digital records on the blockchain, ensuring that the system's efficacy extends beyond digital efficiency to actual physical accuracy.

2.5.3. Document Management

A construction project typically has high complexities, meaning a vast number of different types of documents are generated every day. Document management systems in construction firms often hold responsibility to handle critical project documents like architectural drawings, engineering plans and specifications, or project schedules. Some major difficulties faced by the construction organizations are data security and traceability. Integrating blockchain technology with document and information management will be likely to completely change the way organizations manage their documents. Das et al. (2022) developed a prototype of a smart contract mechanism that facilitates blockchain integration with document management for construction applications. With this approach, 1.) smart contract technology can automate document approval workflows that are irreversible and irrevocable, 2.) blockchain network ensures that the document changes are permanently recorded and cannot be reversed. 3.) the blockchain-based data structure guarantees the integrity of document version history.

2.5.4. Construction Payment Automation

Most construction projects encounter issues related to late payment and cash flow. Ramachandra and Rotimi (2011) reported that the construction industry has a prevalent culture of chained payment settlements and long default settlement durations compared to other industries, which results in a significant number of incomplete payments or non-payment. A more efficient cash flow management is urgently needed for the contemporary construction firms. Moreover, there exists trust issues between clients and suppliers when it comes to material purchase, leading to the involvement of third-party entities such as banks or financial institutions. The added participants tend to generate additional costs related to transaction fees and taxes (Perera et al., 2020).

The two problems mentioned above can be addressed by adopting blockchain technology. With blockchain technology, blockchain-enabled digital wallets and project bank accounts can facilitate automatic payments based on contractual conditions and completed work in a decentralized manner. This creates a transparent, efficient and secure environment where payment information is shared and recorded at the project level (Hamledari & Fischer, 2021). Payment automation also generates more trust between buyers and sellers due to a greater enforceability of the smart contract. This eliminates the need for any intermediaries, further reducing the cost of a construction project.

2.5.5. Integration with NFTs

The integration of Non-Fungible Tokens (NFTs) with the Structural Engineering and Construction (SEC) sector has witnessed an innovative transformation in recent years. Various scholars have addressed key challenges and provided solutions through technological integration, highlighting a cutting-edge approach to contemporary problems.

One critical concern is the management of copyright and certification of digital files within BIM, particularly in complex and large-scale projects. Casillo et al. (2022) aimed to tackle this problem by leveraging blockchain technology and NFTs to manage the ownership of digital assets securely. This approach aligns with the broader perspective of blockchain's capacity to track changes and ownership, recognized as a significant advantage for asset information management systems (Raslan et al., 2020).

The challenge of payment administration within construction projects and the dependence on intermediated payment applications was addressed by Hamledari and Fischer (2021). They developed an autonomous payment administration solution that integrated blockchain-enabled smart contracts, cryptocurrencies, and NFTs. This method was implemented successfully, eliminating traditional inefficiencies in payment processes.

In terms of asset ownership and property rights, Mistrangelo et al. (2023) developed a model for tokenization of assets, supported by GIS, BIM, and blockchain technologies. Their research emphasized the flexibility required in property ownership arrangements, an approach that coincides with the concept of property tokenization. This method introduces the use of digital tokens to signify ownership, and according to Wang and Nixon (2021), holds great potential to enhance financial liquidity and investment opportunities in real estate.

Lastly, the challenge of sustainable development in the construction industry was addressed by Theodoros Dounas et al. (2021). They introduced a digital infrastructure layer for architectural assets and building components, using blockchain-secured topology graphs and NFTs. This solution focused on enabling circular economies, material passports, and whole lifecycle Building Information Modeling BIM.

The state-of-the-art integration of NFTs with the SEC sector represents a significant stride towards technological advancement. By addressing multifaceted problems related to ownership, payments, asset tokenization, and sustainability, researchers are paving the way for more streamlined, secure, and innovative processes within the construction and real estate industries. The application of blockchain technology and NFTs has proven to be a catalyst for change, providing solutions that are in sync with the evolving demands of the modern world.

2.5.6. Other Possible Integrations

Blockchain technology can be integrated to many other applications such as property management, asset management, construction management, building maintenance system, energy management, embodied carbon management, waste management, and so on. The decentralized nature of blockchain network brings more security, transparency, efficiency, and trust to the AEC sector, and facilitates better communication and collaboration among stakeholders.

2.6. Conclusion

This chapter explores the theoretical background and technological aspects of blockchain. It becomes clear that the AEC sector contends with crucial issues in collaboration, ownership, responsibility, and identity management, further complicated by the intricate and multifaceted nature of construction projects. The potential of blockchain to enhance data management, organize supply chains, and automate contractual operations within BIM is evident, but its application in intricately addressing the aspects of responsibility, ownership, and identity verification in construction projects is less explored.

This chapter underscores the need for a more integrated approach that blends blockchain's technological strengths with the practical requirements of the AEC sector. There exists a significant opportunity for research that develops and tests blockchain solutions specifically tailored to the operational and collaborative challenges of the AEC sector. The subsequent chapters aim to bridge these gaps, proposing a blockchain-based platform that not only enhances digital efficiency but also resonates with the practical demands and complexities inherent in construction projects.

3. Research Design

3.1. Problem Statement

In the Architecture, Engineering, and Construction (AEC) industry, managing and synchronizing project data among diverse stakeholders is a complex challenge. Inconsistencies in data handling, unclear data ownership, and inefficient tracking of changes frequently lead to delays, increased costs, and disputes, particularly during collaborative design and construction phases. Traditional systems managing project data often lack transparency and security, leading to unrecorded data modifications and blurred accountability.

Blockchain technology, while subject to academic discussion, has not yet seen many applications in the AEC sector. Its potential as a solution remains largely theoretical, with limited evidence of its effectiveness in construction projects. As such, the integration of blockchain within this field is currently an assumption awaiting more robust validation through practical experimentation and research. Previous academic research has explored various blockchain applications, but none have developed an integrated system that synergizes all available blockchain tools to form a comprehensive framework for project management.

Thus, this research explores the development of a blockchain-based platform tailored for the AEC sector. The platform is designed with a focus on practicality and feasibility within the constraints of an MSc thesis. It aims to integrate blockchain's key attributes, such as immutability and decentralized consensus, to enhance project data management. The use of the InterPlanetary File System (IPFS) is proposed for efficient handling of design files on a scalable level. Additionally, the research considers the application of Non-Fungible Tokens (NFTs) and smart contracts to facilitate clearer data ownership and project governance. This study seeks to contribute to the field by presenting a prototype that illustrates how blockchain technology can be applied in the AEC sector, albeit on a smaller scale than full end-to-end lifecycle management. The aim is to provide a foundational step towards more extensive applications in future research.

3.2. Research Objective

This research aims to propose a comprehensive blockchain-based platform to organize design process management in the AEC industry. The objective is to facilitate a decentralized and transparent framework for initiating and managing architectural projects, addressing critical issues like data ownership, provenance, and traceability.

The proposed system is designed to facilitate collaboration among participants from specific design disciplines, including structural engineers, architects, and façade designers, on projects initiated on the blockchain. Using the Ethereum blockchain, the system will ensure immutable recording of all project-related data, enhancing the integrity and traceability of information. The implementation of Non-Fungible Tokens (NFTs) is central to this system, serving as a mechanism for clear ownership representation and version control of design elements. NFTs will provide an auditable trail of design modifications, thus securing intellectual property rights and fostering accountability among stakeholders.

Smart contracts will play a pivotal role in automating various aspects of project management, including contractual obligations, payments, and compliance verification. The automation seeks to aid in streamlining processes and could contribute to reducing potential disputes by providing a clearer framework for the allocation of responsibilities and rights. The design of the system aspires to facilitate effective collaboration among all parties involved, including project owners, designers, and engineers. It is intended to support improved communication and clarify lines of authority. However, it's important to note that the potential for resolving disputes and the extent to which the system can ensure effective collaboration will be subject to further exploration and may not be fully demonstrated within the scope of this project.

Additionally, while IPFS will be utilized for efficient storage of design files, the primary focus of the research will be on leveraging blockchain for enhancing the management of design projects. The goal is to create a blockchain-based platform that not only addresses storage needs but also significantly improves collaboration, transparency, and efficiency in the AEC industry.

3.3. Research Questions

This thesis will focus on answering a main research question aligned with each research objective:

Main research question 1

- ❖ How can the integration of blockchain technology change the management and collaboration in architectural projects, potentially leading to a more transparent and streamlined design process in the AEC sector?

Research sub-questions

- What specific features of blockchain technology can be leveraged to improve data management and ensure transparency in the handling of design data in the AEC industry?
- How can different token standards, such as ERC721, ERC4671, and ERC6551, be efficiently integrated within the project management system to optimize the management of roles, ownership, and project contributions in the AEC sector?
- In what ways can smart contracts be designed to automate critical aspects of the design process, ensuring a seamless flow throughout the entire lifecycle of an AEC project?
- In which scenario could the proposed prototype be utilized to showcase and evaluate the system's performance, and what are the observed outcomes?
- What are the potential challenges and limitations in implementing a blockchain, IPFS, and NFT-based system for design data management, and how can these be addressed to optimize efficiency and security?

3.4. Research Approach & Strategy

This chapter describes the research approach that will be taken to answer the research questions outlined in the previous chapter. There are six parts in this section, as described below:

3.4.1. Literature Review

A review of current literature will be conducted to explore the integration of blockchain within the AEC sector, specifically focusing on the utilization of NFTs, smart contracts, and the IPFS system for the better handling of construction projects. Different decentralized storage solutions, such as IPFS, will be analysed alongside blockchain technologies to understand their suitability for storing complex design data. Moreover, the integration of NFTs in identifying ownership and version control will be investigated. An important aspect of this review will include an examination of how smart contracts can be integrated into the AEC sector to automate and enforce project agreements and transactions. This exploration will cover the potential of smart contracts in improving efficiency, reducing disputes, and ensuring compliance in project management. The literature review will also delve into the challenges and benefits associated with smart contract implementation in construction projects, particularly in relation to collaborative workflows and data sharing.

Through this process, gaps in existing methods and models will be identified, along with potential opportunities for the innovative combination of smart contract, decentralized file storage, and NFTs for enhanced design data management within the AEC industry. The aim is to build a comprehensive understanding of how these technologies can be synergized to address current limitations in design data management and improve overall project execution in the AEC sector. The literature review is summarized and presented in chapter 2.

3.4.2. Understanding State-of-the-art

This section, outlined in chapter 4, delves into a comparative analysis of existing blockchain frameworks within the AEC sector. The aim is to dissect and understand the various approaches, methodologies, and technologies adopted in current research to grasp the state-of-the-art in blockchain application within this sector. This analysis will not only shed light on the achievements and limitations of existing studies but also help in identifying gaps and opportunities for innovation in the proposed system. Insights from the comparative analysis are crucial in shaping the development of the proposed blockchain-based framework. This new system will address the gaps identified in current research while integrating successful aspects of existing models. By doing so, the system aligns with the latest advancements in the field, establishing a foundation for its development and enhancing the application of blockchain technology in the AEC sector.

3.4.3. Conceptual Framework Development

Based on the insights from the literature review, a conceptual framework for the proposed solution is developed and presented in chapter 5. This process involves:

- Examining the combination of blockchain platforms (Ethereum or Hyperledger Fabric) with decentralized file storage solutions such as IPFS, and evaluating critical factors such as interoperability, scalability, and security.

- Outlining the process for integrating NFTs for ownership identification and version control of design files will be outlined. This section will detail how NFTs add value to the design process, enabling clear ownership tracking and version management.
- Developing a smart contract with functions for automating and enforcing project management tasks. This includes the integration of contractual obligations, identity verification, and timely payment, enhancing efficiency and transparency in project management.
- Detailing the method for storing and retrieving design files off-chain on IPFS and connecting them to the blockchain through unique identifiers, while using smart contract functions to ensure integrity, security, and ease of access.

3.4.4. Prototype Development

This step, which involves the development of the prototype of the blockchain-based system, is demonstrated in chapter 5. The prototype will focus on creating a blockchain-based system for managing design processes in the AEC industry, employing Python, JavaScript and Solidity for programming, alongside IPFS for decentralized file storage. The key steps include:

- Constructing a system for launching architectural projects on the blockchain, enabling multi-disciplinary collaboration and secure handling of large design files via IPFS.
- Crafting smart contracts for automating project management tasks, such as contractual agreements and integrating these with IPFS and NFTs for ownership and version control.
- Developing intuitive interfaces and APIs for easy system interaction, including project initiation, design uploads, and NFT management.
- Testing the system with a concrete design scenario to validate its applicability and ensuring data integrity and reliability.
- Assessing the system's efficiency, data security, and the effectiveness of smart contracts in project management.
- Ensuring smart contracts operate correctly, especially in managing IPFS integration and NFTs, and implementing predefined terms like royalties for design reuse.

3.4.5. Performance Evaluation and Optimization

Illustrated in chapter 6 and 7, the performance of the prototype is systematically evaluated under a scenario. This process also involves setting up benchmarks for performance and gathering data through testing. Based on the results obtained from the testing and performance evaluation, an optimization of the prototype will be conducted. This involves:

- Refining smart contracts for improved performance and reliability.
- Optimizing the interfaces or APIs for more user-friendly data input and output.

3.4.6. Report and Presentation

Based on the results from the previous sections, the research findings, development process, testing result, and the final optimized solution will be documented as a concrete academic paper. In addition, a presentation of the findings will be prepared and presented to the academic committee at the end of this master thesis.

4. State-of-the-art

This chapter serves as the foundation for this thesis. In this chapter, a comparative analysis is conducted, exploring various frameworks that integrate blockchain technology within the AEC sector. This analysis begins with a summary of each framework, detailing their core objectives, methodologies, and unique attributes. These frameworks, ranging from decentralized architectural design process to the integration of blockchain with Building Information Modeling (BIM), are studied to understand how they leverage blockchain technology to address specific challenges in the AEC sector.

A critical element of this analysis is the examination of how each approach utilizes blockchain's inherent features like immutability, decentralized consensus, and smart contracts. The focus is also on how these systems employ advanced components such as the InterPlanetary File System (IPFS) for data storage and Non-Fungible Tokens (NFTs) for ownership and intellectual property management. Next, a comparative table is presented, synthesizing the key objectives, main components, and distinctive features of each framework. This table serves as a roadmap, illuminating the diverse strategies and technological foundations that characterize the intersection of blockchain and the AEC industry.

The synthesis and analysis section provides a holistic view of the current state of blockchain integration in the AEC sector, identifying gaps and potential areas for further exploration. Derived from understanding the research gaps and the comparative analysis, the system requirements for the proposed framework can be crafted (presented in the next chapter). This chapter thus sets the stage for the development of a blockchain-integrated platform, aiming to address the challenges identified in the AEC sector comprehensively.

4.1. Summary of Framework from Other Literature

Framework for Decentralized Architectural Design – BIM and Blockchain Integration (Dounas et al., 2020)

The framework designed by Dounas et al. seeks to leverage the synergy of blockchain technology and Building Information Modeling (BIM). At its core, the BIM manager plays a pivotal role, initializing the process by establishing a smart contract on the Ethereum blockchain. This contract is comprehensive, encompassing various parameters like the problem ID, data storage method (using IPFS), expected inputs/outputs, performance criteria, reward mechanisms, and an expiry date for the project. Agents, who could be human designers or AI algorithms, register by providing their Ethereum addresses and a user ID, integrating themselves into the blockchain ecosystem. The problem-solving phase is dynamic, with agents uploading their design solutions to IPFS, and then engaging with the blockchain to submit their work. Smart contracts autonomously evaluate each submission by comparing its value to both the current optimal solution and a pre-set threshold. The most effective solution triggers a series of actions including reward distribution and updating the design consensus. The framework is also adaptable, offering modes of operation that can be either competitive or collaborative, governed by a DAO or the problem owner. The entire process is recorded on the blockchain, ensuring transparency and immutability of the design evolution.

Protecting BIM Design Intellectual Property with Blockchain: Review and Framework (Darabseh & Joo, 2021)

Focused on safeguarding the intellectual property inherent in BIM designs, this framework integrates the robustness of Hyperledger Fabric with the decentralized storage capabilities of IPFS. It commences with authors uploading their BIM files, complete with ownership information and file format specifics (IFC files), while also setting access parameters. These files are then securely stored in IPFS, generating unique hash codes that, along with metadata, are stored in Hyperledger Fabric. The user interface plays a critical role, processing access requests based on the rights defined by the authors. Once access is granted, users can authenticate the design files through a metadata check or external tools. The framework elevates security through private communication channels in Hyperledger and incorporates Hyperledger MSP for dynamic security management, including setting access time limits and handling certificate revocations in security breaches. For auditing and compliance, all actions and rights usage are meticulously logged within Hyperledger Fabric, promoting transparency and accountability.

Blockchain Supported BIM Data Provenance for Construction Projects (Celik et al., 2023)

This framework utilizes blockchain to enhance data provenance and integrity in construction projects. It starts with the client setting the stage for the project, including configuration and the initiation of communication with various project disciplines through email. These disciplines are then involved in the downloading and updating of the BIM model, in accordance with the project plan. Crucial to this framework is the creation and deployment of smart contracts, which govern the authorization and management of BIM data updates. These contracts are not static; they are subject to operations like addition, deletion, and modification, all aimed at ensuring data authentication and integrity. Every change or update is recorded as metadata on the blockchain, alongside BIM properties, ensuring an auditable trail of modifications. The framework also includes a comprehensive cost analysis component, monitoring the consumption of blockchain resources (gas) and optimizing them. The emphasis on compliance and auditing ensures that all project activities are transparent and accountable.

Blockchain and NFT: A Novel Approach to Support BIM and Architectural Design (Casillo et al., 2022)

Innovatively blending blockchain with NFTs, this framework introduces a novel approach to BIM and architectural design. The process begins with extracting a unique fingerprint from IFC files using cryptographic hashing, forming the foundation of the NFT's metadata. This data, when minted as NFTs under the ERC-1155 standard, guarantees uniqueness and prevents duplication, effectively certifying the authenticity and originality of architectural elements. The framework's practicality was tested with Revit families in the Heritage IT Jordan project, demonstrating its effectiveness in certifying the authenticity and uniqueness of architectural designs. The potential economic and qualitative benefits of this integration are significant, suggesting avenues for new market creation, enhanced copyright management, and anti-plagiarism measures in the realm of architecture and design.

Smart Contract Swarm and Multi-Branch Structure for Secure and Efficient BIM Versioning in Blockchain-Aided Common Data Environment (Tao et al., 2023)

This framework proposes a novel Two-Layer Container CDE (TLCCDE) model, integrating blockchain and IPFS to create a decentralized environment for BIM versioning. The Smart Contract Swarm (SCS) automates versioning actions, while the Multi-Branch Structure (MBS) efficiently manages version branches. A key aspect of this framework is the version approval channel, allowing for separate tracks of approved and unapproved BIM data, enhancing data security and integrity. The framework's efficacy is evaluated using design examples, assessing aspects like latency and throughput to ensure both security and efficiency. Key components include the TLCCDE interface for user interactions, Hyperledger Fabric for the decentralized ledger, and IPFS for file storage. The MBS algorithm, crucial for data extraction and version status updates, works alongside ISO 19650 standards, guiding versioning procedures in a standardized manner.

Incentivizing High-Quality Data Sets in Construction Using Blockchain: A Feasibility Study in the Swiss Industry (Hunhevicz et al., 2020)

Targeting the enhancement of data quality in construction projects, this framework explores the use of blockchain to incentivize the submission of high-quality data. The process begins with the development and testing of smart contracts using Solidity and Remix, offering a simulated Ethereum environment for rapid prototyping. The workflow is comprehensive, encompassing element definition, contract signing, and state variable management, all governed by smart contract logic. Role-based access control is a key security feature, ensuring that updates and data inputs are executed only by authorized parties. The data structure is organized using Solidity structs, aligning data input functions with workflow stages. The incentive mechanism is particularly innovative, employing tokens (either ERC20 or ERC721) to motivate stakeholders to provide high-quality data. A distinctive role in this framework is the Data Verifier, responsible for assessing data quality and rewarding contributors with tokens, thereby promoting a culture of high data integrity and reliability.

4.2. Comparative Table

Table 3 is a comparative table which distills the essence of various pioneering frameworks integrating blockchain technology within the AEC sector. It briefly encapsulates each framework's key objectives, illustrating the targeted outcomes and intentions behind their development. Central components utilized, such as Ethereum and InterPlanetary File System (IPFS), highlight the technological backbone that powers these innovative solutions.

Furthermore, the table delineates the unique features of each framework—these are the distinctive attributes that set them apart, from DAO-managed modes to unique fingerprint extraction from IFC files. This comparative analysis serves as a roadmap for understanding the diverse approaches and technological underpinnings that define the cutting-edge intersection of blockchain and the AEC industry.

	Key Objectives	**Main Components**	**Unique Features**
Framework for Decentralized Architectural Design - BIM and Blockchain Integration	- Optimize architectural design processes - Streamline communication and consensus - Provide transparent record-keeping	- Ethereum - Solidity Smart Contract - IPFS - DAO	- Competitive or collaborative modes managed by DAO or problem owner - Immutable design records
Protecting BIM Design Intellectual Property with Blockchain	- Secure intellectual property of BIM designs - Facilitate authenticity checks - Ensure transparent usage tracking	- Hyperledger Fabric - Hyperledger Composer - Hyperledger MSP - IPFS - IFC	- Private communication through Hyperledger Channels - Time-limited access and certificate revocation for security incidents
Blockchain Supported BIM Data Provenance for Construction Projects	- Enhance data provenance - Ensure data integrity and authenticity	- Ethereum - Solidity Smart Contract - IFC - Web3.js	- Real-world testing of smart contracts on Kovan Testnet - Gas consumption monitoring for optimization
Blockchain and NFT: A Novel Approach to Support BIM and Architectural Design	- Use NFTs to certify authenticity and uniqueness in architectural elements - Explore economic and qualitative benefits	- Ethereum - NFT (ERC-1155) - IFC	- Unique fingerprint extraction from IFC files - Integration of NFTs for architectural elements
Smart Contract Swarm and Multi-Branch Structure for Secure and Efficient BIM Versioning in Blockchain-Aided Common Data Environment	- Automate versioning control - Enhance tracking efficiency of version updates - Evaluate security and efficiency	- Hyperledger Fabric - IPFS - Smart Contract Swarm - Multi-Branch Structure - ISO 19650 Standards	- Two-Layer Container CDE model using Hyperledger Fabric - Multi-Branch Structure for version management
Incentivizing High-Quality Data Sets in Construction Using Blockchain	- Incentivize high-quality data submission to enhance data quality - manage workflow stages and access control - ensure data integrity	- Reward Tokens - Ethereum - Solidity Smart Contract	- Token-based incentive structure (ERC20 and ERC721) - Role-based access control for security

Table 3 – Comparison between different approaches of integrating blockchain technology within the AEC sector

4.3. Synthesis and Analysis

The collective examination of contemporary research unveils a significant shift toward the integration of blockchain in the AEC sector, manifesting primarily through smart contract implementation and decentralized file systems like IPFS. These frameworks exhibit a strong inclination towards ensuring the reliability and traceability of design documentation, highlighting blockchain's potential to significantly enhance security, transparency, and collaboration within the AEC industry. The use of Non-Fungible Tokens (NFTs) is an emergent trend, particularly in asserting ownership and securing intellectual property rights for unique architectural elements and designs.

The synthesis reveals that while these frameworks constructively address several core challenges, including efficient version control and data provenance, they often overlook the need for a real-time, responsive project management system that can dynamically adapt to the nuanced workflows of the AEC sector. The literature suggests a gap in the granularity of role management and the level of immediacy in collaborative efforts. Furthermore, there appears to be a lack of focus on incentivizing the quality of contributions through economic mechanisms within the existing blockchain applications.

4.4 Integration into the System

The system developed for this research links the scope of existing literature by cohesively integrating a suite of blockchain tools to form an all-encompassing management system. While prior research has delved into aspects such as IPFS for data storage, blockchain for data provenance, NFTs for ownership, and smart contracts for automation, this research combines these components into a singular, robust framework. This integration is not merely additive; it's synergistic, creating a comprehensive platform that supports the entire design lifecycle, from conceptualization to completion.

This general strategy directly addresses the fragmentation seen in current methodologies. By harnessing the full potential of blockchain capabilities, the framework establishes a model for complete lifecycle management within the AEC sector. It sets up a comprehensive ecosystem where every interaction, transaction, and exchange are meticulously documented and facilitated within the blockchain infrastructure, representing a leap forward from fragmentary applications to an integrated system that encapsulates every phase of the design process.

Another critical point of this research is the adoption of unique token standards like ERC4671 and ERC6551, selected not just for their novelty but for their capacity to meet the intricate demands of the AEC sector. ERC4671, implemented to verify and authenticate users' qualifications, alongside ERC6551, employed for its capability to allow tokens to interact with smart contracts, are instrumental in forging a system that is both secure and efficient.

In essence, this research doesn't merely iterate upon existing applications; it attempts to reveal the possibilities of blockchain in the AEC sector, offering a versatile and robust system that stands as a testament to the untapped potential of comprehensive blockchain integration into industry practices.

5. Framework Development

In this chapter, an outline of the strategic approach for constructing a blockchain-based system is presented. This chapter methodically walks through each development phase, beginning with the planning and requirements determination, where both functional and non-functional aspects such as user interaction, system performance, scalability, and security are defined. It then progresses into the initial setup of the backend, highlighting the integration of key development tools and technologies, including React for frontend development and Express for the backend, along with the initiation of smart contracts developed in Solidity.

Further, the chapter delves into the subsequent phases of the development process, covering the deployment and testing of smart contracts on a test network, the crafting of the frontend interface, and the development of the backend. Each phase is explored in detail, emphasizing the critical aspects of project creation, management, and user interaction. The chapter concludes by synthesizing the entire developmental journey, underscoring the integration of various technologies and methodologies employed to create a cohesive, functional blockchain-based system tailored for the AEC sector.

5.1. Development Plan

This segment delineates the strategic development plan employed to establish a blockchain-based platform to advance data management within the AEC sector. The prototype is systematically structured into phased segments, each addressing critical developmental milestones from conceptualization to deployment.

Phase 1: Planning and Requirements

Functional and non-functional requirements were defined, underscoring user interactions, system performance, scalability, and security considerations. The selection of the technology stack was crucial, involving a deliberate choice of blockchain platforms, programming languages, and supporting libraries to ensure system robustness and compatibility.

Phase 2: Initial Backend Setup

In this phase, the development environment was established, equipped with integrated development environments (IDEs), version control, and essential development tools such as React for frontend development, and Express for backend. The initiation of smart contracts was developed in Solidity language with a particular focus on user interaction and project management logic.

Phase 3: Contract Deployment and Testing

Phase 3 involved deploying the smart contracts to a test network (testnet) and engaging in rigorous end-to-end testing. This phase was pivotal in validating the functionality of the system, ensuring seamless smart contract interactions and robust frontend-backend integration.

Phase 4: Frontend Development

This part of the development plan centered on establishing an intuitive user interface using React, a popular JavaScript library, and MetaMask for secure Ethereum transactions and authentication. API endpoints were developed to facilitate effective communication between the frontend and backend.

Phase 5: Backend Development

Phase 5 saw the integration of the decentralized storage system IPFS, along with web3.js, a collection of libraries enabling Ethereum functionalities, and the implementation of a role-based access control using NFTs to manage user permissions comprehensively. A secure database model was established using MongoDB Atlas, a fully managed cloud database.

Phase 6: User Interface Enhancement

The frontend underwent further refinement in this step, with a keen focus on user experience and design. Features enabling real-time updates were implemented to enhance user engagement with the system.

Phase 7: Result and Documentation

This last step involved testing a realistic scenario using the developed platform to illustrate and test the efficiency of the system, while compiling detailed documentation for presenting the results.

Technology Stack

The frontend and backend components were meticulously designed to provide a seamless user experience and robust system integrity. The front-end featured a React-based interface with MetaMask integration for signature verification and a query feature allowing designers to find specific versions of their design files. The backend was powered by Brownie for smart contract deployment and web3.js for interaction, with Express from Node.js facilitating communication (API endpoints) between the front and back ends.

The methodology followed a disciplined and iterative approach, integrating both secondary evidence from a comprehensive literature survey and primary evidence from real-world construction scenarios. This dual-source evidence model informed the design and implementation of a blockchain-based data provenance framework tailored for the AEC industry. The research aimed to establish a decentralized, scalable, and secure model for BIM data sharing, incentivizing stakeholder collaboration through transparent and immutable recording of data exchanges.

5.2. System Requirements

Embarking on the integration of blockchain within the AEC sector, the following elements which encapsulate the essence of the comparative analysis are required for converging key objectives, main components, and unique features to forge a comprehensive platform for project collaboration and data management.

User Authentication and Identity Management:

- Secure sign-up and login mechanism, essential for protecting user information and enforcing role-based access control.
- ERC-6551 token-based system for identity verification, ensuring that each user's interactions are authenticated and securely recorded.
- Integration with MongoDB for private storage of personal information associated with user identity tokens.

Project Creation and Management:

- Project Owners can deploy new instances of project contracts, specifying project details to initiate design competitions.
- A staking mechanism for Project Owners to secure rewards in Ether, promoting commitment and incentivizing participation.
- Functionality to assign designers and distribute ERC-6551 tokens, organizing the storage of design files.

Design Collaboration and Integration:

- A job board tailored to the Designer's qualifications, enabling them to find and engage with suitable projects.
- Features to support project entry, collaboration, and design submission, incorporating smart contract functions for a streamlined experience.
- Design folder tokens to serve as repositories for design files, fostering organized management and version control.

Transparency and Tracking:

- Real-time updates and notifications to facilitate collaboration and keep all stakeholders informed on project progress and design modifications.
- Transparent tracking of design versions and changes, utilizing smart contracts to log all modifications and ensure data provenance.

Ownership and Intellectual Property:

- Mechanisms for verifying designer qualifications and minting non-tradable tokens that represent their professional credentials.
- Secure management of design ownership, allowing for the minting and transfer of ERC-721 tokens that represent design submissions.

Project Evaluation and Reward System:

- Features for the Project Owner to select winning designs and manage the distribution of rewards. Note that the project owner also acts as project manager in this system.
- Royalty settings for winning designers to secure future compensation for their designs. The designers can from any disciplines like Architectural Design, Structural Design, Façade Design, and so on.

Marketplace and Trade Facilitation:

- A platform for designers to sell or trade their designs, providing an opportunity to monetize their efforts and creativity.
- Token-based mechanisms to facilitate the sale and purchase of designs, ensuring secure and transparent transactions.

Post-Project Management:

- Functionality to finalize all transactions and close the project, including the handover of design folders and reward distribution.

- Achievement tokens to recognize the participation and contributions of designers, enhancing their profile and reputation on the platform.

These system requirements are crafted to support the dynamic and collaborative nature of architectural projects in the AEC sector. They align with the main components and unique features detailed in the comparative analysis table, such as Ethereum and IPFS for data storage and smart contract deployment, as well as the innovative use of NFTs for ownership verification and project management efficiency. Together, these features can represent a possible solution that addresses the complex challenges of the AEC industry, facilitating enhanced transparency and accountability.

5.3. Smart Contract Development

The intricate architecture of the blockchain-based system designed for managing architectural projects, as well as the rationale and functionalities of key smart contracts, are explained comprehensively in this section. These smart contracts collectively form the backbone of the system, addressing project lifecycle management, design file tokenization, and efficient project initiation. In addition, this section covers how the smart contracts interlink to create a transparent, efficient, and cost-effective framework, ensuring integrity and streamlined operations in architectural project management. This part is essential for understanding the innovative application of blockchain technology in the AEC sector.

5.3.1. ERC-721

IdentityTokenDesigner.sol

This is an ERC721-compliant smart contract designed to represent and manage the identities of designers within a collaborative AEC project. It provides a blockchain-based mechanism to mint unique tokens that embody the roles and privileges of each designer, ensuring clear delineation of responsibilities and contributions. Upon creation, each token is associated with an IPFS hash that securely stores the metadata pertinent to the designer's identity and work. The contract incorporates functionalities to prevent the same entity from owning multiple tokens, thereby enforcing singular identity representation. It also includes provisions to update metadata, handle the transfer of ownership, and tag potentially malicious activities. Finally, this smart contract can be paused for emergency stops, thus enhancing the security and governance of the digital identity within the project ecosystem.

IdentityTokenOwner.sol

This contract is created under the ERC721 standard to encapsulate the identity of project owners within the AEC sector. This contract mirrors `IdentityTokenDesigner.sol` in functionality, with a focus on ownership rights, offering a similar structure to support seamless, secure ownership transfer and metadata management within the project ecosystem. Tagging malicious activities and pausing contract functionalities also present in this contract.

5.3.2. ERC-6551

TBARegistry.sol

This smart contract serves as a pivotal component in the elevation of ERC721 tokens to the enhanced ERC6551 standard. It operates by binding Token Bound Accounts (TBAs) to ERC721 tokens minted from any contract. This contract utilizes the Ethereum `Create2` feature for deterministic address generation, ensuring that each TBA is uniquely and securely tied to its respective token. As the registry overseeing these associations, `TBARegistry.sol` is critical for the upgrade process, providing the necessary infrastructure to track and manage the linkage between ERC721 tokens and their expanded ERC6551 functionalities, thereby enabling a more dynamic and versatile token within the blockchain ecosystem.

IdentityTokenDesignTBA.sol

This contract serves as the TBA for tokens minted through `IdentityTokenDesigner.sol`. It is an advanced representation of a designer's identity within the blockchain, extending the functionality of a standard ERC721 token through a set of specialized functions that facilitate interaction with the broader system architecture. This contract employs functions like `callStakeDesign` or `callUnstakeDesign` to allow designers to engage with the project management aspects of the platform, such as staking their designs for review or unstaking them. Other project-related specific functions include creating design file tokens, setting royalty information, and managing token approvals. These aspects will be covered more specifically later in this chapter.

Uniquely, the contract is equipped with mechanisms for executing generic calls which allows the designers' tokens to interact with any contract, thus enhancing the operational flexibility. It also handles Ether transfers and the safe transfer of ERC721 and ERC1155 tokens, ensuring its ability to securely receive or transfer different types of tokens. The contract's ability to receive and execute transactions makes it a critical node for operational workflows within the system, embodying the ERC6551 standard's capacity for enriched interaction patterns in the AEC industry.

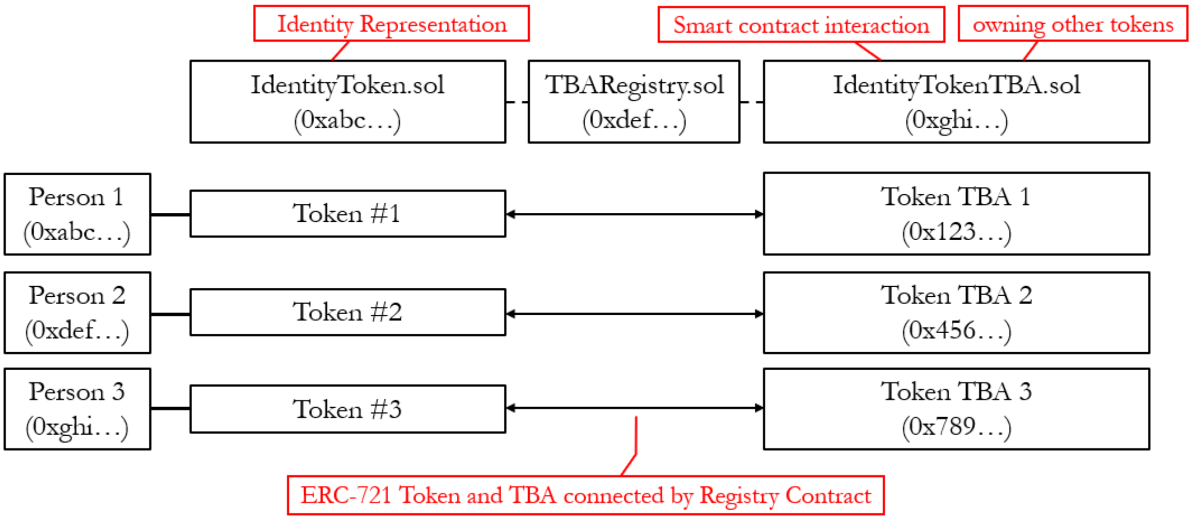


Figure 12 – Diagram explaining the relationship between Identity Token and its associated TBA

IdentityTokenOwnerTBA.sol

Paralleling `IdentityTokenDesignerTBA.sol`, this contract is a more streamlined and generic TBA custom-made for upgrading `IdentityTokenOwner.sol` to ERC6551. This contract focuses on fundamental TBA functionalities, such as executing calls, handling Ether transfers, and managing ERC721 and ERC1155 tokens. It facilitates essential interactions like receiving, transferring, and validating signatures for tokens, serving as a versatile and essential component in the blockchain-based system for managing and verifying ownership within the AEC project environment.

5.3.3. ERC-4671

Certificate.sol

Adopting to the ERC4671 standard, this contract is designed for on-chain certification management. ERC4671 standard can issue Non-Tradable Tokens (NTTs) as digital certificates, validating the professional qualifications and eligibility of designers. These NTTs, being non-transferable, ensure the certification remains exclusively with the original recipient.

Each discipline within the AEC sector is represented by its unique `Certificate.sol` contract, named aptly to reflect the specific field it certifies, like "Structural Designer" or "Interior Designer." This structured approach allows for a clear and organized certification process within the blockchain framework. The immutable nature of blockchain technology means these digital certificates offer a reliable, secure record of a designer's professional credentials.

To acquire a certificate, designers must submit their real-world credentials, such as a professional design license, for system administrators to review. Approved applicants receive a unique token linked to an IPFS hash with their certification details, digitizing their professional accreditation (figure 13).

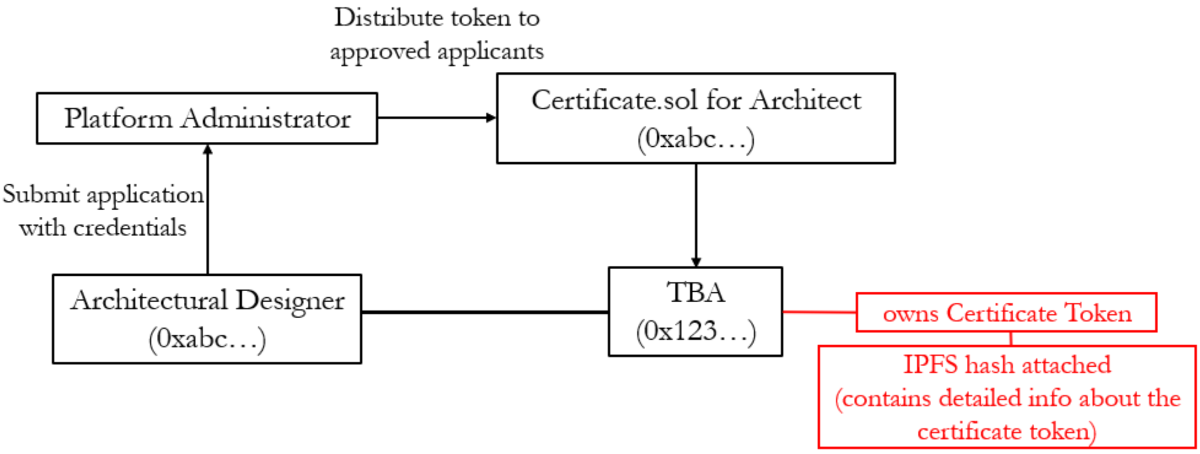


Figure 13 – Diagram explaining the workflow of Certificate Token Application

Crucially, possession of this digital certificate is a prerequisite for participating in projects on the platform. Designers without this certification cannot join or contribute to projects, ensuring that only qualified professionals engage in the collaborative process. This requirement reinforces the system's credibility and upholds the professional integrity of the AEC industry's workforce.

Furthermore, the contract is equipped with functionalities to revoke or remove certificates, addressing certification expiration or fraudulent activities. This dynamic feature ensures the system remains current, accurate, and reflective of actual professional qualifications.

`Certificate.sol` creates a transparent framework for certifying AEC professionals. It not only streamlines the verification process but also embeds trust and authenticity in the digital representation of professional qualifications, enhancing the integrity and efficiency of collaboration within architectural and design projects.

Achievement.sol

Also based on the ERC4671 standard, this contract functions as a dynamic tool for recognizing and representing the achievements or reputations of designers. This contract allows for the issuance of unique tokens as digital badges, symbolizing either commendations or demerits in a designer's professional journey. Similar to `Certificate.sol`, `Achievement.sol` has a designated name and symbol set in its constructor, intuitively reflecting the nature of the achievement or reputation it represents, whether positive or negative.

The contract enables platform owners to reward designers with tokens for their accomplishments or, conversely, mark tokens for undesirable behaviour or performance. These tokens are linked to a base URI for metadata storage, providing detailed contextual information about the achievement or reputation they represent. The contract includes functions for revoking or removing tokens, allowing for flexibility in managing the dynamic professional profiles of designers. In essence, `Achievement.sol` offers a versatile and transparent way to acknowledge the diverse spectrum of professional conduct and accomplishments in the AEC industry, enhancing the system's capacity to incentivize excellence and manage reputation.

5.3.4. Design Folder

DesignFolderMaster.sol

This contract is uniquely designed to represent design folders. Functioning as an ERC721 token, the clone of this contract is deployed for each new project, creating a distinct connection between the project and the design files generated by designers. The project owner, upon initiating a project, deploys this contract and mints design folder tokens, which are then distributed to the participating designers.

Each designer is assigned a unique design folder token, encapsulating the designs they produce during the project. This systematized approach ensures that every design element is securely stored and efficiently managed within its respective folder. Additionally, the contract incorporates functionalities to set and manage royalties, providing a financial incentive and recognition for the designers' contributions.

TBAs will be linked to the tokens minted from this contract, enhancing the basic ERC721 token to the more dynamic ERC6551 standard. This upgrade enables the design folders to hold other tokens, further extending their utility in the project ecosystem. Through `DesignFolderMaster.sol`, the platform establishes a structured, secure, and incentivized environment for managing design contributions in construction projects.

DesignFolderTBA.sol

The `DesignFolderTBA.sol` contract is a streamlined TBA specifically designed to function as a digital folder. Its primary role is to hold, transfer, and receive tokens, embodying the essence of a design folder in the blockchain context. Lacking complex functionalities, it straightforwardly serves its purpose, ensuring secure and efficient management of tokens.

Rationale

The rationale behind the creation and use of the Design Folder Token, adhering to the ERC6551 standard, is deeply rooted in the necessity for efficient management and transfer of design assets in complex architectural projects. In the dynamic realm of architectural design, particularly for intricate projects, designers inevitably generate a multitude of design files. These files, tokenized as individual ERC721 tokens (explained in the following section), can rapidly accumulate, posing a significant challenge in terms of management and organization. The Design Folder Token concept addresses this issue by grouping these myriad design files into a single, manageable folder. This aggregation not only simplifies the handling of design assets but also streamlines the project management process.

Moreover, designers often engage in multiple projects concurrently, each yielding distinct design files associated with different projects. The segregation and association of these files with their respective projects can become increasingly cumbersome. The Design Folder Token serves as a solution, providing a clear and organized structure where designs from each project are neatly compartmentalized, thus enhancing the clarity and ease of management across various projects.

A critical aspect of using Design Folder Tokens lies in their efficiency, especially in terms of transaction costs. In a scenario where a designer wishes to sell their designs, transferring numerous individual design file tokens could incur substantial gas fees. However, by consolidating these files within a Design Folder Token, only a single transfer is required, significantly reducing gas costs. This approach not only ensures gas efficiency but also maintains the integrity of the design process by transferring the ownership of all design iterations and files to the buyer. This comprehensive transfer prevents designers from reusing preliminary designs for different clients, thereby safeguarding the uniqueness and exclusivity of the design solutions provided.

Lastly, the Design Folder Token allows designers to set royalties. This feature ensures that designers continue to receive compensation for their intellectual property, should the buyer choose to reuse or resell the design. This approach strikes a balance between rewarding the original creators and providing buyers with full ownership and usage rights of the acquired designs. In short, the Design Folder Token embodies a thoughtful, efficient, and equitable solution for managing and transferring design assets in the AEC industry.

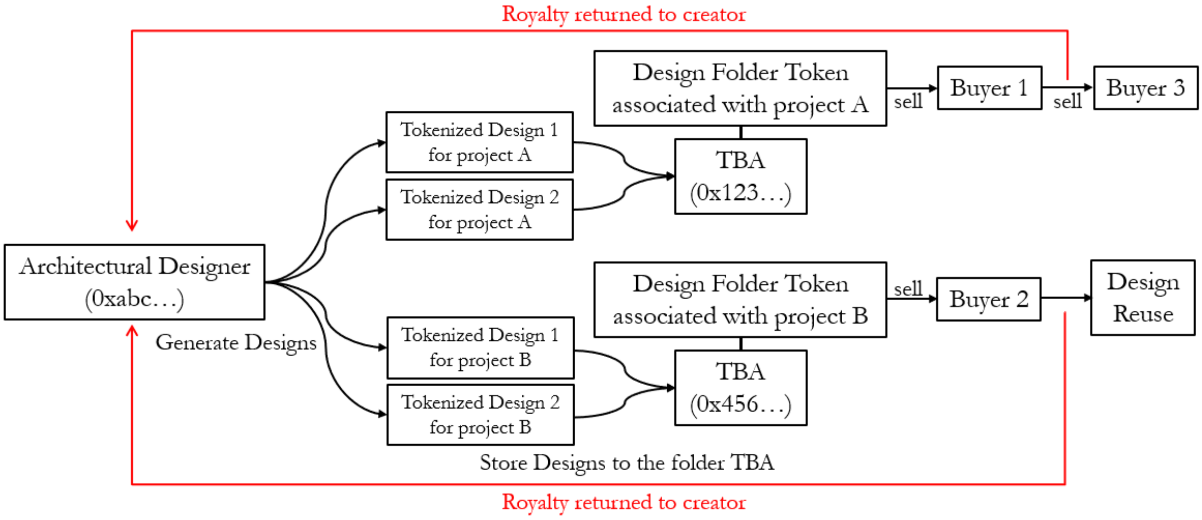


Figure 14 – Diagram explaining the workflow of design folder

5.3.5. Design File Tracker

DesignFileTrackerMaster.sol

This contract plays a pivotal role in the management of design files within architectural projects. As an ERC721 token, this contract is used for tracking and organizing individual design files produced during a project.

The essence of this contract lies in its ability to tokenize each design file, thereby assigning a unique identity to every file through a corresponding ERC721 token. This tokenization links each design file to a specific IPFS hash, which stores the file's metadata securely and decentralizedly. This method ensures that each design file is not only distinct and identifiable but also easily accessible and traceable within the blockchain network.

A notable feature of this contract is its selectivity in minting privileges. Only approved addresses, as defined within the contract, are authorized to create new design file tokens. This selective approach maintains a controlled environment, ensuring that only legitimate and relevant entities can contribute design files to the project.

Integration with the `DesignFolderMaster.sol` contract is a key aspect of `DesignFileTrackerMaster.sol`. This integration allows for the close association of design file tokens with their respective design folders, thereby enhancing organizational efficiency. Each design file token is minted to a specific folder, ensuring clear and concise management of files within each project.

Rationale

The adoption of the `DesignFileTrackerMaster.sol` contract within the architectural project management system is driven by a strategic need for efficient, transparent, and secure management of design files. This contract is central to the process of tokenizing design files, a method that enhances both the integrity and traceability of each file within the broader context of architectural projects.

At the core of this system is the process where designers upload their design files to IPFS, receiving a unique IPFS hash in return. This hash, indicative of the design file, forms part of a comprehensive metadata structure that includes details like file name, size, type, version, description, creator's address, timestamp, and the file's IPFS hash. The metadata itself is then uploaded to IPFS, generating another distinct hash that is used to mint a token via the `DesignFileTrackerMaster.sol` contract. This method effectively links the design file's detailed metadata to a blockchain token, achieving an immutable record on the blockchain. Such tokenization not only facilitates the tracking of file versions and data provenance but also clearly delineates the ownership and creatorship of the design files.

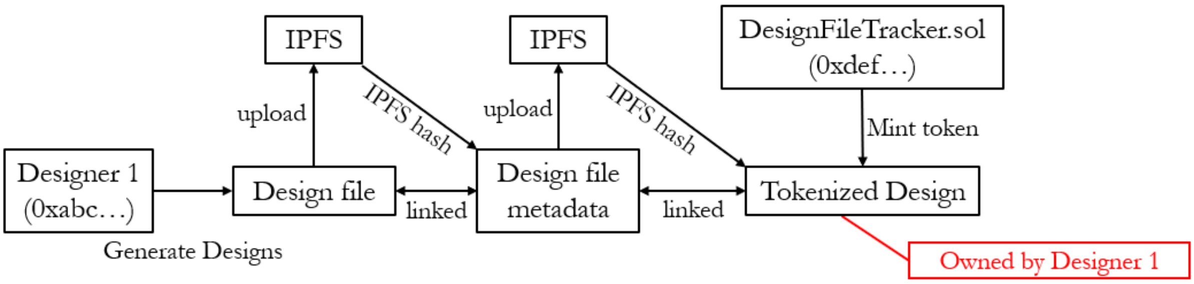


Figure 15 – Diagram explaining the workflow of tokenizing design files

Similar to `DesignFolderMaster.sol`, for every new project, a clone of the `DesignFileTrackerMaster.sol` contract is deployed, linked exclusively to that project. This approach ensures that design file tokens are project-specific and that only designers possessing corresponding design folders can tokenize their designs for that particular project. This selective minting process, where the minted tokens are automatically sent to the designer's folder, reinforces the clarity and organization within the project's design file management.

The system's architecture, where design file tokens are transferred by moving the entire design folder, addresses potential ambiguities in ownership rights. It ensures that purchasing the final design implicitly includes ownership of all underlying preliminary designs, avoiding any overlap or reuse issues. In essence, the `DesignFileTrackerMaster.sol` contract underpins a system that is not only efficient and streamlined but also one that upholds the principles of ownership integrity and creative authenticity in the architectural design process.

5.3.6. Project Manager

The `ProjectManagerMaster.sol` contract is a comprehensive and the most critical component in the architectural project management system. It is the operational backbone of the system, streamlining the workflow, ensuring accountability, and maintaining a high standard of transparency and immutability throughout the project's duration. This contract coordinates the entire lifecycle of a project, from initiation to completion, ensuring efficient collaboration among designers, clear delineation of roles, and transparent management of rewards and design ownership. All the key functions in the smart contract are explained in detail below:

1. initialize – Sets up the contract with essential project information like name, IPFS hash that is linked to the project details stored on the IPFS, required disciplines, rewards to the designers, and the address of the contract owner. It ensures all foundational elements of the project are defined from the outset.
2. stakeRewards – Allows the project owner to stake the required rewards for the project. This function secures the funds necessary to incentivize designers and marks the readiness of the project to commence.
3. unstakeRewards – Enables the project owner to withdraw the staked rewards, applicable only before the project's initiation. This function provides flexibility in funds management before the project kicks off.
4. assignDesigners – Assigns designers to the project based on their disciplines by storing the designers' address to the smart contract. It checks each designer's credentials against the required certificates, ensuring that the assigned individuals are qualified for participating the project.
5. initiateProject – Marks the official start of the project. This function is called once all rewards are staked and designers are assigned, setting the project in motion. Once a project is initiated, the staked rewards can no longer be unstaked by the project owner.
6. distributeDesignFolders – Triggers the deployment of a clone of `DesignFolderMaster.sol` contract, and distributes design folder tokens to assigned designers from step 4. It links each designer to a unique folder to help them organize the design files more efficiently. The newly deployed Design Folder smart contract is linked to this Project Manager contract.
7. deployDesignFileTracker – Deploys a clone of the `DesignFileTrackerMaster.sol` contract, linking it to this Project Manager contract. This step is crucial for allowing the designers to track and manage design files associated with the project.
8. selectWinner – Selects winners for the project from the pool of assigned designers. This function is key in determining who will receive the rewards based on the design they made for the project.

9. stakeDesign – Enables winners to stake their design folders (which contain all the tokenized design files), indicating their completion of the project's deliverables. It's a critical step in the handover process of designs to the project owner.
10. unstakeDesign – Allows winners to unstake their designs, usually before the handover to the project owner. This function provides flexibility in managing design assets.
11. approveRoyalty – Authorizes the royalties the winners set on the design folders they staked. This function is a significant aspect of the project, ensuring fair compensation for the designers' intellectual contributions.
12. designHandover – Facilitates the transfer of design ownership from the winners to the project owner, and transfer of the rewards to the winners. This function is the final step in the project lifecycle, marking the completion of the design phase. After design handover, this project manager contract will be renounced, meaning that no one holds control over this contract anymore, preventing any possible malicious activity in the future.
13. updateProjectIPFS – Allows the administrator to update the project's IPFS hash, ensuring the project information remains current and accurate. This operation can merely be executed by the administrator to avoid the project owner to tamper the project information.
14. retrieveStake – Permits the administrator to retrieve the staked rewards, typically used for retrieving funds from the smart contract in case of unexpected events post-project initiation.

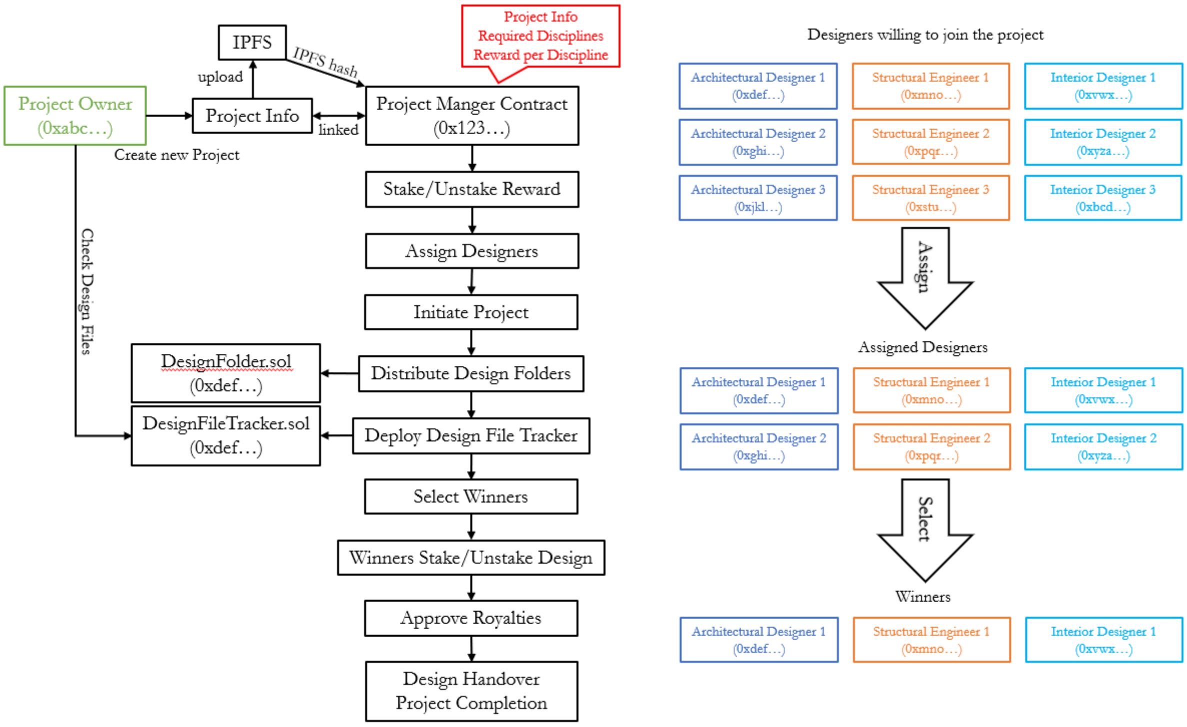


Figure 16 – Diagram explaining the workflow of the project implementing the smart contract

Rationale

The `ProjectManagerMaster.sol` contract embodies a radical approach to managing architectural projects, addressing key challenges in the industry through blockchain technology. Its creation is driven by the need for transparency, immutability, and efficiency in project management, particularly in the AEC sector. Some of the important points are summarised in the followings:

- Centralization of Project Data – Each new project initiates the deployment of a clone of a unique `ProjectManagerMaster.sol` contract on the blockchain. This contract becomes a central repository for all critical project information, including project details (in the form of IPFS hash), required disciplines, designer assignments, and winner selection. Storing this data on the blockchain ensures that all information is tamper-proof, transparent, and perpetually accessible. This feature is particularly crucial for post-project reviews or dispute resolutions, offering an immutable record of the project's history and decisions.
- Comprehensive Project Lifecycle Management – The contract is designed to encapsulate the entire lifecycle of an architectural project. From initial designer selection to final design handover, it mirrors real-world project workflows, offering a foundational framework adaptable to the complex nuances of actual projects. This adaptability ensures that while the contract serves as a core structure, it can be tailored or updated to suit specific project requirements.
- Stake Mechanism for Fairness and Accountability – A distinctive aspect of this contract is its stake mechanism, which requires project owners to stake rewards prior to project initiation and designers to stake their designs before handover. This approach addresses common industry issues like late payments and ensures commitment from all parties, leading to smoother project execution.
- Automated Workflow and Stepwise Execution – The contract ingeniously uses smart contract features to automate and streamline project management. Each phase of the project, from initiation to completion, is sequentially structured, preventing any critical step from being overlooked. For instance, the project cannot be initiated until the rewards are staked, ensuring financial commitment upfront. This systematic approach eliminates manual oversight, enhances efficiency, and ensures that each project phase is completed before moving on to the next.

To summarise, the `ProjectManagerMaster.sol` contract is a strategic solution tailored to the AEC sector's needs. It leverages blockchain technology to bring transparency, efficiency, and security to project management, setting a new standard for managing complex architectural projects. This contract redefines how architectural projects are managed, ensuring integrity and fairness throughout the project lifecycle.

5.3.7. Clone Factory

CloneFactory.sol

This contract serves as an efficient tool for creating clones of the `DesignFolderMaster.sol` and `DesignFileTrackerMaster.sol` contracts. Utilizing OpenZeppelin's `Clones` library, it facilitates cost-effective deployment of these contracts for new projects. Upon invocation, it generates a clone of the designated master contract, initializes it with project-specific parameters, and then emits an event to signal the creation. This streamlined cloning process simplifies the setup of the essential components for managing design folders and file tracking in architectural projects.

ManagerCloneFactory.sol

In a similar manner, this contract is a streamlined solution for generating clones of the `ProjectManagerMaster.sol` contract. It also leverages the OpenZeppelin `Clones` library to create new instances of the `ProjectManagerMaster.sol` contract efficiently. This process is vital for each new architectural project, enabling the customization of project parameters such as name, IPFS hash, required disciplines, certificate addresses, and rewards. The cloning mechanism ensures a cost-effective deployment of project-specific management infrastructure, vital for the smooth operation and organization of architectural projects.

Rationale

The utilization of `CloneFactory` and `ManagerCloneFactory` in the architectural project management system represents a strategic approach to optimizing gas efficiency on the Ethereum blockchain. The essence of these factories lies in their ability to significantly reduce the costs associated with deploying new smart contracts. In an environment like Ethereum, where deploying a new contract can be prohibitively expensive, cloning an existing contract like `DesignFolderMaster.sol`, `DesignFileTrackerMaster.sol`, or `ProjectManagerMaster.sol` offers a cost-effective alternative. This method not only ensures economic viability due to lower gas expenses but also facilitates rapid and consistent deployment of project-specific management infrastructures. The standardized nature of cloned contracts guarantees uniformity and reliability across various projects, contributing to the system's overall efficiency. Please refer to “system evaluation” section for more detailed gas estimations.

5.4. Frontend Development

The frontend development section of this project particularly focuses on creating a user-friendly and intuitive interface, catering to both seasoned users and those new to web3 applications. Utilizing React, a powerful JavaScript library, the frontend design emphasizes dynamic interaction and seamless user experience. The integration of MetaMask, a popular blockchain wallet, plays a pivotal role in facilitating secure and straightforward interactions with Ethereum-based smart contracts. Combined with Web3.js, these tools enable efficient transaction processing and identity verification, crucial for role-based access within the system. This section details the rationale and implementation strategies behind these technologies, underscoring their importance in making blockchain applications accessible and user-friendly.

React

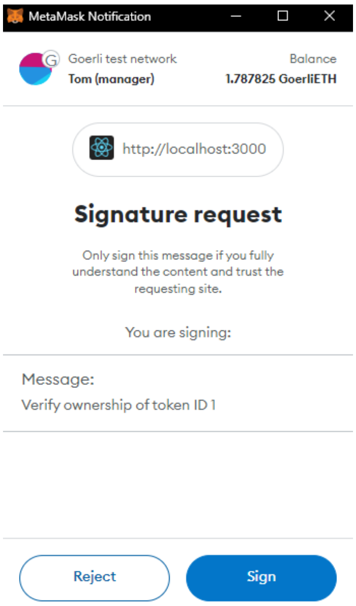
React is chosen as the main tool for frontend Development. React is a popular JavaScript library for building user interfaces, particularly known for its efficient rendering and responsive design capabilities. It enables the creation of dynamic and interactive web pages with reusable components. React's component-based architecture streamlines the development process, making it an excellent choice for developing sophisticated and scalable frontend applications with enhanced user experience and maintainability.

MetaMask

The integration of MetaMask into the frontend of the blockchain-based architectural project management system plays a crucial role in facilitating user interaction with the smart contracts. MetaMask, a widely adopted cryptocurrency wallet and gateway to blockchain apps, is renowned for its user-friendly interface, making it an ideal choice for the system. Its widespread use ensures accessibility and familiarity for many users, thereby streamlining their experience in engaging with the platform.

MetaMask acts as an intermediary between the users and the smart contracts. When users wish to access specific functionalities of the smart contracts – be it creating new projects or tokenizing design files – MetaMask seamlessly facilitates these interactions. Users can initiate operations directly from the webpage's interface, with MetaMask handling the blockchain interactions in the background.

A key feature of MetaMask in this system is its use for identity verification through digital signatures. Users are required to possess corresponding identity tokens when logging in. MetaMask is employed to sign messages, proving the ownership of these tokens. This mechanism is essential for various activities, including user login, project creation, and designer participation in projects. By signing a message in MetaMask, users verify their token ownership, ensuring that only authorized individuals can perform specific actions within the system. This approach not only enhances security but also embeds a layer of identity verification and role-based access control, critical for the smooth functioning of the project management platform.



Goerli test network
Tom (manager)
Balance
1.787825 GoerliETH

http://localhost:3000

Signature request

Only sign this message if you fully understand the content and trust the requesting site.

You are signing:

Message:
Verify ownership of token ID 1

Figure 17 – MetaMask asking for token ownership verification

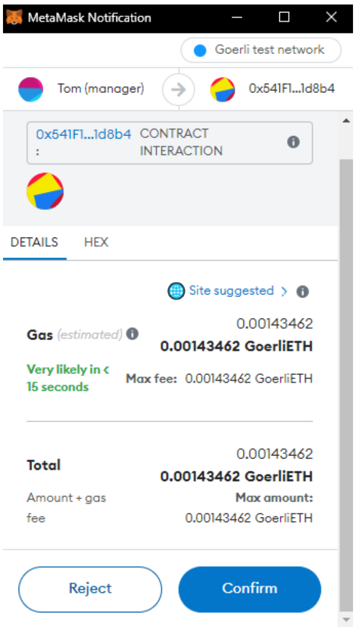
Web3.js

Web3.js is a collection of JavaScript libraries that enable a web application to interact with the Ethereum blockchain. It acts as a bridge between the Ethereum network and a web interface, allowing for seamless communication and transaction execution. Web3.js provides the necessary tools to connect, make calls to smart contracts, and listen for events on the Ethereum blockchain.

In the project management system, web3.js is integrated alongside MetaMask to facilitate interactions with the smart contracts. When a user performs an action that requires blockchain interaction, such as creating a new project, MetaMask is triggered to handle the authentication and transaction signing. Concurrently, web3.js is employed to formulate the blockchain transaction. It prepares the necessary data, encodes it for the Ethereum network, and sends it through MetaMask.

MetaMask, upon receiving the transaction request from web3.js, prompts the user to review and approve it. This process includes verifying transaction details such as the gas price, gas limit, and any Ether to be transferred (Figure 18). After the user's approval, MetaMask broadcasts the transaction to the Ethereum network.

Web3.js also monitors the transaction status and listens for confirmations or rejections from the network. This feedback is crucial for updating the user interface and reflecting the changes or results of the transaction in the system.



Goerli test network
Tom (manager)
0x541F1...1d8b4

0x541F1...1d8b4 : CONTRACT INTERACTION

Gas (estimated) 0.00143462
0.00143462 GoerliETH
Very likely in < 15 seconds
Max fee: 0.00143462 GoerliETH

Total 0.00143462
0.00143462 GoerliETH
Amount + gas fee
Max amount: 0.00143462 GoerliETH

Figure 18 – Use of MetaMask and Web3.js for contract interaction

By leveraging web3.js with MetaMask, the system ensures a secure and efficient way for users to interact with the smart contracts. This integration allows for the execution of complex blockchain operations through a user-friendly web interface, making the platform accessible even to those with limited blockchain experience.

5.5. Backend Development

Solidity

Solidity is chosen for writing various types of smart contracts explained in the previous section. It is a statically-typed programming language designed for developing smart contracts that run on the Ethereum Virtual Machine (EVM). It's the primary language for writing Ethereum smart contracts and is influenced by C++, Python, and JavaScript. Solidity enables the creation of complex contractual agreements and automated transactions directly on the blockchain. Its syntax is familiar to those with experience in modern programming languages, making it a logical choice for developing secure and efficient smart contracts integral to blockchain-based applications, such as the project management system in this project.

Goerli Testnet

The testing of smart contracts was performed on Goerli Testnet. The Goerli Testnet is a public Ethereum test network, designed to simulate the Ethereum Mainnet. It offers a sandbox environment for developers to test and debug smart contracts without incurring the costs associated with the main blockchain. Using Goerli provides a practical and risk-free platform to validate the functionality and performance of smart contracts under real-world conditions. This approach is crucial for ensuring that contracts work as intended before deploying them on the Ethereum Mainnet, thereby minimizing potential errors and optimizing resource usage.

Brownie

Brownie, a Python-based framework, was crucial for testing and deploying the smart contracts in this project. Known for its user-friendly approach to Ethereum contract development, Brownie enabled effective testing, ensuring that smart contracts functioned correctly and securely. Its integration with the Ethereum network, particularly the Goerli Testnet, allowed for real-world deployment scenarios without incurring mainnet costs. This testing environment was vital for verifying the contracts' behavior in realistic conditions. Brownie's streamlined process for deploying to the Ethereum blockchain was instrumental in smoothly transitioning the project from development to a testnet deployment.

Pinata

Pinata is a service that offers easy and reliable access to the InterPlanetary File System (IPFS). Pinata enhances IPFS by providing additional features like persistent file storage and content management tools. Its use in the project ensures secure, efficient, and permanent storage of design files and metadata. Pinata's integration facilitates decentralized data handling, ensuring that files remain accessible and immutable, crucial for maintaining the integrity of project-related documents and designs. For this platform, Pinata was used for storage of project-related information and design files generated by the designers.

MongoDB Atlas

MongoDB Atlas is a fully-managed cloud database service that offers MongoDB, a popular NoSQL database, hosted in the cloud. It provides a flexible and scalable database solution, ideal for handling large volumes of data with diverse structures. For this project, MongoDB Atlas was chosen to store confidential information like user details, which are not suitable for public storage on IPFS due to its transparent nature. MongoDB Atlas ensures secure, private, and efficient management of sensitive data, complementing the decentralized storage of IPFS by providing a robust solution for handling private information essential for user management and authentication.

Express

Express is a minimal and flexible Node.js web application framework, renowned for its simplicity and speed in developing robust APIs. It is an ideal choice for setting up server-side functionalities and creating RESTful API endpoints, which are crucial for handling requests and responses between the frontend and backend. In this project, Express was employed to develop several key API endpoints:

- Storing Confidential User Info – This endpoint securely stores user information in MongoDB Atlas. It handles the reception and safekeeping of sensitive data like user credentials or personal details, ensuring privacy and security.
- Retrieving User Info – Complementary to the first, this endpoint facilitates the retrieval of stored user information from MongoDB Atlas. It's essential for functions like user verification or profile management, allowing for secure access to user data when required.
- Uploading Files to Pinata – This endpoint manages the upload of files to Pinata. It streamlines the process of storing files on the decentralized IPFS network, ensuring their persistent availability and accessibility.
- Retrieving/Downloading Files from Pinata – This endpoint is designed to fetch information or download files stored on Pinata IPFS. It provides a means to access and retrieve the decentralized data as needed.
- Receiving and Verifying Signatures – This critical security endpoint receives digital signatures generated by MetaMask from the frontend and verifies their authenticity. This verification process is crucial for confirming user identity and ensuring that actions, like contract interactions or transactions, are executed by legitimate, authorized users.

Together, these Express endpoints form the backbone of the server-side logic, bridging the frontend's user interface with the backend's data storage and blockchain functionalities, enhancing the system's overall efficiency and security.

6. Scenario: MEGA as a Case Study

This chapter delves into the application of the blockchain-based architectural project management system, utilizing the "MEGA" project at TU Delft Faculty of Architecture as a reference model. It presents an exploration of the adapted scenario, focusing on a competition between two groups. The chapter outlines the roles and responsibilities of the project owner in this setup, emphasizing their involvement in project initiation, designer selection, and final decision-making. This scenario serves as a backdrop to demonstrate the system's capabilities in enhancing transparency, managing data provenance, defining design data ownership, and improving overall project management efficiency.

The second part of the chapter outlines the workflows for both project owners and designers within the system. It provides a step-by-step guide for project owners, from registration to project closure, highlighting key processes like staking rewards and managing design submissions. The designer's workflow covers aspects from sign-up and certification to design submission and potential marketplace opportunities. This breakdown of workflows underscores the system's functionality in fostering collaboration, maintaining accountability, and streamlining project management. Accompanied by an illustrative diagram, the chapter offers a visual understanding of the system's operation and the interconnected roles of different stakeholders.

6.1. Scenario

“MEGA”, a project at TU Delft Faculty of Architecture, emphasizes multidisciplinary collaboration among students to deliver integrated building designs. This project enforces a collaborative among specialists, where students work in multidisciplinary teams to deliver an integrated design of a complex building (mostly a multifunctional high-rise building). The submitted designs from various teams undergo an extensive evaluation by industry professionals, who assess and determine the best design among the numerous submissions. MEGA, adapted for this evaluation, offers an ideal scenario to showcase the capabilities of the blockchain-based architectural project management system.

While MEGA involves more disciplines, this scenario focuses on a competition among two groups, each comprising an architectural designer, a structural designer, and a façade designer (3 disciplines). A project owner initiates this competition, seeking innovative designs for a complex building. In the adapted scenario, the project owner is responsible for setting up the project on the platform, defining requirements and rewards, and ultimately selecting the winning design from the submissions of the two groups. Each team, working independently, tackles the design challenge, with members contributing their expertise in their respective fields.

This scenario, though a simplified version of the actual "MEGA" project, effectively mirrors the collaborative aspects of architectural projects. It provides a practical context to demonstrate how the blockchain system can address common issues in such environments. These include enhancing transparency in design updates, clarifying design data ownership through Non-Fungible Tokens (NFTs), and improving project management efficiency with smart contracts.

The scenario explores various situations reflecting real-life challenges the author encountered during the MEGA project. These situations are summarized and explained in the following parts. The blockchain-based system's capability to manage the complexities inherent in collaborative AEC projects is also illustrated.

6.1.1. Lack of Transparency

In integrated design projects, a common challenge is the lack of transparency, which often leads to significant coordination issues among different disciplines. Human errors, such as failing to update design changes or miscommunications, exacerbate these transparency issues. This lack of clear and accessible information can severely hinder effective collaboration, resulting in inconsistencies and contradictions in the integrated design.

For example, consider a scenario in a complex construction project where an architect makes critical alterations to the building's facade design due to aesthetic or functional improvements. However, these changes are not transparently communicated to the structural engineering team. As a result, the structural engineers, working with the initial design specifications, continue to develop structural plans that are no longer compatible with the revised architectural design. This oversight leads to significant discrepancies between the architectural vision and the structural feasibility. The issue, once identified, results in substantial redesign efforts, project delays, and financial overruns, underscoring the critical need for a transparent, real-time sharing of design updates among all stakeholders in the project.

Blockchain technology can mitigate such issues by enforcing enhanced transparency. With a blockchain-based system, every time a discipline modifies their design, it's updated on the blockchain, making it immediately visible to all involved parties. This ensures that all disciplines are continuously informed of the latest design changes, promoting more synchronized and cohesive project development.

6.1.2. Data Provenance and Responsibility

In a collaborative environment, the absence of a robust system to track design versions and changes can lead to disputes and errors cascading across disciplines. Continuing with the example mentioned in the previous section, let's consider a situation where a design error occurs. Initially, the architect updates their design but doesn't effectively communicate this change to the structural engineer. Later, it becomes evident that this oversight led to a misalignment between the architectural and structural plans. When questioned, the architect might be tempted to obscure their mistake, perhaps by not acknowledging the change or shifting blame to others.

Blockchain technology can effectively address this issue. Each design update, including the architect's revision, is logged on the blockchain with a timestamp and the identity of the contributor. This transparent record-keeping makes it clear who made specific changes and when. So, in this scenario, the blockchain ledger would show the exact moment the architect made their alteration. This level of accountability, provided by the blockchain's data provenance feature, ensures that the origin of errors is easily traceable and responsibility is clearly assigned. This not only fosters a culture of transparency and accountability but also helps in quickly pinpointing and rectifying design errors, thus mitigating time and cost overruns that such errors might cause.

6.1.3. Design Data Ownership

Properly defining and transferring ownership of design data, from creation by individual designers to the eventual handover to the project owner, is crucial yet often inadequately addressed. A practical example of this is when a project transitions from the design phase to construction and the designs need to be handed over to the project owner. The ambiguity often arises around who owns the designs post-handover: the designers who created them or the project owner who commissioned and paid for them.

For instance, an architect might design a unique façade for a building. Once the design phase is complete and the design is approved by the project manager, it's handed over to the project owner. However, questions might arise about whether the architect still holds any rights to that design. Can they reuse or resell elements of that design for other projects, or does handing over the design to the project owner transfer all ownership rights?

Blockchain technology, particularly the use of NFTs for representing ownership, can clarify this situation. When a design is completed and approved, it can be tokenized as an NFT. This NFT serves as a digital certificate of ownership. Once the design is handed over to the project owner, the NFT is transferred to them, clearly indicating the transfer of all ownership rights. This transfer is recorded immutably on the blockchain, leaving no room for ambiguity. The project owner, now holding the NFT, has full rights over the design, including the right to use, modify, or even resell it. Conversely, the designer, upon transferring the NFT, relinquishes these rights, ensuring they cannot legitimately reuse or resell the design elements, as it would infringe upon the rights of the new owner.

A vital aspect of this process is the ability for designers to set royalties on their designs. As part of the NFT creation, designers can specify royalty terms, ensuring they receive a portion of the profits if their design is reused or resold. This mechanism provides a fair compensation model, recognizing the designers' efforts and creativity even after the primary transaction. It ensures that while the project owner has full rights to the design, the original creator continues to benefit from their creation, especially if it gains further commercial value. Thus, blockchain and NFTs not only bring transparency and enforceability to design data ownership in the AEC sector but also establish a fair and equitable framework for intellectual property rights and compensation.

6.1.4. Project Management Efficiency

The transition to blockchain-based project management introduces complexities, particularly for those new to this technology. The task of tracking diverse design information and coordinating between disciplines on a blockchain platform can be daunting. This complexity is compounded by the need to maintain real-time updates and ensure seamless collaboration. Traditional management approaches falter in this new environment, struggling to adapt to the dynamic nature of blockchain-enabled project development.

Blockchain technology introduces a feasible solution with smart contracts. These self-executing contracts automatically record every transaction and interaction, bringing structure and clarity to project management. For instance, when an architect updates a design, it's immediately logged on the blockchain, ensuring all stakeholders are up to date. This real-time tracking enhances synchronization across disciplines, leading to more efficient project development.

Smart contracts in blockchain also streamline the ownership transfer of design data. As projects move from design to construction, these contracts automate the handover of rights from designers to project owners. The use of NFTs for tokenizing designs clarifies ownership post-handover, with smart contracts recording this transfer immutably. This clarity, combined with the ability for designers to set royalties on their work, ensures fair compensation and simplifies what was traditionally a complex process.

6.2. Project Owner Workflow

The workflow for a project owner in the blockchain-based architectural project management system is meticulously designed to guide them through each stage of a project. It begins with the crucial step of registration and identity token minting, followed by a series of structured phases that ensure seamless project execution and management. A step-to-step demonstration is presented below:

1. **Sign-up** – The first step involves the project owner registering on the platform and minting their identity token. This process requires providing personal information, which is stored privately in MongoDB. The identity token is crucial for accessing and performing subsequent project management functions.
2. **Project Creation** – The project owner deploys a new instance of the `ProjectManagerMaster.sol` contract. This setup includes defining the project name, required disciplines and their rewards, uploading detailed project information to IPFS and retrieving the IFPS hash, and associating this information to the newly deployed smart contract.
3. **Stake Reward** – Before proceeding with the project, the owner must stake the necessary rewards in Ether to the project manager contract. These rewards will be allocated to the winning designers at the end of the project.
4. **Assign Designers** – Through the user interface, the project owner can check the information about the designers who are willing to participate into the project. At this step, the owner assigns the designers with appropriate certificate tokens to the project. The addresses of these assigned designers are stored on the project manager contract.
5. **Initiate Project** – After staking the rewards and assigning the designers, the project owner uses the `initiate()` function in the contract. This step is crucial as it commits the project owner to the project and prevents them from withdrawing the staked rewards prematurely.
6. **Distribute Design Folders** – The project owner deploys a clone of `DesignFolderMaster.sol` contracts and distributes design folder tokens to the assigned designers, organizing the storage of design files. The newly deployed design folder contract is tied to this project.
7. **Deploy Design File Tracker** – A clone of `DesignFileTrackerMaster.sol` contract is deployed and linked to this project. The addresses of the assigned designers are passed to this contract, ensuring only assigned designers can tokenize their design files.
8. **Monitor Design Progress** – As the designers starts the design process, uploads their design to IPFS and tokenizes their design file, the project owner oversees project development, reviews submissions, and provides feedback via the platform.
9. **Select Winners** – After the design phase, winners for each discipline are chosen based on their submissions.
10. **Approve Royalties** – Winning designers stake their design folders containing the design file tokens. The project owner approves the royalties set by the designers.
11. **Reward Handover and Project Closure** – On behalf of the project owner, the project manager contract transfers the rewards to winners, the design folders to the project owner, and finalizes all transactions, signifying the completion of the project.

This comprehensive workflow encapsulates the essence of the project management system, providing the project owner with a clear and efficient path from project inception to completion. It ensures every critical aspect, from designer assignment to final design handover, is systematically addressed, culminating in a well-orchestrated and successful project closure.

6.3. Designer Workflow

Below is the workflow structured to guide the designers (from any disciplines) from initial registration through to the completion of a project. This workflow ensures that designers can effectively participate in design competitions, collaborate with other disciplines, and manage their intellectual property with transparency and efficiency. This detailed guide outlines the key phases:

1. **Sign-up** – The journey begins with designers registering on the platform, a process that involves creating an identity token. This token encapsulates their personal information, securely stored within MongoDB, and serves as the foundation for their interactions within the system.
2. **Certificate Verification** – Following registration, designers undergo a verification process to authenticate their professional qualifications. Upon successful verification, a non-tradable token, symbolizing their credentials, is minted and linked to their identity token, solidifying their eligibility to participate in projects.
3. **Search Project** – Designers gain access to a tailored job board, aligning with their qualifications. This board displays a variety of projects, each with comprehensive descriptions, enabling designers to make informed decisions on which projects to pursue.
4. **Enter Project** – Designers select projects that resonate with their skills and apply for participation. Entry into a project requires holding the relevant certificate token. For multi-disciplinary projects, the system ensures that a collaboration of various specialists is formed. Designers await the project owner's approval to commence their contribution.
5. **Project Participation and Receive Design Folders** – Once approved and the project is initiated by the owner, designers receive a design folder token linked with the project. This unique token acts as a repository for all design files during the project, fostering organized file management.
6. **Design File Creation and Tokenization** – In this phase, designers upload their design files to IPFS and tokenize them via the `DesignFileTrackerMaster.sol` contract deployed by the project owner, thereby minting ERC721 tokens. These tokens, representing the ownership of the design files, are automatically allocated to the designer's design folder linked to the project.
7. **Collaboration and Updates** – Collaboration is key in this phase. Designers work in tandem with colleagues from other disciplines, ensuring their designs are in harmony. They are notified of any updates or revisions in designs from other team members via the platform, maintaining coherence in the project's development.
8. **Setting Royalties** – As the project draws to a close, designers can choose to set royalties on their designs. This foresight allows them to secure future compensation if their designs are reused or repurposed.
9. **Stake Design** – Winners are selected by the project owner, and the winners are required to stake their design on the project manager smart contract.
10. **Design Handover and Receive Reward** – The final stage involves the transfer of design folders to the project owner, signifying the completion of the designer's role in the project. Subsequently, designers receive their due rewards, a testament to their valuable contributions, along with achievement tokens as recognition for their participation.
11. **Sell Designs** – Designers who do not win the competition have the option to sell or trade their designs on the platform's marketplace. This opportunity allows them to monetize their efforts, offering their unique designs to other interested parties. This step is crucial as it provides a compensation mechanism for their time and creativity, acknowledging that their designs, although not selected for the specific project, hold value and potential for other applications.

This comprehensive workflow delineates the journey of a designer within the blockchain-based system, from their initial engagement to the successful conclusion of a project. It underscores the system's commitment to streamlined processes, transparent interactions, and the safeguarding of intellectual property, culminating in a rewarding experience for all designers involved.

4.3.4. Workflow Illustration

The following diagram illustrates the workflow covering both project owners and designers within the blockchain-based architectural project management platform. For a detailed understanding of the specific steps involved in the project workflow and how they are executed on the platform, kindly refer to Appendix A. This appendix contains screenshots of the webpages developed for this project, providing a clear visual representation of the system's functionality.

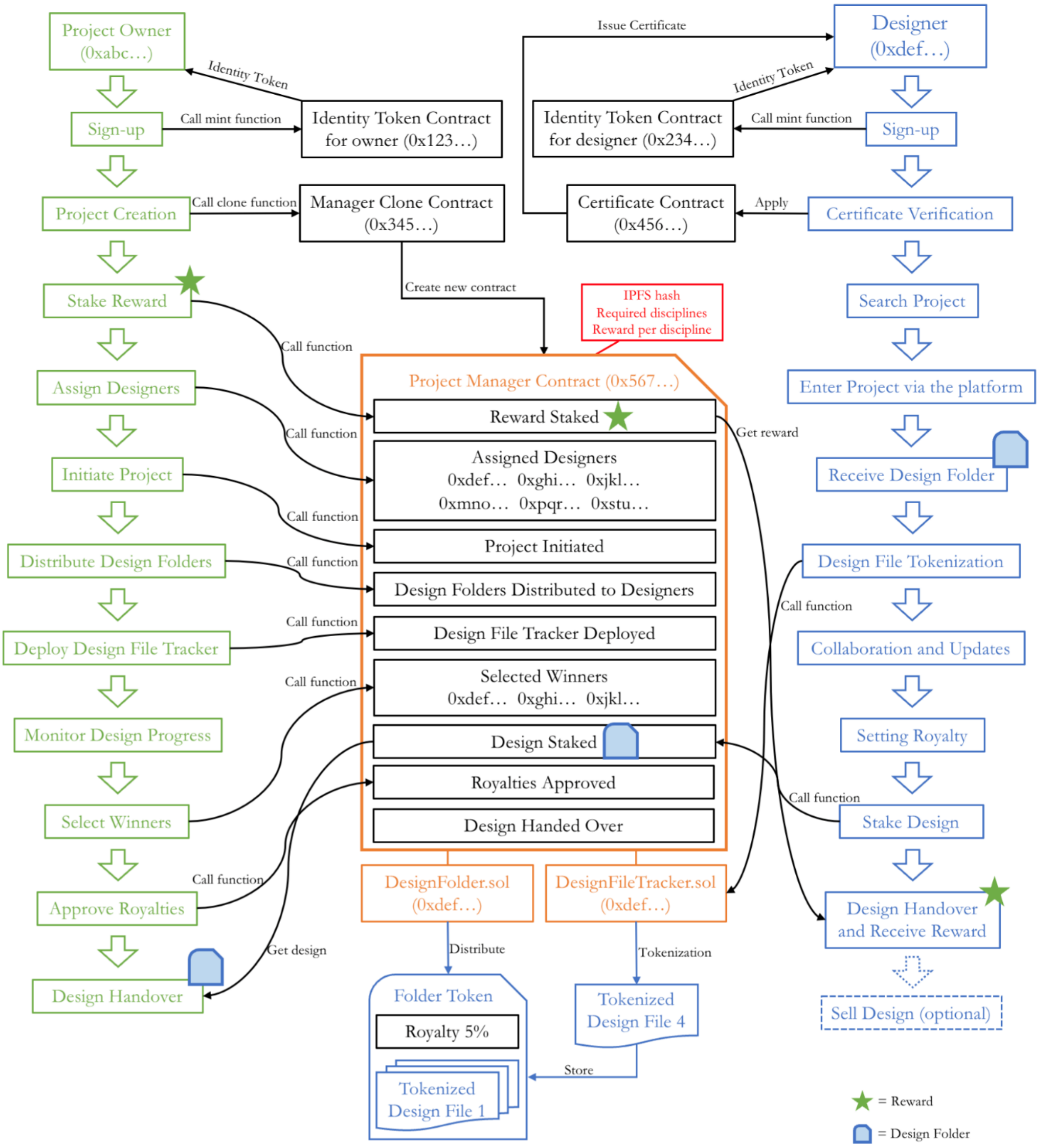


Figure 19 – Diagram explaining the integrated workflow of project owners and designers.

7. System Evaluation

This section critically examines the blockchain-based project management platform, analyzing its performance across various key aspects. Through detailed analysis, this section explores transparency, data provenance, design ownership, project management efficiency, security, and cost implications. The evaluation aims to assess how the platform addresses the challenges of collaborative architectural projects, such as the MEGA scenario, by leveraging blockchain technology. It provides insights into the system's advantages in fostering a cohesive work environment, its robustness in maintaining data integrity, and the economic considerations for both project owners and designers. This section serves as a comprehensive assessment of the platform's capabilities and potential areas for enhancement.

7.1. Transparency in Collaborative Environment

The blockchain-based project management system significantly addresses the challenge of lack of transparency in collaborative design environments, as commonly encountered in scenarios like the MEGA project. This system introduces an open and transparent workspace where all design-related information, except for sensitive personal data, is shared across the platform. By doing so, it eliminates the barriers that often lead to ineffective collaboration and inconsistencies in integrated design projects.

The transparency of the system is exemplified by its approach to sharing design files. All designs are accessible to different disciplines involved in a project, effectively preventing contradictions and misalignments between the designs generated by different disciplines. This open access to designs ensures that each discipline can work cohesively, maintaining consistency throughout the project's development. Furthermore, the system ensures that designs are shared with the project owner in a timely manner, fostering a closer and more responsive relationship between the designers and the project owner. This linkage is crucial in ensuring that the design outcomes align closely with the project owner's requirements and expectations.

While the high degree of transparency greatly enhances team collaboration and ties between the project owner and designers, it also introduces potential concerns, such as the risk of design concept theft due to easy access to design files stored on IPFS. The system can be upgraded to mitigate this risk by allowing for the encryption of design files before their upload, ensuring that sensitive intellectual property is protected while maintaining the benefits of a transparent workspace.

This system successfully transforms the traditionally opaque nature of collaborative design projects into an environment of clarity and openness. By doing so, it not only streamlines the collaborative process but also aligns it more closely with the dynamic needs of complex architectural projects like MEGA, establishing a new standard for transparency and efficiency in the field.

7.2. Data Provenance and Responsibility

Data provenance and responsibility are vital in collaborative design projects like the MEGA scenario. The platform's approach to tokenizing design files using IPFS and smart contracts fundamentally changes how design versions and data origins are tracked and managed. Tokenization on the blockchain ensures a clear and immutable record of each file version, with every upload to IPFS being timestamped and securely recorded. This creates a transparent history of modifications, updates, and responsible individuals, crucial in collaborative environments to tackle ambiguity in responsibility allocation.

However, this transparency brings challenges. The easy access to design iterations on the blockchain might expose ideas prematurely, risking intellectual property breaches. Additionally, the system's reliance on blockchain technology may limit accessibility for users less familiar with such platforms, potentially narrowing the user base. While the platform efficiently tracks design changes and responsibilities, it doesn't inherently resolve conflicts arising from differing design interpretations or discrepancies between project requirements and outcomes.

Despite these challenges, the platform's use of blockchain and IPFS for data tokenization enhances transparency and reinforces accountability. It provides undeniable proof of each designer's contributions and modifications, establishing a robust framework for managing data provenance and responsibility. This is essential for the smooth operation and success of complex, collaborative design projects, but it necessitates balancing openness with the protection of intellectual property and design integrity.

7.3. Design Data Ownership

The platform utilizes blockchain technology to tokenize design files, where each design file uploaded to IPFS is associated with an ERC721 token. This approach explicitly establishes and represents ownership, a crucial aspect in scenarios involving multiple collaborators.

The immutable nature of blockchain records every transaction related to design files, offering transparency and certainty to ownership claims. This feature is particularly beneficial in preventing misunderstandings and disputes over design ownership in complex projects. When a project concludes, the platform facilitates a streamlined transfer of design ownership from individual designers to the project owner. Designers stake their design folders, containing all related design file tokens, indicating a consensual transfer of ownership.

Furthermore, the system respects and protects designers' intellectual property rights beyond the transfer of ownership. It enables designers to set royalties on their designs, ensuring continued benefit from their creative work if reused or resold. This approach not only recognizes the designers' contributions but also provides a financial incentive for their participation.

The platform, however, faces challenges such as potential unauthorized copying or misuse of designs due to the accessibility of files on IPFS. Addressing this issue could involve integrating encryption mechanisms for design files, adding a layer of security to protect designers' intellectual property.

7.4. Project Management Efficiency

The primary strength of the project management system lies in the streamlined workflow it provides, underpinned by smart contracts like `ProjectManagerMaster.sol`. This structured approach meticulously guides project owners and designers through every project phase, from initiation to completion. Automation is another key advantage, with processes such as design file tokenization and ownership transfer being efficiently handled by the system, significantly reducing manual effort and potential for human error.

Enhanced collaboration is a hallmark of this platform. The system's design ensures transparency and easy access to project data, thereby fostering seamless interaction and alignment among different disciplines. The immutable nature of blockchain technology further bolsters this aspect, ensuring all project activities are transparently and permanently recorded, enhancing accountability and traceability.

However, the system's reliance on blockchain technology presents a steep learning curve for those unfamiliar with digital and blockchain concepts, potentially hindering its adoption. Additionally, the system's effectiveness is closely tied to robust digital infrastructure. In scenarios of limited or unreliable digital access, its utility may diminish. Overhead costs associated with blockchain operations, such as smart contract deployment and transaction fees, pose another challenge, particularly in cost-sensitive projects (see cost analysis for more details). Lastly, the transparent nature of blockchain and the use of IPFS for design file sharing raise privacy and intellectual property concerns, necessitating additional security measures like encryption to protect sensitive design data.

While the platform enhances the efficiency in project management with its automated and transparent processes, it faces hurdles in user accessibility, digital dependence, cost considerations, and privacy issues. Balancing these elements is key to the system's widespread applicability and success in real-world project management scenarios.

7.5. Security

When assessing the security features of the platform, it is important to delve into both its safeguards and the areas where vulnerabilities may arise. Given that the system is built on the foundation of blockchain technology, the most crucial security concern is the exploitation of smart contracts. If a smart contract is compromised, it can lead to significant consequences, including loss of digital assets, unauthorized access to sensitive information, and undermining the integrity of the entire system. Such breaches not only have immediate financial implications but can also erode user trust in the platform, which is particularly detrimental in blockchain-based systems where security is paramount.

Given the significant risks associated with smart contract exploitation, the platform's smart contracts were extensively revised and optimized by the author to ensure security. A key aspect of the platform’s security is the sophisticated and abuse-proof design of its smart contracts. These contracts incorporate controlled access and permissions, ensuring that actions within the contracts can only be executed by authorized users. This level of control is crucial for maintaining the legitimacy and security of every transaction.

Moreover, the system employs trusted contracts from OpenZeppelin, a benchmark in secure smart contract development. Features such as the non-reentrancy guard, which is incorporated in functions managing digital asset transfers, mitigate the risk of common vulnerabilities like reentrancy attacks. The inclusion of the onlyOwner modifier further secures critical functions, safeguarding them against unauthorized use and breaches.

Another noticeable feature of the platform's smart contracts is their upgradeable design, allowing for continuous adjustments in response to evolving security needs or potential vulnerabilities. This adaptability is crucial, especially if an exploitable point is identified, enabling the contracts to be paused and updated to a more secure version. Such a proactive approach not only fortifies the system against current threats but also prepares it for future security challenges.

Despite the careful design and security measures, the smart contracts in the system have not undergone extensive review and verification by other smart contract developers. This lack of external validation may leave unnoticed vulnerabilities, creating potential loopholes for exploitation. Even with the advanced features and upgradeable nature of the contracts, the absence of a thorough peer review process poses a significant risk. Acknowledging that no contract is entirely immune to security threats, continuous scrutiny, updates, and peer reviews are vital to maintain the highest security standards in the dynamic landscape of blockchain technology

In addition to the security concerns arising from potential smart contract exploitation, the openness of the blockchain, while beneficial for transparency, could potentially expose sensitive design information to a broader audience, including competitors. As stated several times before in this paper, the reliance on IPFS for storing design files raises concerns about data privacy, as once uploaded, data becomes publicly accessible unless adequately encrypted. This could lead to intellectual property risks if sensitive designs are not protected properly.

Another critical concern is the steep learning curve associated with blockchain technology. Unfamiliarity with blockchain systems can leave users vulnerable to fraud and hacking activities prevalent in the blockchain space. Users with limited blockchain knowledge may inadvertently expose themselves to risks of asset loss, making the platform less appealing to a broader audience. Educating users on blockchain security practices is crucial to mitigate these risks and ensure the safe and effective use of the platform.

In essence, while the platform demonstrates strong data integrity and automated security through smart contracts, it faces challenges in ensuring user data privacy and broadening its accessibility to those less familiar with blockchain technology. These aspects underscore the importance of user education and the implementation of additional security measures to protect sensitive design information in a collaborative environment.

7.6. System Stability

Assessing the stability of the platform hinges on two pivotal questions: its consistent functionality and vulnerability to compromise. Firstly, the system's continuous operation is not guaranteed. The entire development, encompassing the smart contracts, website, and user interface, was undertaken solely by the author, lacking external professional review. This approach raises potential risks of undetected bugs and errors that could lead to system malfunctions or failures. In the complex domain of blockchain-based systems, the absence of peer review can leave critical issues unnoticed, posing a threat to operational reliability. Additional expert inspection and verification are necessary to identify these latent issues and enhance the system's stability.

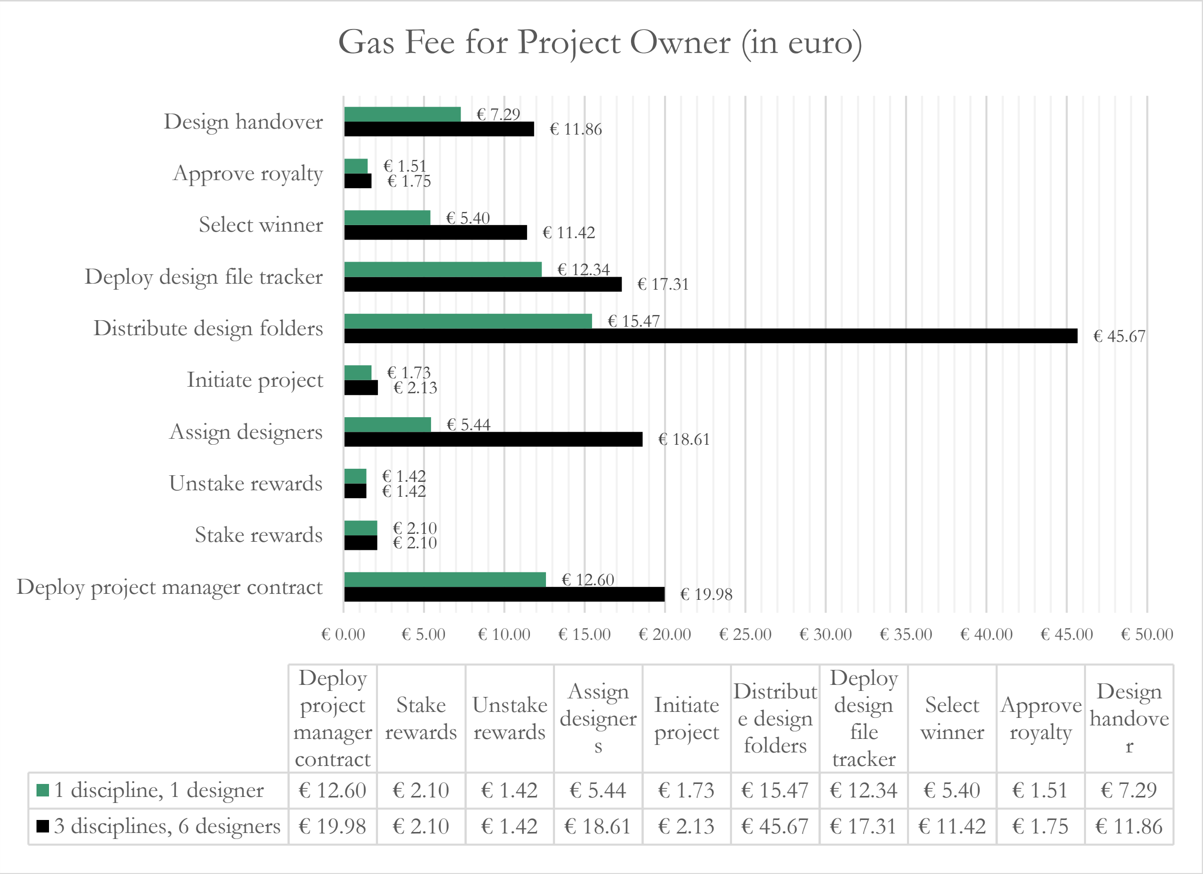
Secondly, the possibility of the system being compromised is a concern. While significant attention has been given to crafting the smart contracts, the intricacies of blockchain coding mean that vulnerabilities may still exist. These vulnerabilities, if exploited, could have serious outcomes, compromising the platform's integrity and security. Beyond the smart contracts, other system components like the website's code may also contain overlooked flaws. Given the importance of smart contracts in blockchain systems, a comprehensive and thorough code review is imperative. This review should encompass all aspects of the system to ensure a robust defense against potential breaches.

In the realm of software and blockchain technology, no system can be considered entirely invulnerable. The dynamic nature of technology, coupled with constantly evolving threats, necessitates ongoing updates and improvements. Regular testing, external audits, and updates are vital to maintain the system's stability and security.

To conclude, although the platform is developed with an emphasis on security and efficiency, its stability is not absolute. The lack of collaborative development and external review introduces risks of undiscovered vulnerabilities. To address these concerns, the system requires extensive reviews by blockchain and software development experts. These steps are crucial not only for identifying current issues but also for protecting the system against future threats, ensuring its resilience and reliability in a constantly evolving technological landscape.

7.7. Cost Analysis – Project Owner

Chart 1 delineates the gas fees incurred by a project owner on the Ethereum blockchain over the course of a project's lifecycle. The fees are calculated based on the Ethereum price of 2025 euros per ETH as of December 12, 2023. These fees are subject to fluctuation, impacted by the volatile nature of Ethereum's price and potential network congestion, which can increase costs unpredictably.



	Deploy project manager contract	Stake rewards	Unstake rewards	Assign designers	Initiate project	Distribute design folders	Deploy design file tracker	Select winner	Approve royalty	Design handover
🟩 1 discipline, 1 designer	€ 12.60	€ 2.10	€ 1.42	€ 5.44	€ 1.73	€ 15.47	€ 12.34	€ 5.40	€ 1.51	€ 7.29
■ 3 disciplines, 6 designers	€ 19.98	€ 2.10	€ 1.42	€ 18.61	€ 2.13	€ 45.67	€ 17.31	€ 11.42	€ 1.75	€ 11.86

Chart 1 – Gas fee incurred by the project owners over the course of the project's lifecycle

As depicted in the chart, for a simple project with one discipline and designer, the total cycle cost is relatively manageable. However, as project complexity grows to encompass three disciplines and six designers, the total fees for a single project cycle increase significantly. This is evident when comparing the total costs for both scenarios (€77 vs €144), which demonstrate a more pronounced financial impact as the number of designers scales up.

While the initial cost of creating a project remains relatively low, the cumulative expense can become substantial with the inclusion of more designers. It's important to note that the project owner holds the decision over the number of participants, allowing for cost control by limiting this number. Such flexibility can be particularly advantageous for projects with tighter budgets or smaller scopes.

Of course, the number of participants in a project is influenced not just by the decision of the project owner but also by the complexity and specific circumstances of the project itself. Generally, projects of greater complexity necessitate the involvement of a larger number of stakeholders, whereas smaller projects may require fewer participants. In the realm of larger construction projects, which typically entail substantial budgets, the gas fees associated with this platform might constitute only a minor portion of the total expenditures. Therefore, for project owners who possess adequate financial resources, the advantages of a comprehensive and secure project management system could potentially outweigh the cost of gas fees. Conversely, in the case of smaller-scale projects with limited budgets, a reduced number of designers may be sufficient, thus enabling the project owner to make a strategic decision to assign only the necessary number of designers, thereby conserving on gas costs.

Accordingly, project owners are advised to consider the platform's sophisticated capabilities and the security benefits of blockchain transactions in relation to these variable and, at times, significant costs. It is imperative that decisions are made in alignment with the project's scale and financial scope, considering the varying requirements dictated by the project's size and complexity.

The gas fee analysis reveals strategic gas cost optimization efforts through smart contract optimization and the use of clone contracts for deployment. The contrast in deployment costs is clear when comparing the original and clone contract deployment fees (see table 4). For instance, deploying the original Project Manager contract costs a substantial €120.05, whereas its clone counterpart requires a mere €12.60. This pattern of cost reduction is consistent across other contracts like the Design Folder and Design File Tracker. These figures highlight the smart contract efficiency, where contract simplicity and cloning significantly reduce gas expenses. Despite the dependency of deployment costs on the number of disciplines and designers involved, the utilization of clone contracts trims down the financial burden for project owners. This strategic decision to employ clone contracts aligns with the goal of maintaining low gas fees, thereby making the system more economically viable without compromising its functionality.

	Original contract deployment	Clone contract deployment
Project Manager	€120.05	€12.60
Design Folder	€79.42	€15.47
Design File Tracker	€76.41	€12.34

Table 4 – Deployment cost of different contracts (original vs clone). The cost for the clone contract deployment assumes 1 required discipline and 1 assigned designer.

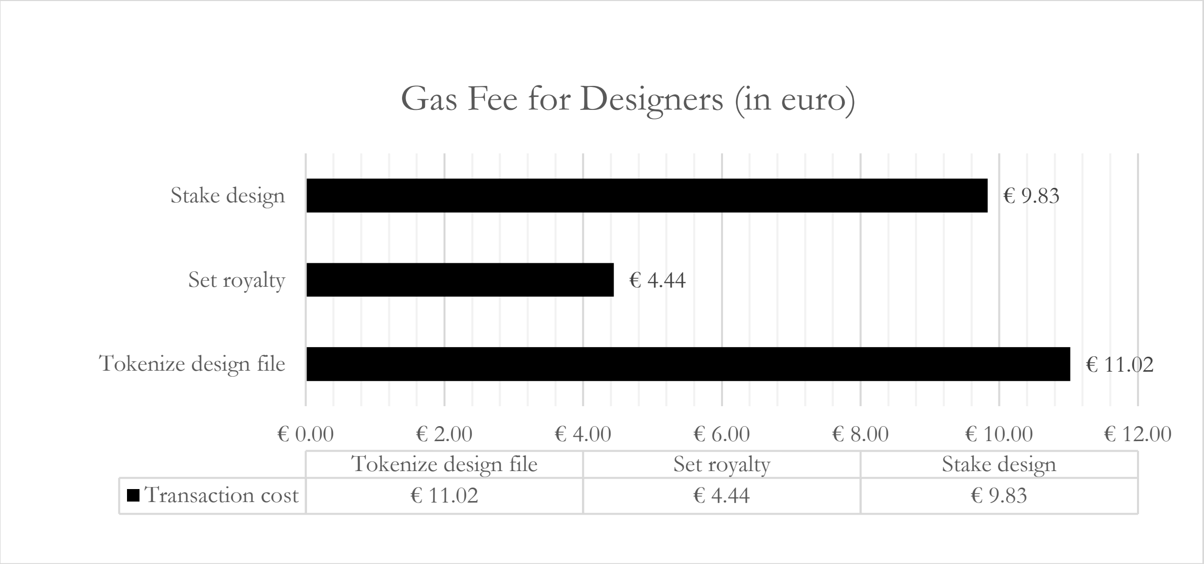
7.8. Cost Analysis – Designer

The gas fee analysis for designers surfaces certain economic considerations, particularly around the tokenization of design files. Tokenization, a frequent necessity due to iterative design updates, incurs the highest gas cost at €11.02. This recurring expense may cause designers to hesitate before updating files, potentially restrain the iterative design process vital in a collaborative environment. Addressing this challenge is imperative to maintain the system's collaborative integrity; future enhancements could involve further smart contract optimization or alternative methods to mitigate gas costs.

On the other hand, the costs for staking design and setting royalties are less concerning, standing at €9.83 and €4.44 respectively. These are one-time transactions and, although necessary, represent a smaller fraction of overall expenses, posing less of a financial deterrent to designers.

However, it's important to recognize the financial benefits for designers in this system. While there is an upfront cost associated with uploading and updating designs due to gas fees, the blockchain's record-keeping offers long-term advantages. Designers retain clear ownership of their designs, and the established royalties provide an opportunity for ongoing revenue. When designs are reused for similar projects or resold to new owners, designers receive royalties, creating a balance between the initial costs and potential continuous returns. This aspect of the system adds an economic incentive for designers, offsetting the initial gas fees with the prospect of future financial gains.

Overall, while the system shines in facilitating the design process through blockchain technology, the economic burden placed on designers for frequent file updates could be a potential barrier. It's crucial for the system's long-term viability to balance the need for iterative design with the cost implications of blockchain transactions. The current gas fees for one-time actions like staking and setting royalties are within reasonable bounds and unlikely to dissuade participation. However, the cumulative cost impact for designers, particularly in large-scale projects requiring continuous updates, warrants attention and strategic planning to ensure that the platform remains both accessible and economically sustainable for its users.



	Tokenize design file	Set royalty	Stake design
■ Transaction cost	€ 11.02	€ 4.44	€ 9.83

Chart 2 – Gas fee incurred by the designers over the course of the project's lifecycle. Note that design file tokenization occurs several times when the designers update their designs, raising the cumulative gas cost.

8. Discussion

8.1. Discussion of the Results

The evaluation of the blockchain-based project management system reveals a complex interplay between technological innovation and practical application challenges. Firstly, the system's approach to transparency and data provenance demonstrates a way to manage collaborative environments like the MEGA project. By ensuring open access to design files and maintaining a clear, immutable record of design changes, the platform reduces the opacity that often hampers collaborative projects. However, this transparency comes with the caveat of potential intellectual property risks and the challenge of maintaining data privacy. The need for balance between openness and security is evident, as is the importance of incorporating additional security measures, such as file encryption, to protect sensitive information.

Secondly, the platform's handling of design data ownership and project management efficiency highlights the benefits of blockchain in organizing complex project workflows. The use of NFTs for clear ownership representation and smart contracts for automating processes like file tokenization and ownership transfer showcases the system's potential in enhancing operational efficiency. Nonetheless, these advancements are not without their challenges. The steep learning curve associated with blockchain technology and the reliance on robust digital infrastructure may limit the system's accessibility, particularly for users unfamiliar with blockchain. Furthermore, the associated costs, both for project owners and designers, raise concerns about the platform's economic viability, especially in large-scale projects that require frequent design updates and iterations.

Lastly, the security analysis underscores the inherent strengths of blockchain in safeguarding data integrity and automating key project functions with smart contract. Yet, it also brings to light the vulnerabilities related to user familiarity with blockchain systems and potential exposure of sensitive information. The platform's dependence on user education and the need for enhanced security protocols to protect design data are critical areas for improvement.

In the Tavistock Report (Tavistock Institute of Human Relations, 1966), two of the main issues are identified as fragmentation in the AEC industry structure and an overreliance on formal systems. This thesis proposes a blockchain-based system that partially addresses these challenges. The fragmentation within the industry, stemming from informational gaps and diverse stakeholder perspectives, is an inherent condition that current technology alone cannot resolve. The proposed system, leveraging the decentralized nature of blockchain technology, does not aim to directly eliminate fragmentation. Instead, it fosters a collaborative environment where participants are encouraged to work together seamlessly, not by bridging knowledge gaps, but by capitalizing on the AEC sector's fragmented and decentralized nature. While the platform is in its infancy and limited in functionalities, the integration of blockchain in the AEC sector holds the potential to progressively overcome fragmentation through enhanced collaboration and system optimization.

Moreover, the system addresses the issue of over-reliance on formal aspects in project management. The prevalent focus on formal structures often overlooks the vital informal (social) aspects of construction projects. The use of smart contracts in the proposed system creates a rigid, straightforward workflow, which might seem to neglect the social dynamics of projects. However, this prototype represents just the initial stage, with ample scope for incorporating features that enrich the collaborative and interactive aspects within this structured workflow. A rigidly defined project management process is necessary to navigate the complex web of stakeholder relationships and contractual obligations. The ultimate aim of a blockchain-based system in the AEC sector should be to enhance human interaction within this rigid framework, thus facilitating the development of a productive and engaging collaborative environment. Such an approach is the key to unlocking the full potential of blockchain technology in transforming the AEC sector.

In short, while the system demonstrates potential in improving project management in the AEC sector, its success hinges on addressing these identified challenges, particularly in ensuring stakeholder interactions, user accessibility, balancing cost implications, and enhancing data privacy and security.

8.2. Research Contribution

Integrative Approach to Blockchain in the AEC Sector

One of the contributions of this research lies in its integrative approach, bringing together various blockchain tools to form a comprehensive management system for the AEC sector. Prior studies have explored individual aspects such as IPFS for data storage and smart contracts for automation. On the other hand, this research cohesively combines these elements into a unified system. This synergy not only addresses the fragmentation observed in existing methodologies but also creates a platform that supports the entire design lifecycle, from conceptualization to completion. By doing so, it bridges the gap in real-time, responsive project management systems that can adapt dynamically to the nuanced workflows of the AEC sector.

Implementation of New ERC Standards

Another aspect of this research is the adoption of unique token standards, particularly ERC4671 and ERC6551. These standards were chosen for their suitability in addressing the complicated requirements of the AEC sector. ERC4671 plays a crucial role in authenticating user qualifications, ensuring that participants in a project meet specific professional standards. On the other hand, ERC6551 enhances the functionality of tokens, allowing for interactions with smart contracts. By integrating these new ERC standards, the study demonstrates their effectiveness in addressing specific issues within the AEC sector.

Better Project Management Efficiency

The proposed system also reveals the potential of enhancing project management efficiency within the AEC sector using blockchain technology. Unlike existing blockchain applications in the sector, this system offers a more granular management of roles and immediate collaboration efforts, tailored to the specific needs of architectural projects. The comprehensive nature of the system, encompassing everything from data provenance to ownership and transaction management, provides increased efficiency and responsiveness. The research introduces a possible way in how architectural projects are conceptualized, developed, and executed using blockchain technology.

Exploration of Various Token Standards

A notable contribution of this research is the exploration and integration of diverse ERC token standards, including ERC721, ERC6551 and ERC4671, into the AEC sector's blockchain system. Some of these particular token types have never been integrated into the AEC sector before. By analyzing various token types, their strengths, and limitations, as summarized in Table 5, this study not only demonstrates the individual capabilities of these standards but also how they can be cohesively combined for enhanced functionality. This integrative approach provides insights into the optimal application of ERC standards in architectural project management, marking an advancement in utilizing and integrating different token types in the AEC sector.

Token Standard	Strengths	Limitations
ERC721	- Ability to tokenize unique design assets - Enables clear design ownership and history tracking - Common token standard that is applicable to different situations	- Tokenization of digital assets can be expensive - Limited scalability for handling numerous assets
ERC6551	- Allows for advanced interactions between tokens and smart contracts - Can support complex contractual relationships in construction projects	- Relatively new standard with potential undiscovered issues - Integration complexity with existing AEC project management tools - Requires a deep understanding of blockchain for effective integration
ERC4671	- Securely manage professional credentials on blockchain - Effective in authenticating and verifying user qualifications	- Specific use case of authentication may limit broader applicability

8.3. Research Limitations

Limited Validators

The system's evaluation process faces a limitation in its validation scope. The assessment of the system's functionality and performance was conducted solely by the author, without external validators or user testing. This approach inherently restricts the evaluation's scope and universality, as it lacks input and feedback from a diverse range of users, including professionals in the field. The absence of such varied perspectives could result in an evaluation that does not fully represent the system's effectiveness in practical, real-world scenarios. Future evaluations should incorporate a broader range of validators, including industry professionals and potential end-users, to provide a more comprehensive and balanced assessment of the system's capabilities and areas for improvement.

Limited Test Scenarios

The system's validation is constrained by a limited range of testing scenarios. Due to time constraints, the system was only tested using a single, hypothetical scenario, which may not comprehensively cover the diverse and complex situations that typically arise in architectural project management. This limited scenario testing restricts the ability to thoroughly evaluate the system's adaptability and effectiveness across various real-life situations. To enhance the robustness and applicability of the system, it is imperative to subject it to an increased variety of scenarios, including those that replicate real-life challenges encountered in past projects. Such diverse testing would provide valuable insights into the system's versatility and areas that require refinement.

Limitations in Procurement Method Integration

One notable limitation of the current research lies in the system's focus exclusively on the design phase of construction projects, which operates independently of specific procurement methods. At this stage, the system's primary goal is enhancing collaborative design processes, without accounting for the complexities of procurement routes that are more relevant during the construction phase. While this design-centric approach facilitates streamlined collaboration, it overlooks the potential impacts and intricacies that various construction procurement methods might introduce later in the project lifecycle. This limitation is significant as it acknowledges that, while procurement is a crucial element of construction projects, its direct influence on the design phase, and consequently on the system's current scope, has not been fully explored or integrated.

Furthermore, as the system evolves to include broader functionalities and stakeholders, the necessity to integrate different procurement strategies could become crucial. However, the current version of the system does not address how it might adapt to the specifics of diverse procurement methods in future iterations. While there is potential for the system to bridge gaps between design and construction phases and to maintain design integrity through various stages of a project, this aspect remains unexplored and presents a significant limitation. This perspective highlights a key area where the system could expand its applicability, yet currently, it does not align with the comprehensive needs of construction project management across different procurement scenarios.

Oversimplification of Design Phase

Another limitation of this research is the oversimplification of the design phase management in the proposed system. In real-world architectural projects, the design phase involves complex interactions between various disciplines, and is structured through distinct stages like preliminary and detailed design, each with specific deadlines. This process requires meticulous coordination and approval at each stage. However, the current system delegates the entire management of these phases to the participants without a structured design workflow. This approach neglects the multifaceted nature of design phase progression in real projects, potentially leading to inconsistencies and inefficiencies. Future enhancements should focus on integrating a more detailed and systematic approach to design phase management, reflecting the real-world complexities and ensuring a more accurate and efficient project development process.

Lack of System Optimization

Finally, while the smart contract and website UI underwent optimization post-testing, there are additional aspects of the system that can be improved further. For example, optimizing the system's overall structure could enhance its efficiency. However, due to the limited range of validators and scenarios employed in the evaluation, pinpointing specific areas for further optimization remains challenging. Future iterations of the system should focus on a more comprehensive optimization strategy, encompassing not just the technical components but also the structural and functional aspects. A broader approach to optimization, informed by extensive testing and diverse feedback, would be instrumental in refining the system to better cater to the needs and challenges of the AEC sector.

9. Conclusion & Recommendations

9.1. Conclusion

This thesis has focused on developing a blockchain-based project management system tailored to the AEC sector, exploring the potential of blockchain technology in addressing specific challenges such as transparency, data provenance, and project management efficiency within collaborative design environments. The system combines several blockchain tools to provide a unified platform for managing architectural projects. It features the integration of new ERC standards like ERC4671 and ERC6551, facilitating user qualification verification and enhanced token functionalities. While this integration represents an attempt to address the sector's complexities, the system's real-world applicability and effectiveness remain areas for further exploration.

Reflecting on the literature review, this research distinguishes itself by synergistically integrating various blockchain tools into a comprehensive management system, as opposed to the fragmentary approaches observed in existing literature. Prior research in this area has primarily focused on leveraging blockchain for specific functions like data provenance or intellectual property management using NFTs. However, this thesis goes beyond these isolated applications by creating a system that supports the entire design lifecycle and addresses the nuanced workflows of the AEC sector. This approach represents positive contribution to the field, demonstrating the potential of blockchain in providing a more integrated and responsive project management solution.

The integration of ERC4671 and ERC6551 offers the AEC industry insight into how new token standards can be effectively incorporated and utilized. ERC4671 plays a critical role in enhancing the system's security by authenticating user qualifications, ensuring that participants meet professional standards. Meanwhile, ERC6551 expands the utility of ERC721 tokens, allowing for more dynamic interactions with smart contracts. These unique token standards not only improve the system's functionality but also exemplify how blockchain technology can be tailored to meet the complex demands of the AEC sector.

The potential of blockchain in the AEC sector, when integrated properly, is immense. A well-implemented blockchain system could drastically enhance project management by offering transparency, improving collaboration, and ensuring data integrity. As this research demonstrates, a blockchain-based system can provide a holistic solution that captures the complete lifecycle of a project, from conceptualization to completion. However, to fully realize this potential, continuous research and development are necessitated.

In conclusion, this thesis serves as an exploratory step into the application of blockchain technology in the AEC sector. It offers insights into both the potential benefits and challenges, underscoring the need for further research and development. This study lays the groundwork for future endeavors in this emerging field, highlighting the importance of comprehensive integration and customization of blockchain technologies to suit the specific needs of the AEC sector.

9.2. Recommendations for Future Research

The application of this thesis in industry points toward several recommendations that can increase the potential of blockchain-based project management systems. Firstly, industry professionals should consider integrating such systems gradually, beginning with smaller-scale projects to acclimate teams to the technology and workflow. It is also advised to provide comprehensive training to ensure all users are comfortable with the system's functionalities and security protocols.

Further research is recommended to focus on optimizing smart contract efficiency, reducing gas fees, and exploring alternative blockchain platforms that may offer lower costs or faster transactions. Investigating advanced encryption methods to protect IPFS-stored designs without compromising the ease of access is another crucial area.

For follow-up researchers, a good starting point would be to analyze the usage data from the system's implementation in live projects to identify patterns and areas for improvement. Do focus on user feedback to enhance the system's design and usability. Don't overlook the importance of cross-disciplinary collaboration in these systems, as the integration of insights from areas such as cybersecurity, user experience design, and construction management can lead to more holistic and robust improvements.

Moreover, researchers are encouraged to delve into the challenges associated with procurement method integration within blockchain-based project management systems. This area of study is crucial given the current limitations identified in integrating various procurement approaches into the system's framework. Investigating how to effectively incorporate procurement methods can significantly enhance the applicability of blockchain technology in the broader context of construction project management. Research could focus on developing adaptive features within the system that align with different procurement routes, ensuring flexibility and compatibility with a wide range of project types and scales. This exploration would not only address a current gap in the system but also contribute to a more comprehensive understanding of how blockchain technology can be tailored to meet the diverse needs of the construction industry.

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Appendix A – Webpages

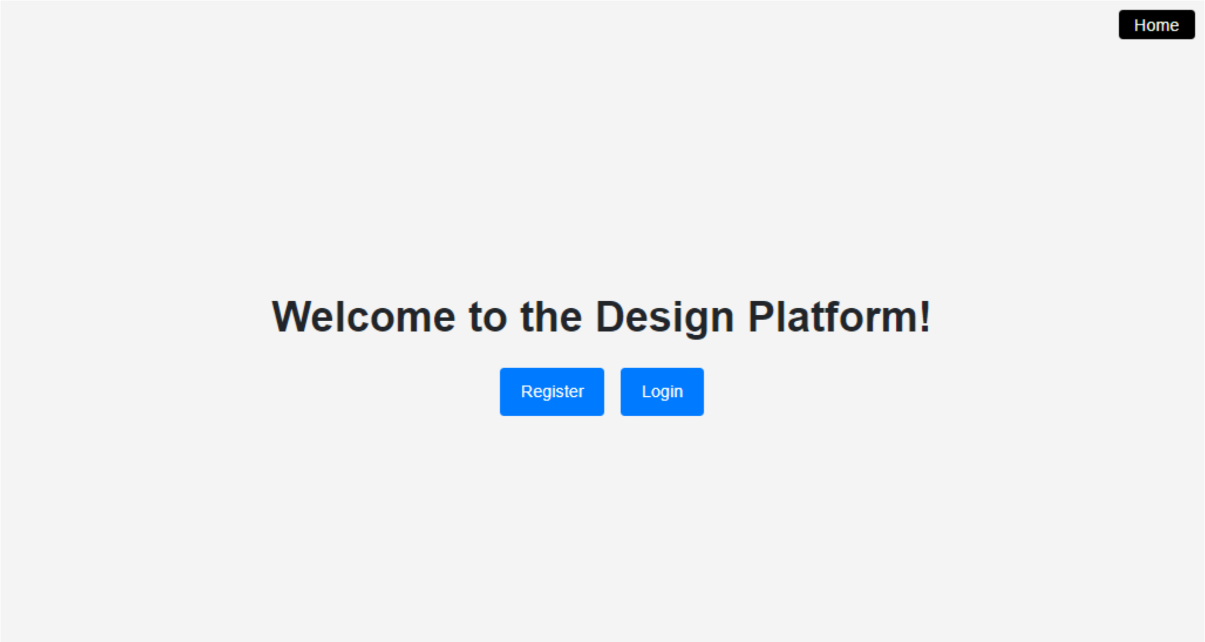


Figure 20 – Main page of the blockchain-based architectural project management system. Users can choose Register to register and mint identity token, or Login if they already own one.

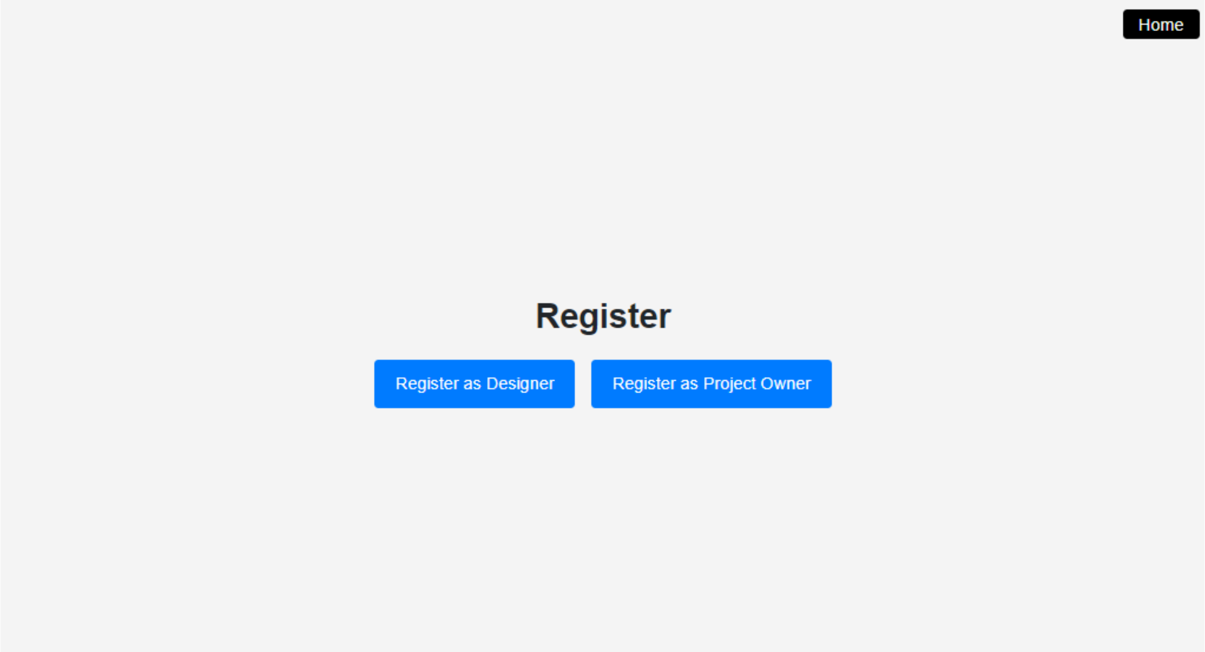


Figure 21 – Register Page. Users can choose to register as a designer or as a project owner.

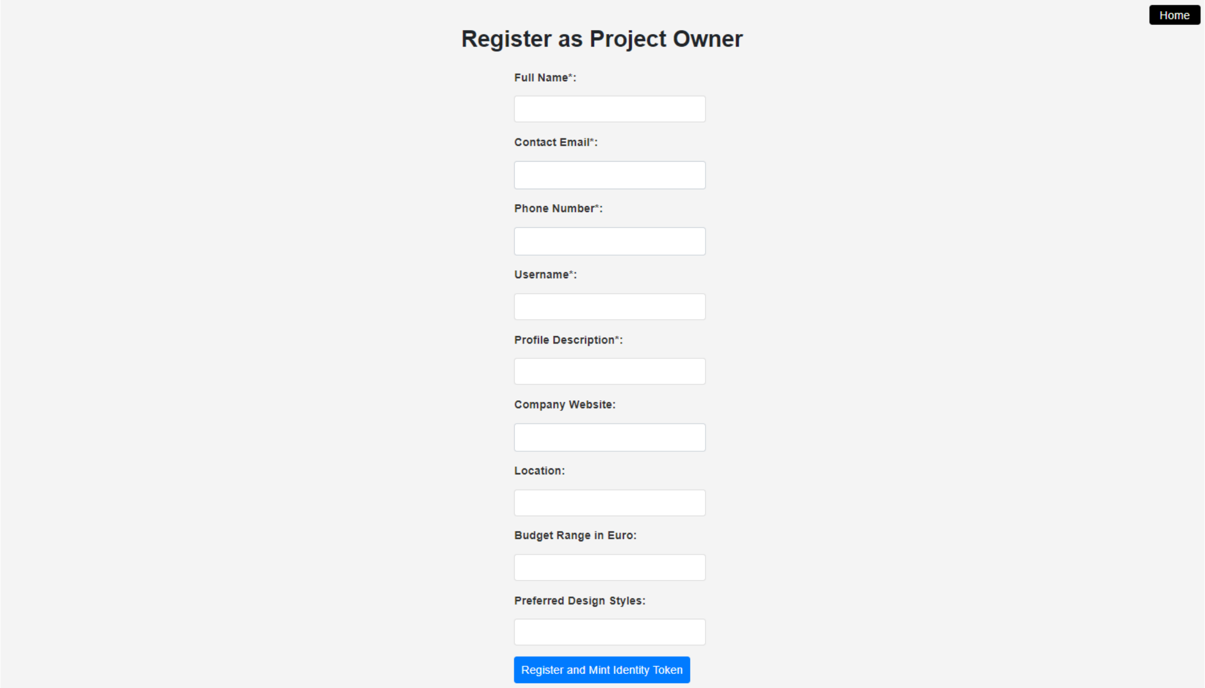


Figure 22 – Registration page for project owners. Users need to input required information for registration. The "Register and Mint Identity Token" button will pop up MetaMask and guide the user to mint the identity token.

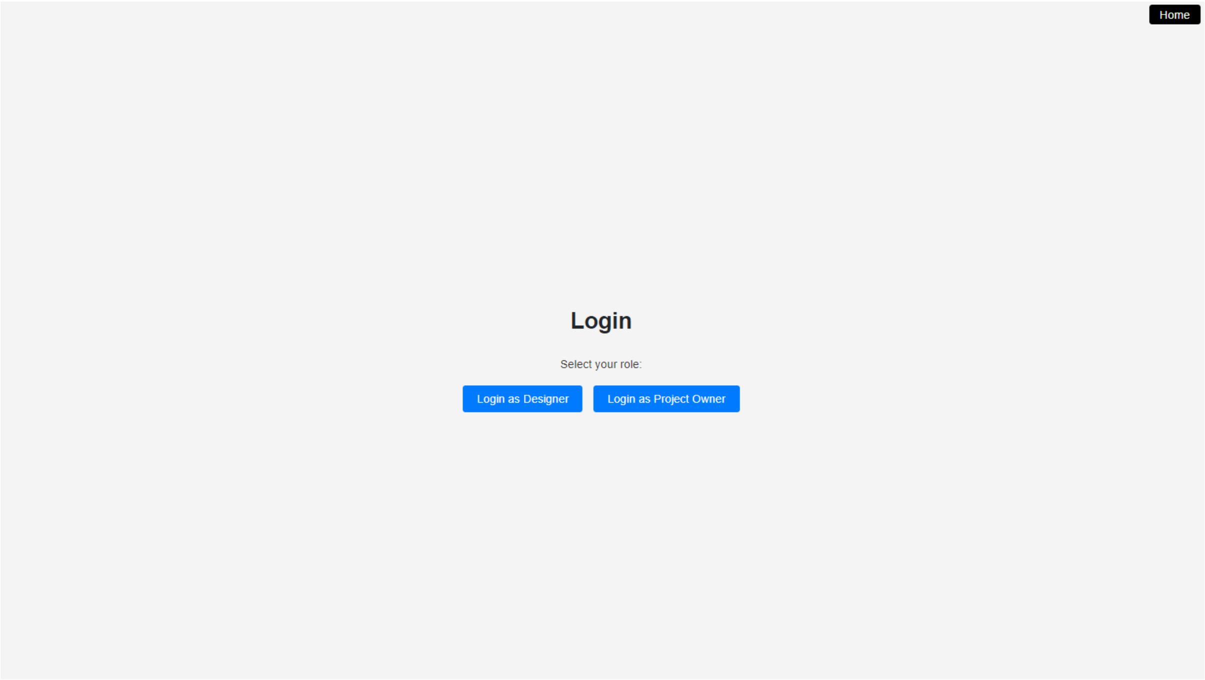
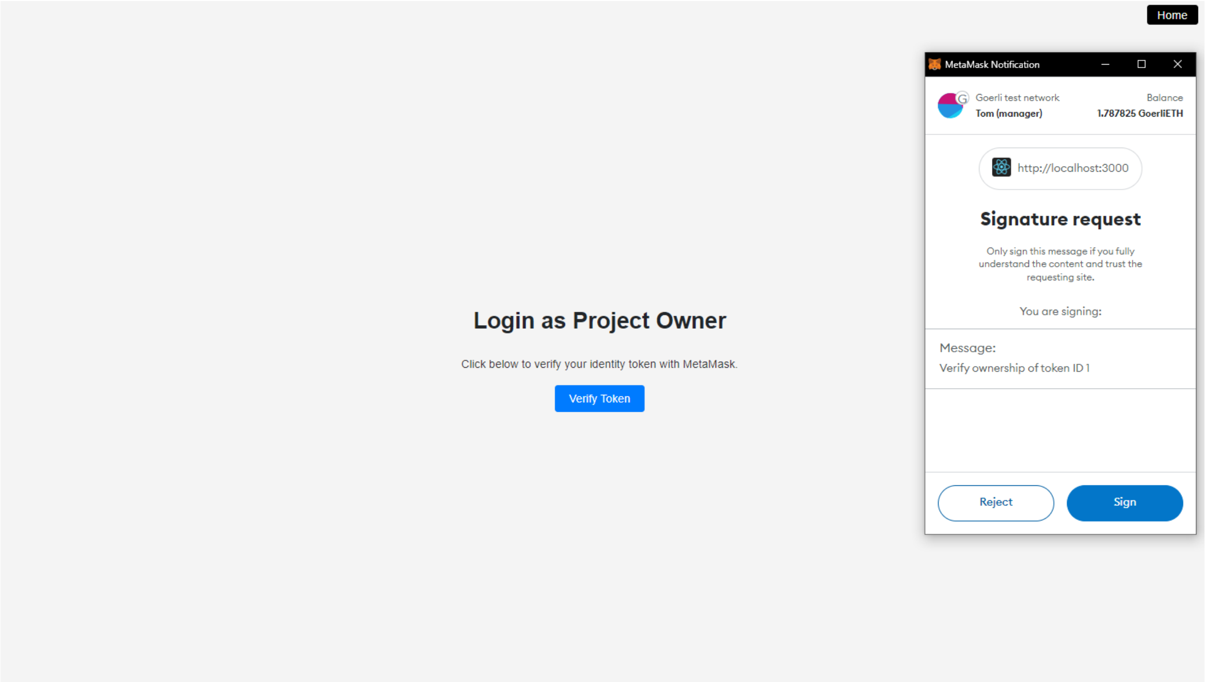


Figure 23 – Login page. Users can choose to either login as a designer or as a project owner.



Login as Project Owner

Click below to verify your identity token with MetaMask.

Goerli test network
Tom (manager)
Balance
1.787825 GoerliETH

http://localhost:3000

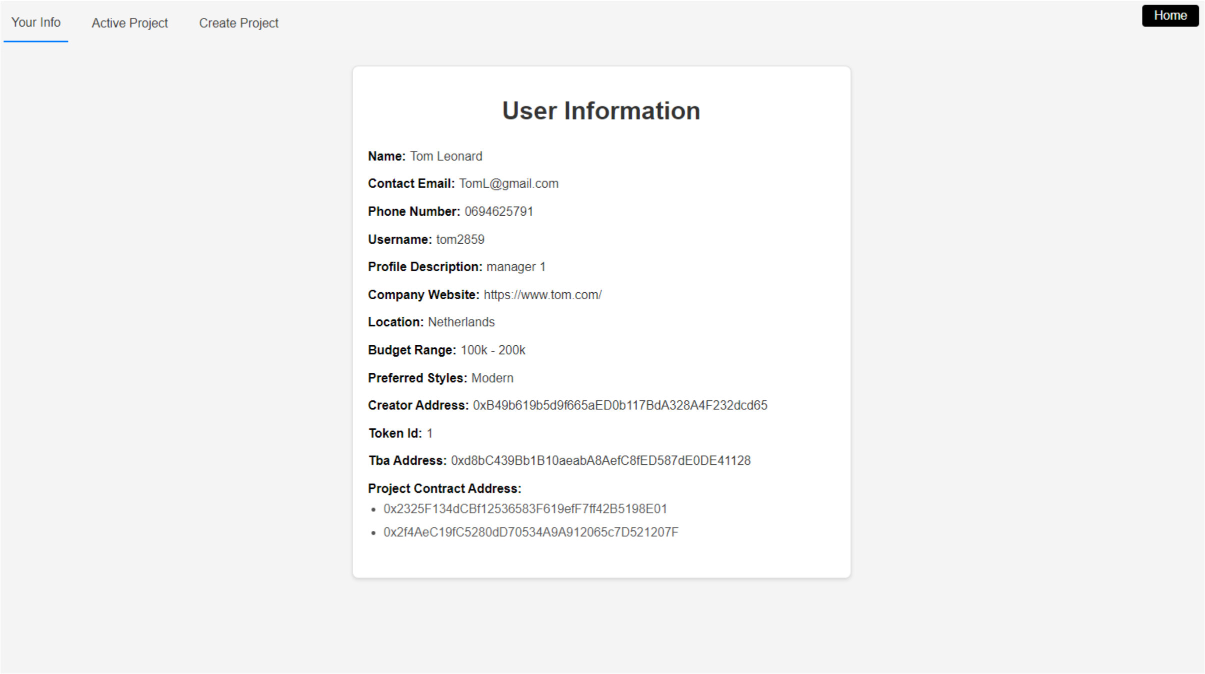
Signature request

Only sign this message if you fully understand the content and trust the requesting site.

You are signing:

Message:
Verify ownership of token ID 1

Figure 23 – Login page for project owners. Users must pass the identity token verification to log in successfully.



User Information

Name: Tom Leonard
Contact Email: TomL@gmail.com
Phone Number: 0694625791
Username: tom2859
Profile Description: manager 1
Company Website: https://www.tom.com/
Location: Netherlands
Budget Range: 100k - 200k
Preferred Styles: Modern
Creator Address: 0xB49b619b5d9f665aED0b117BdA328A4F232dcd65
Token Id: 1
Tba Address: 0xd8bC439Bb1B10aeabA8AefC8fED587dE0DE41128
Project Contract Address:

- 0x2325F134dCBf12536583F619efF7ff42B5198E01
- 0x2f4AeC19fC5280dD70534A9A912065c7D521207F

Figure 24 – Main tab for project owners. After successful login, the projects owners are directed to this tab displaying their information.

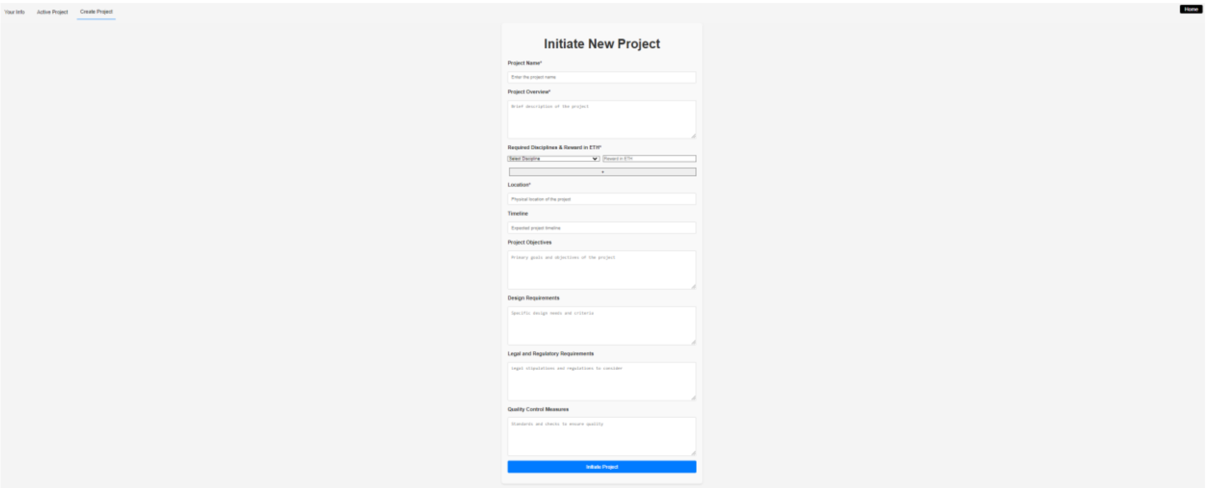
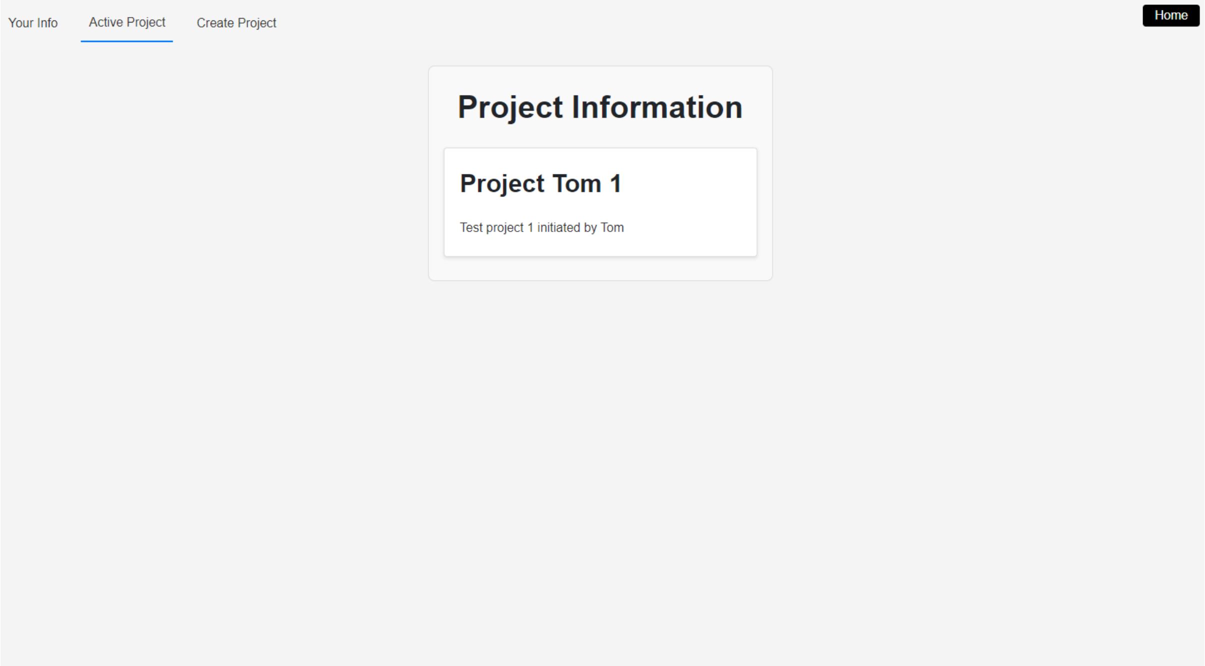


Figure 25 – Create Project tab for project owners. The project owners can specify their requirements about the project in the form, input critical information such as required disciplines as well as their reward. Upon hitting the "Initiate Project" button, the project information will be uploaded to IPFS as json format, the returned IPFS hash will be used to create a clone of Project Manager smart contract.

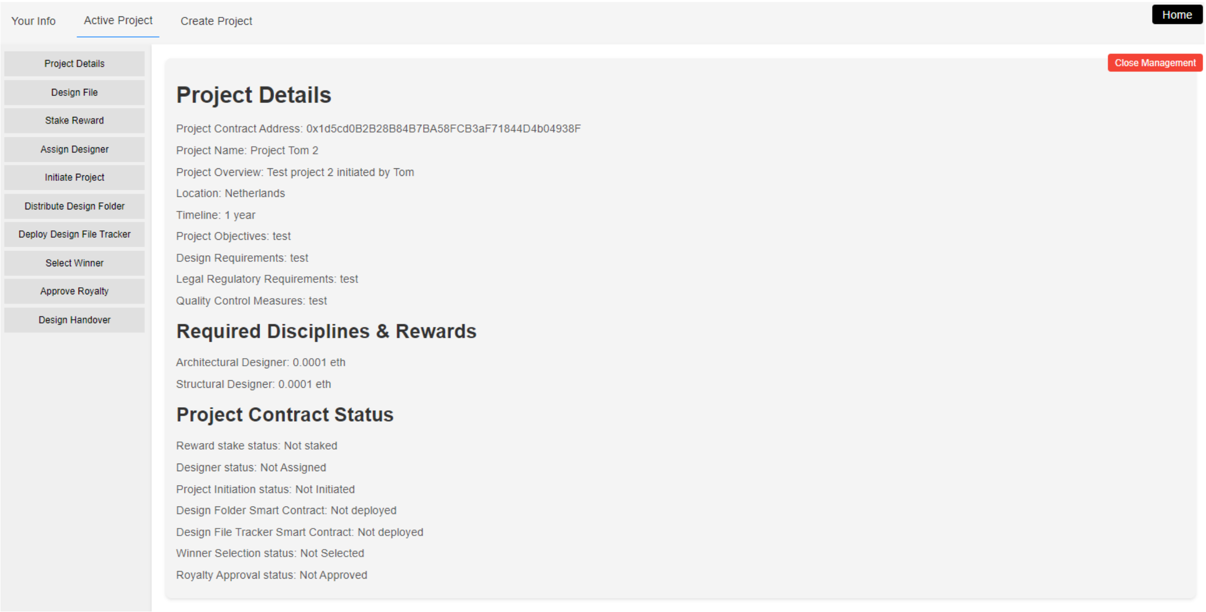


Project Information

Project Tom 1

Test project 1 initiated by Tom

Figure 26 – Active Project tab for project owners. The projects initiated by the owner will be displayed on this tab. Users can select the project card to enter project management user interface to manage their project (see figure 27).



Project Details

Project Contract Address: 0x1d5cd0B2B28B84B7BA58FCB3aF71844D4b04938F

Project Name: Project Tom 2

Project Overview: Test project 2 initiated by Tom

Location: Netherlands

Timeline: 1 year

Project Objectives: test

Design Requirements: test

Legal Regulatory Requirements: test

Quality Control Measures: test

Required Disciplines & Rewards

Architectural Designer: 0.0001 eth

Structural Designer: 0.0001 eth

Project Contract Status

Reward stake status: Not staked

Designer status: Not Assigned

Project Initiation status: Not Initiated

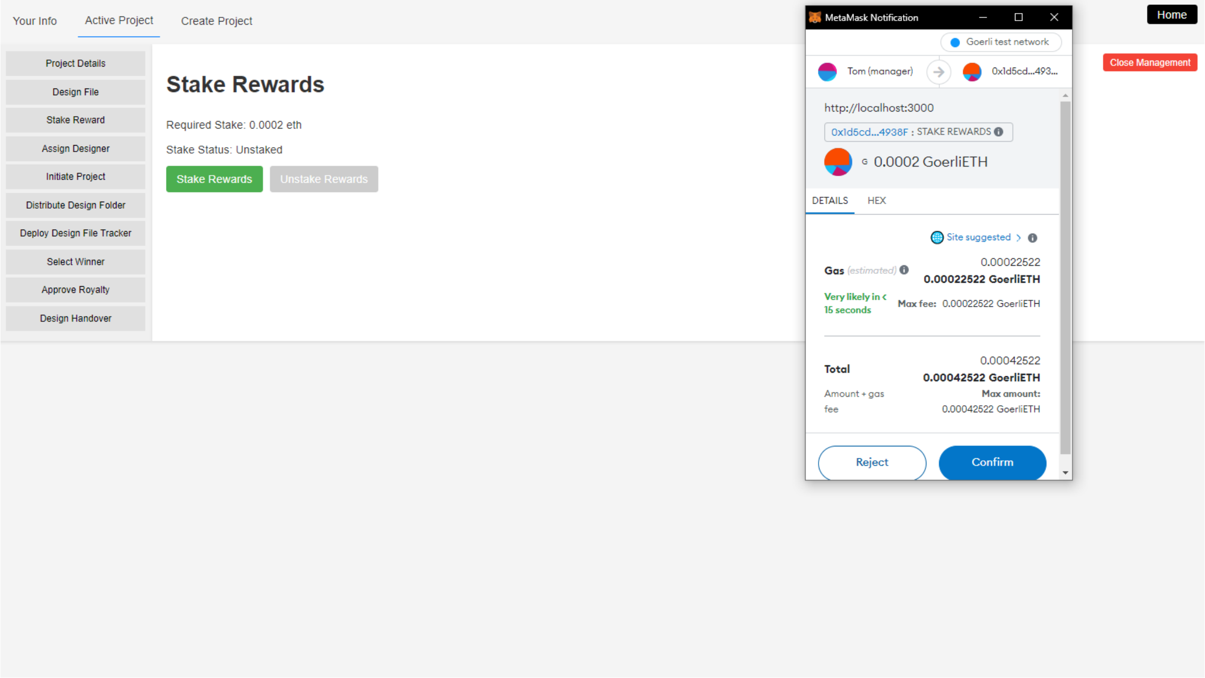
Design Folder Smart Contract: Not deployed

Design File Tracker Smart Contract: Not deployed

Winner Selection status: Not Selected

Royalty Approval status: Not Approved

Figure 27 – Project Details tab for project owners. This is the main page of project management tab. All the project details are summarised and displayed on this page. The project owner can check the project information and project status. This UI is dynamically updated as the project progresses, showing the most updated information of the project.



Stake Rewards

Required Stake: 0.0002 eth

Stake Status: Unstaked

Goerli test network

Tom (manager) → 0x1d5cd...493...

http://localhost:3000

0x1d5cd...4938F : STAKE REWARDS

0.0002 GoerliETH

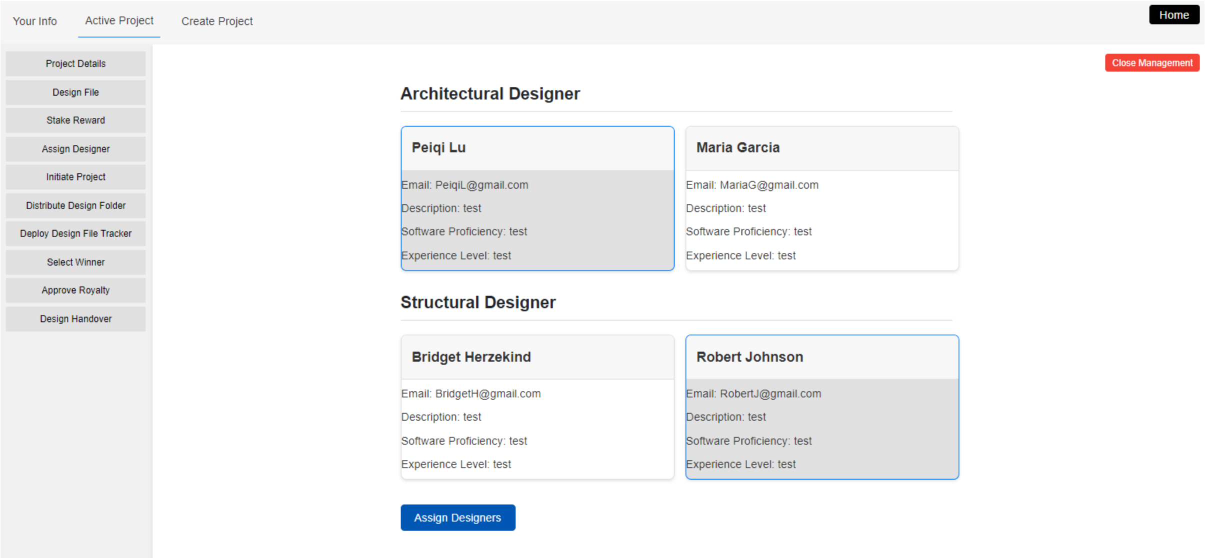
Gas (estimated) 0.00022522 0.00022522 GoerliETH

Very likely in < 15 seconds Max fee: 0.00022522 GoerliETH

Total 0.00042522 0.00042522 GoerliETH

Amount + gas fee Max amount: 0.00042522 GoerliETH

Figure 28 – Stake Reward tab for project owners. The project owner can stake or unstake the rewards (in ETH) at this tab. Upon hitting the button, MetaMask will pop up to inquire the user to confirm the transaction.



Architectural Designer

Peiqi Lu
Email: PeiqiL@gmail.com
Description: test
Software Proficiency: test
Experience Level: test

Maria Garcia
Email: MariaG@gmail.com
Description: test
Software Proficiency: test
Experience Level: test

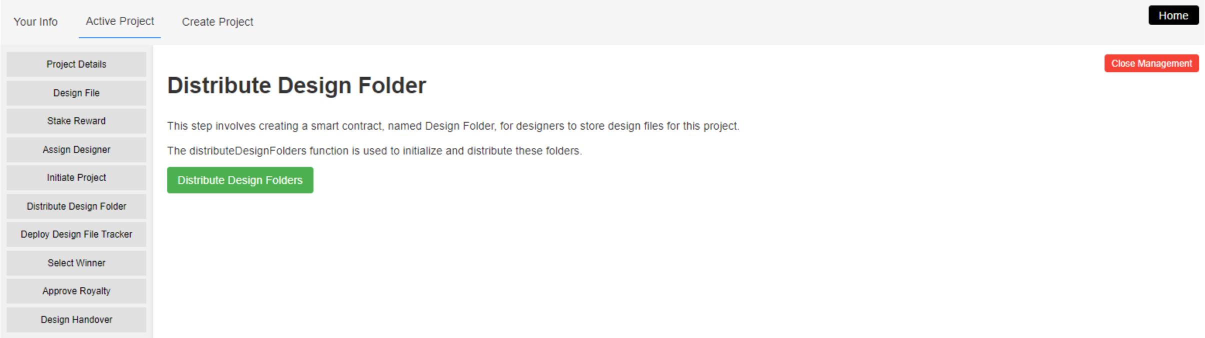
Structural Designer

Bridget Herzekind
Email: BridgetH@gmail.com
Description: test
Software Proficiency: test
Experience Level: test

Robert Johnson
Email: RobertJ@gmail.com
Description: test
Software Proficiency: test
Experience Level: test

Figure 29 – Assign Designer tab for project owner. At this tab, the project owner can check the designers willing to join the project. This page is dynamic, meaning if new designers register for the project, the project owner will be able to see it.

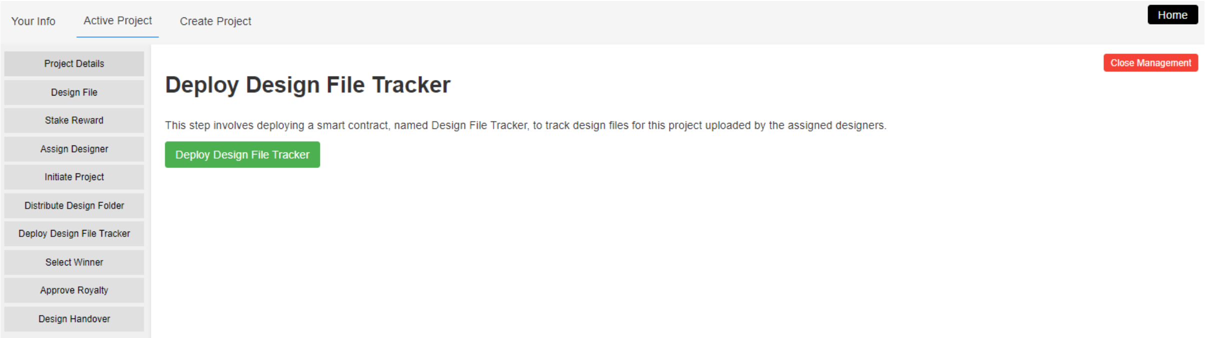
Figure 30 – Initiate Project tab for project owner. The project owner can initiate the project at this tab. The button will only show up when the project owner finished staking the reward and assigning designers. Once the project is initiated, Stake Reward and Assign Designer tab will be disabled.



This step involves creating a smart contract, named Design Folder, for designers to store design files for this project.

The distributeDesignFolders function is used to initialize and distribute these folders.

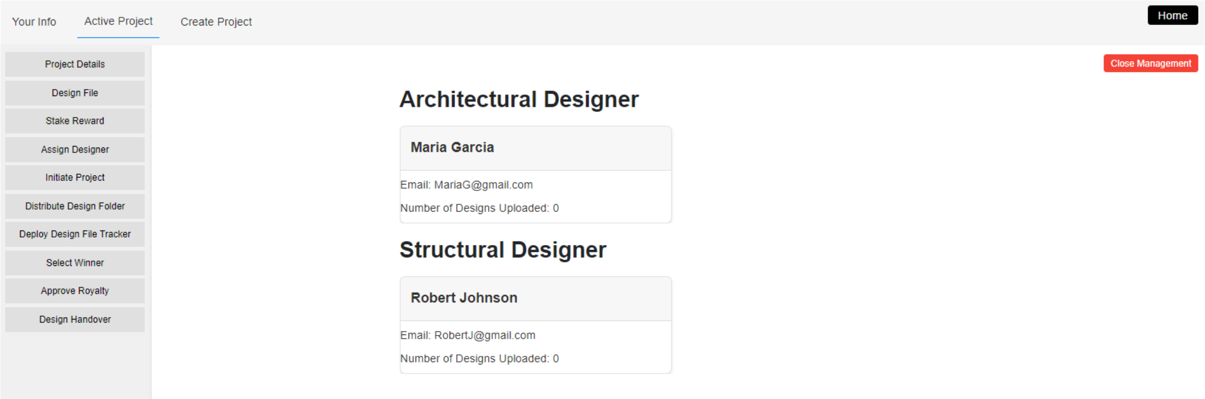
Figure 31 – Distribute Design Folder tab for project owner. This tab only works after the project owner initiated the project. Upon hitting the “Distribute Design Folders” button and confirm the transaction on MetaMask, a clone of `DesignFolderMaster.sol` will be deployed and design folders will be minted and distributed to the assigned designers.



Deploy Design File Tracker

This step involves deploying a smart contract, named Design File Tracker, to track design files for this project uploaded by the assigned designers.

Figure 32 – Deploy Design File Tracker tab for project owner. This tab only works after design folders are distributed. Hitting the button and confirming on MetaMask will trigger the deployment of a clone of `DesignFileTrackerMaster.sol` on the backend. After this step, the designers can upload their design files and tokenize them using `DesignFileTrackerMaster.sol`.



Architectural Designer

Maria Garcia

Email: MariaG@gmail.com

Number of Designs Uploaded: 0

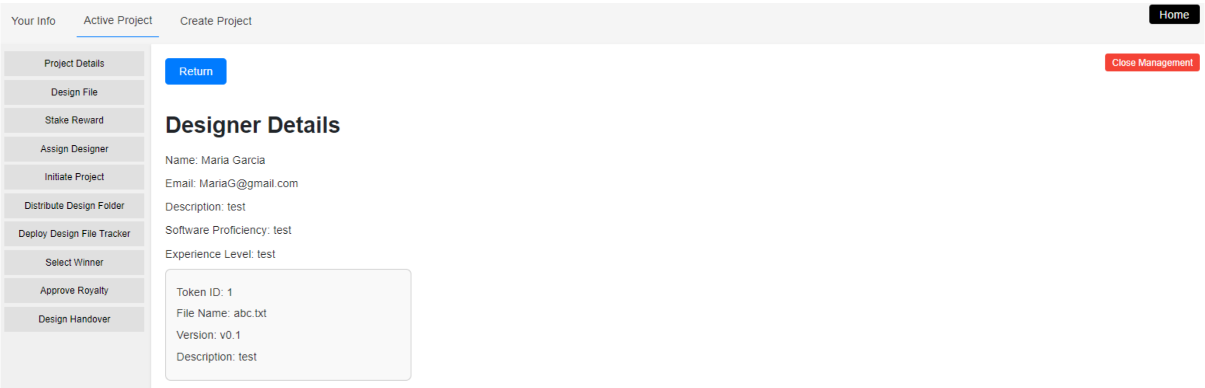
Structural Designer

Robert Johnson

Email: RobertJ@gmail.com

Number of Designs Uploaded: 0

Figure 33 – Design File tab for project owner to keep track of the design files uploaded by the assigned designers. Clicking on the designer card will direct the project owner to a detailed tab which displays specific information about the designers and their tokenized designs (see figure 34).



Designer Details

Name: Maria Garcia

Email: MariaG@gmail.com

Description: test

Software Proficiency: test

Experience Level: test

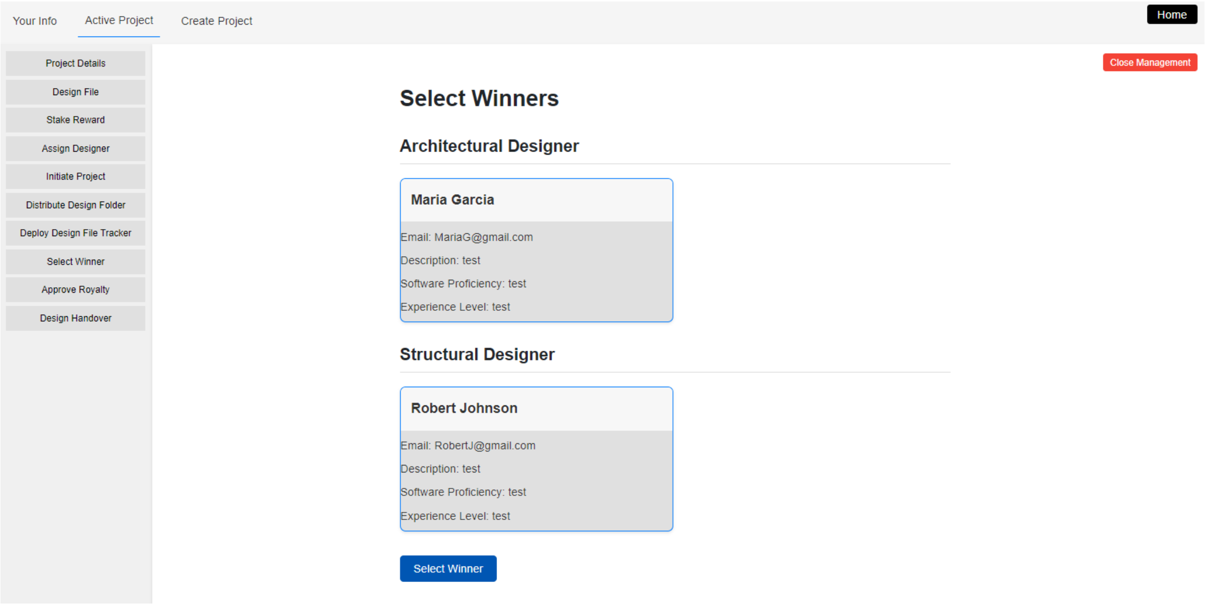
Token ID: 1

File Name: abc.txt

Version: v0.1

Description: test

Figure 34 – Designer Details tab for project owner. This tab can be reached by clicking on the designer card in Design File tab. Information about the designer and the uploaded design files are shown here. By clicking on the design file, the project owner can download the design file from IPFS, which allows the designer to check the design files submitted by the designers.



Select Winners

Architectural Designer

Maria Garcia

Email: MariaG@gmail.com

Description: test

Software Proficiency: test

Experience Level: test

Structural Designer

Robert Johnson

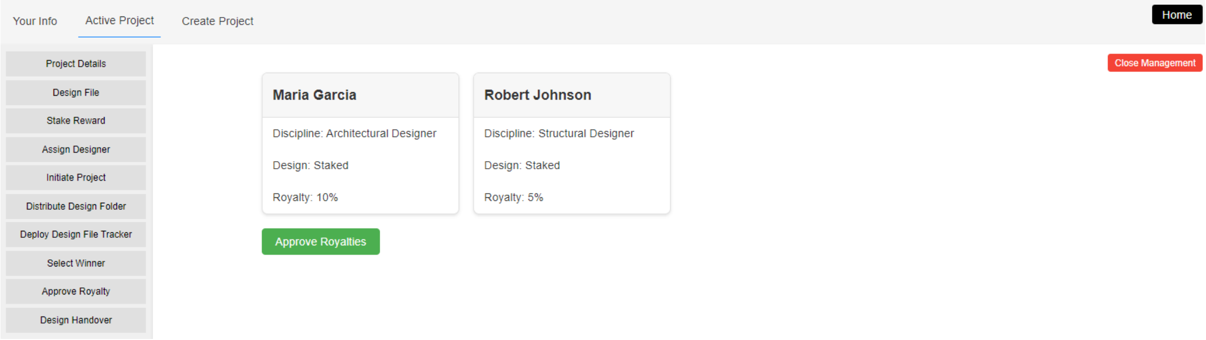
Email: RobertJ@gmail.com

Description: test

Software Proficiency: test

Experience Level: test

Figure 35 – Select Winner tab for project owner to select the winner of the competition. Hitting the "Select Winner" button will pop up MetaMask to ask the project owner to confirm the transaction.



Maria Garcia

Discipline: Architectural Designer

Design: Staked

Royalty: 10%

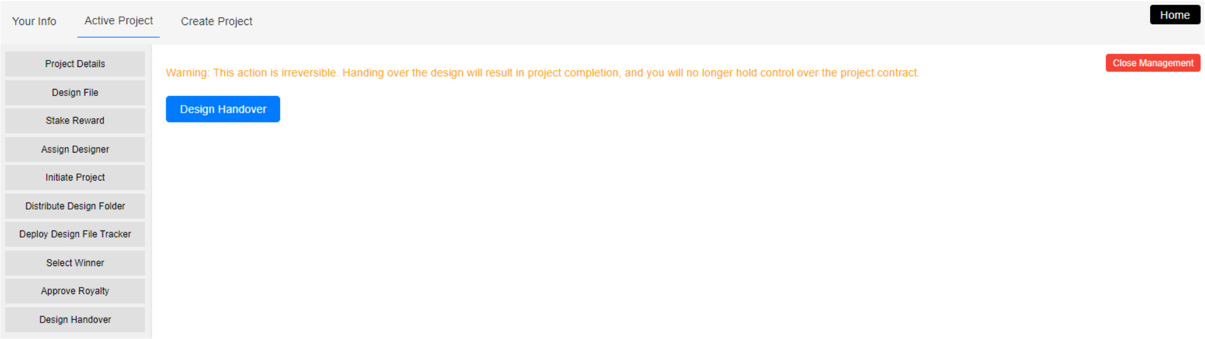
Robert Johnson

Discipline: Structural Designer

Design: Staked

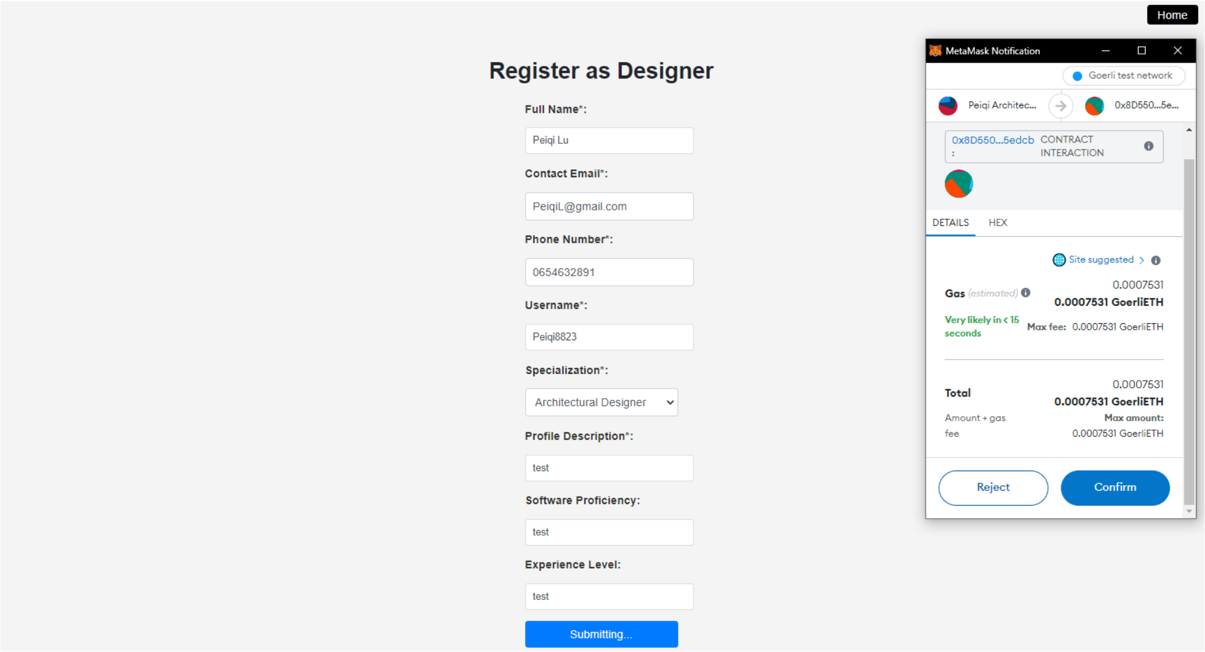
Royalty: 5%

Figure 36 – Approve Royalty tab for project owner. The "Approve Royalties" button will not appear until the designers set the royalties and have their designs staked.



Warning: This action is irreversible. Handing over the design will result in project completion, and you will no longer hold control over the project contract.

Figure 37 – Design Handover tab for project owner. This is the final stage of the project. Hitting "Design Handover" button and confirm on MetaMask will trigger the smart contract to transfer the rewards to the design winners and transfer the design folders to the project owner. The project manager contract will be renounced right after the design handover, and the functions on design folder and design file tracker smart contracts will be paused.

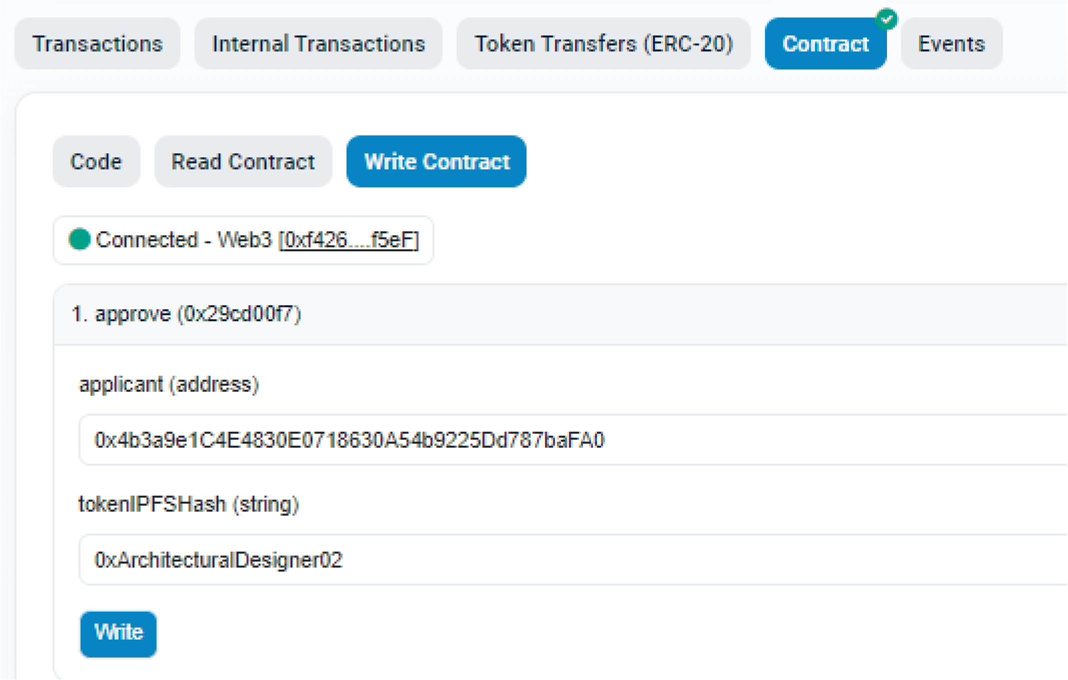


Register as Designer

Full Name*: Peiqi Lu
Contact Email*: PeiqiL@gmail.com
Phone Number*: 0654632891
Username*: Peiqi8823
Specialization*: Architectural Designer
Profile Description*: test
Software Proficiency: test
Experience Level: test

Peiqi Architec... → 0x8D550...5e...
0x8D550...5edcb : CONTRACT INTERACTION
Gas (estimated) 0.0007531 0.0007531 GoerliETH
Very likely in < 15 seconds Max fee: 0.0007531 GoerliETH
Total 0.0007531 0.0007531 GoerliETH
Amount + gas fee Max amount: 0.0007531 GoerliETH

Figure 38 - Registration page for designers. Users need to input required information for registration. The "Register and Mint Identity Token" button will pop up MetaMask and guide the user to mint the identity token. The designers must specify their specializations (disciplines) to apply for the certificate token.



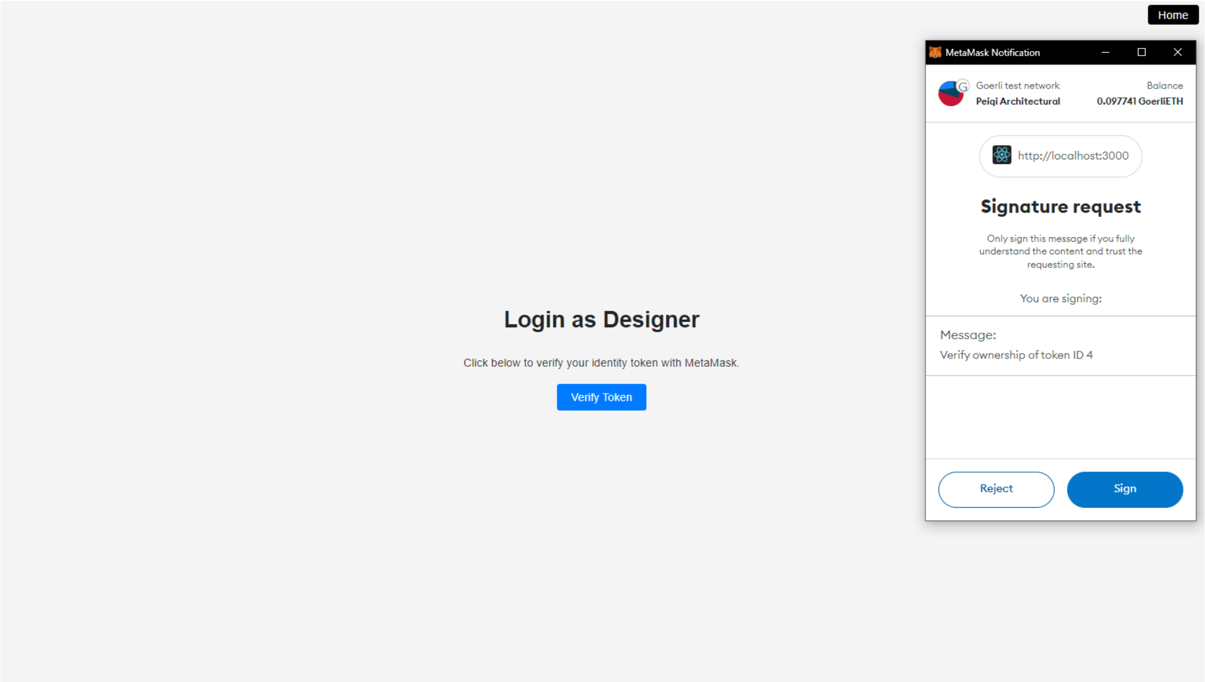
Connected - Web3 [0xf426....f5eF]

1. approve (0x29cd00f7)

applicant (address): 0x4b3a9e1C4E4830E0718630A54b9225Dd787baFA0

tokenIPFSHash (string): 0xArchitecturalDesigner02

Figure 39 – Etherscan page for the administrator to distribute certificate token to the approved desigenrs.



Login as Designer

Click below to verify your identity token with MetaMask.

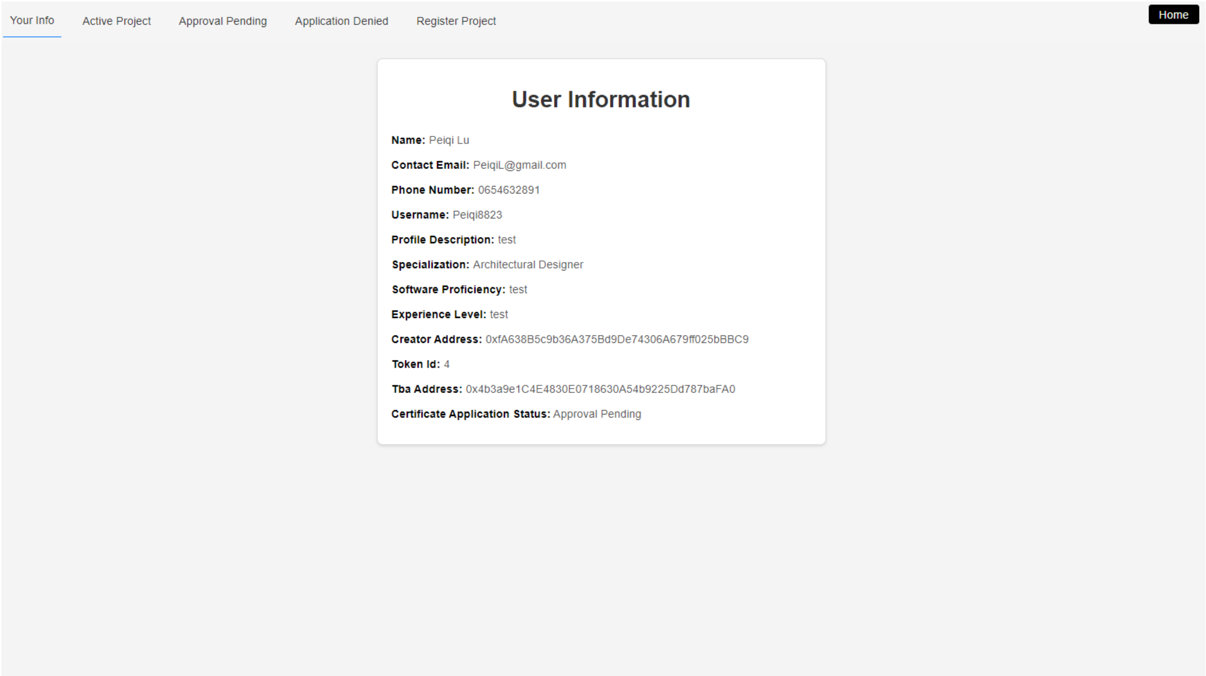
Signature request

Only sign this message if you fully understand the content and trust the requesting site.

You are signing:

Message:
Verify ownership of token ID 4

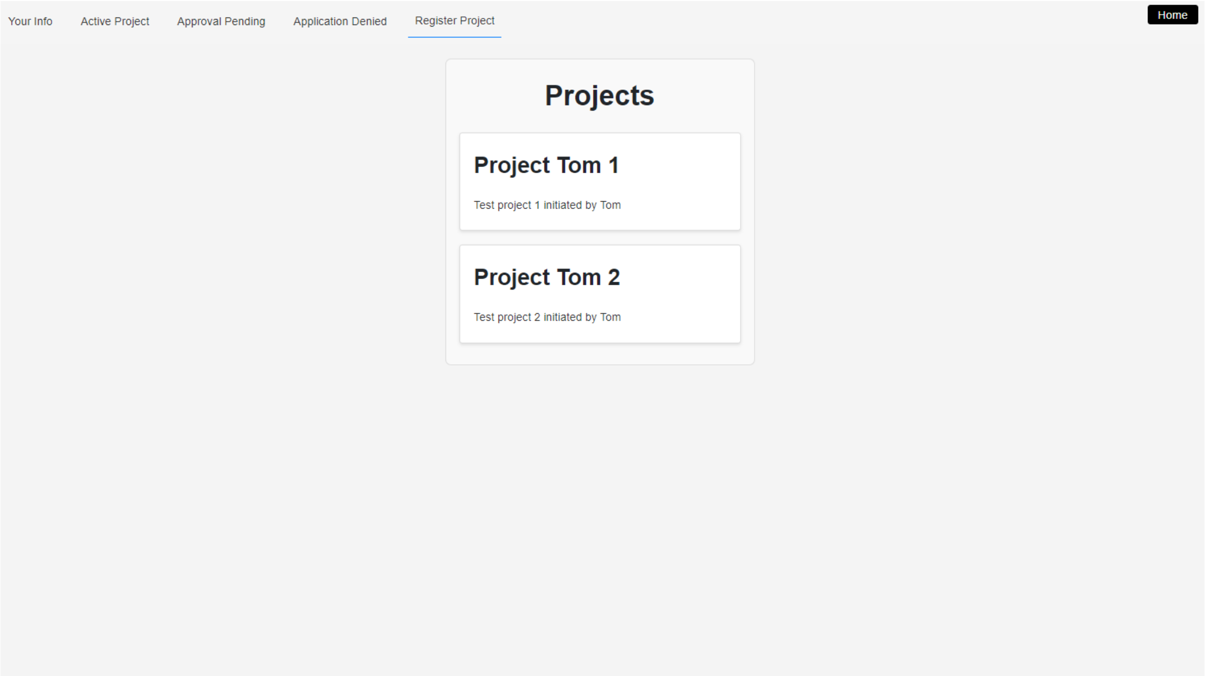
Figure 40 – Login page for designers. Users must pass the identity token verification to log in successfully.



User Information

Name: Peiqi Lu
Contact Email: PeiqiL@gmail.com
Phone Number: 0654632891
Username: Peiqi8823
Profile Description: test
Specialization: Architectural Designer
Software Proficiency: test
Experience Level: test
Creator Address: 0xfA638B5c9b36A375Bd9De74306A679ff025bBBC9
Token Id: 4
Tba Address: 0x4b3a9e1C4E4830E0718630A54b9225Dd787baFA0
Certificate Application Status: Approval Pending

Figure 41 – Main tab for designers. After successful login, the designers are directed to this tab displaying their information.



Projects

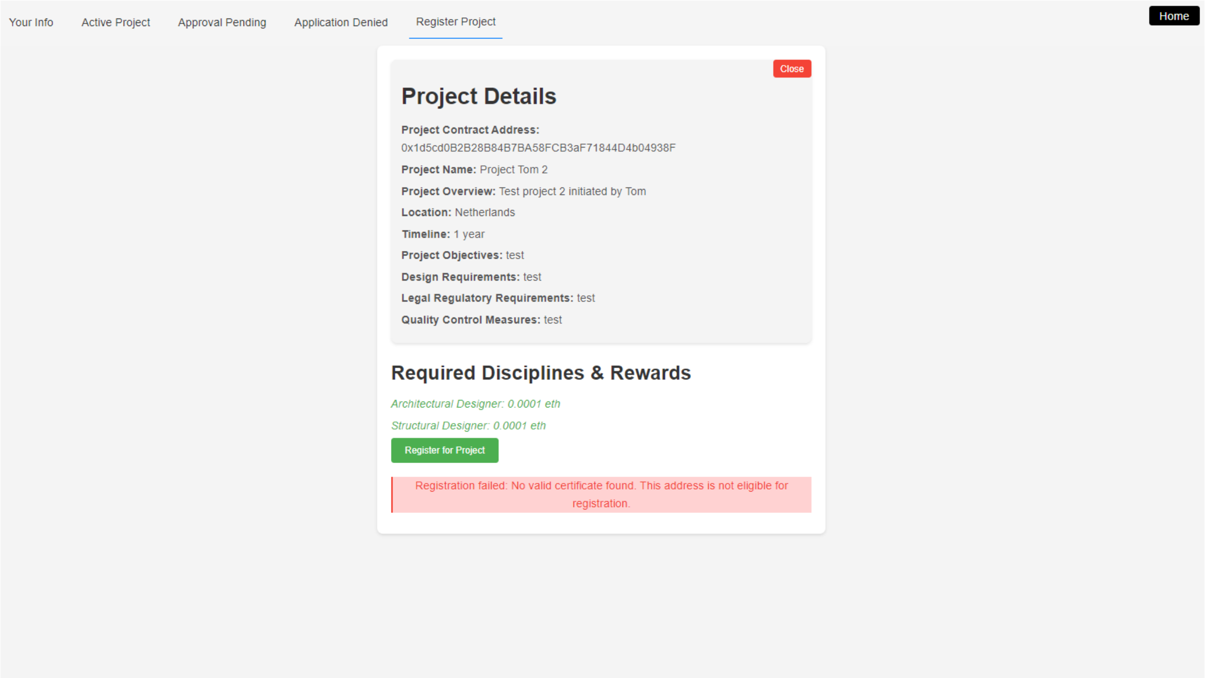
Project Tom 1

Test project 1 initiated by Tom

Project Tom 2

Test project 2 initiated by Tom

Figure 42 – Register Project tab for designers. This is the job tab where projects related to the designers' disciplines are shown. The designers can click on the project card to check the project details.



Project Details

Project Contract Address:
0x1d5cd0B2B28B84B7BA58FCB3aF71844D4b04938F

Project Name: Project Tom 2

Project Overview: Test project 2 initiated by Tom

Location: Netherlands

Timeline: 1 year

Project Objectives: test

Design Requirements: test

Legal Regulatory Requirements: test

Quality Control Measures: test

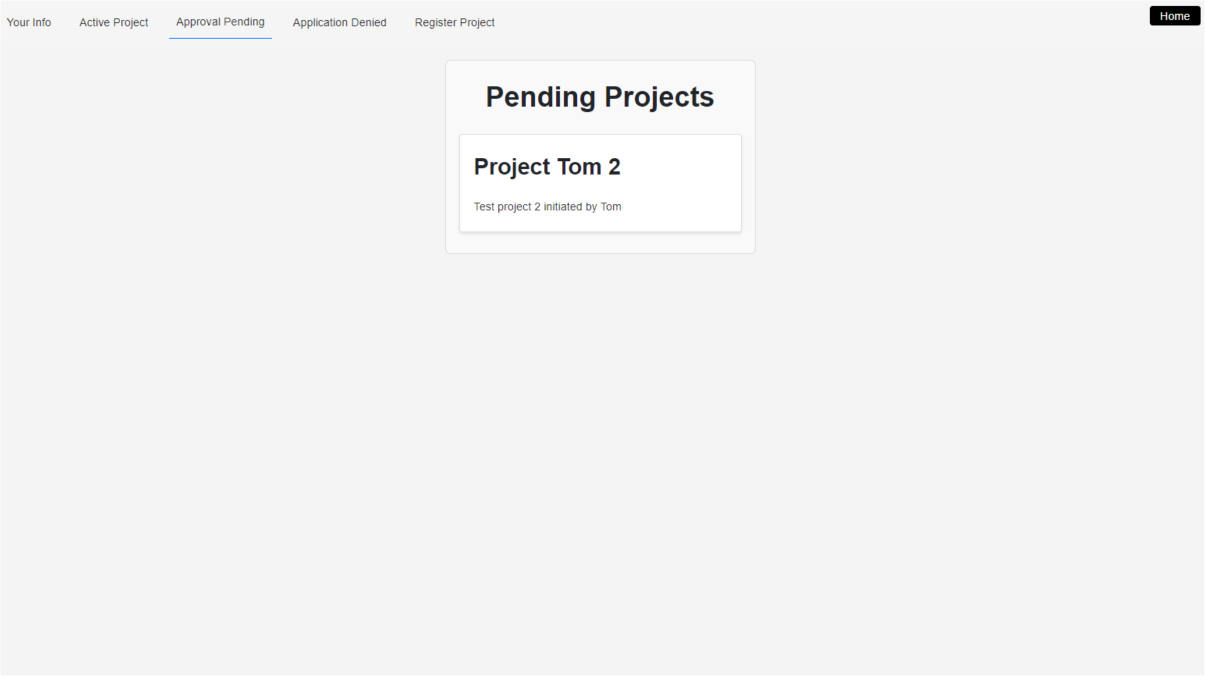
Required Disciplines & Rewards

Architectural Designer: 0.0001 eth

Structural Designer: 0.0001 eth

Registration failed: No valid certificate found. This address is not eligible for registration.

Figure 43 – Project Details tab for designers that displays the project information. The designers can register the project at this tab as well, but the registration will fail if they do not hold certificate tokens.

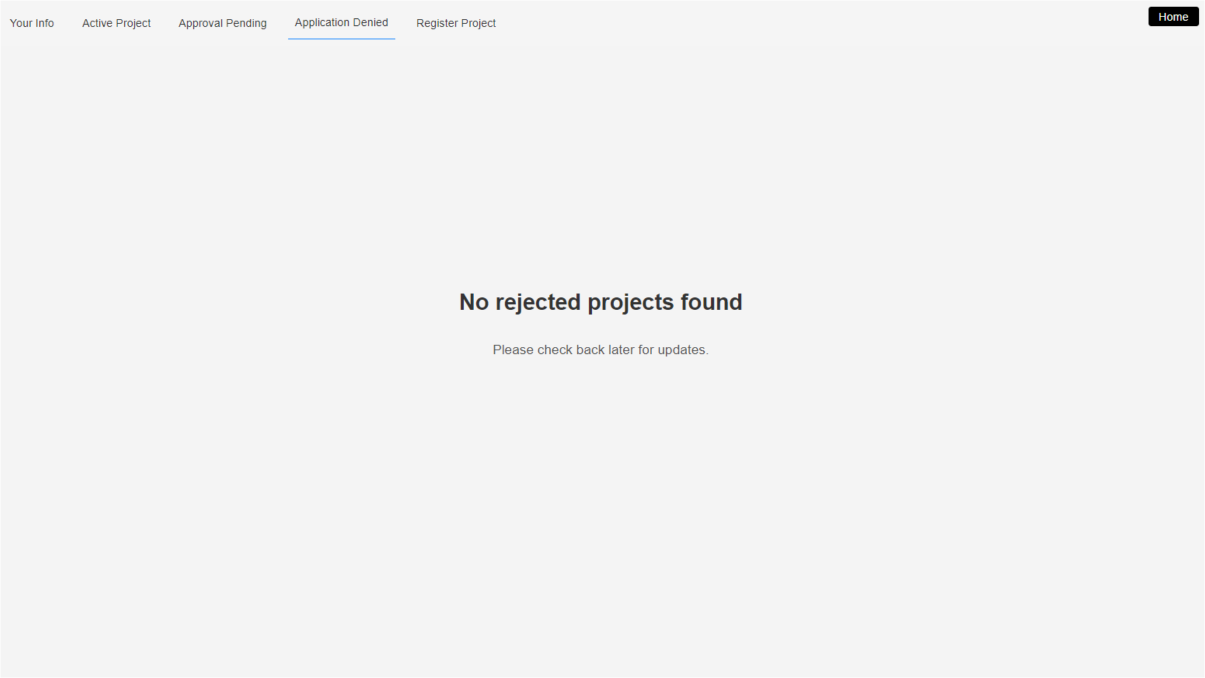


Pending Projects

Project Tom 2

Test project 2 initiated by Tom

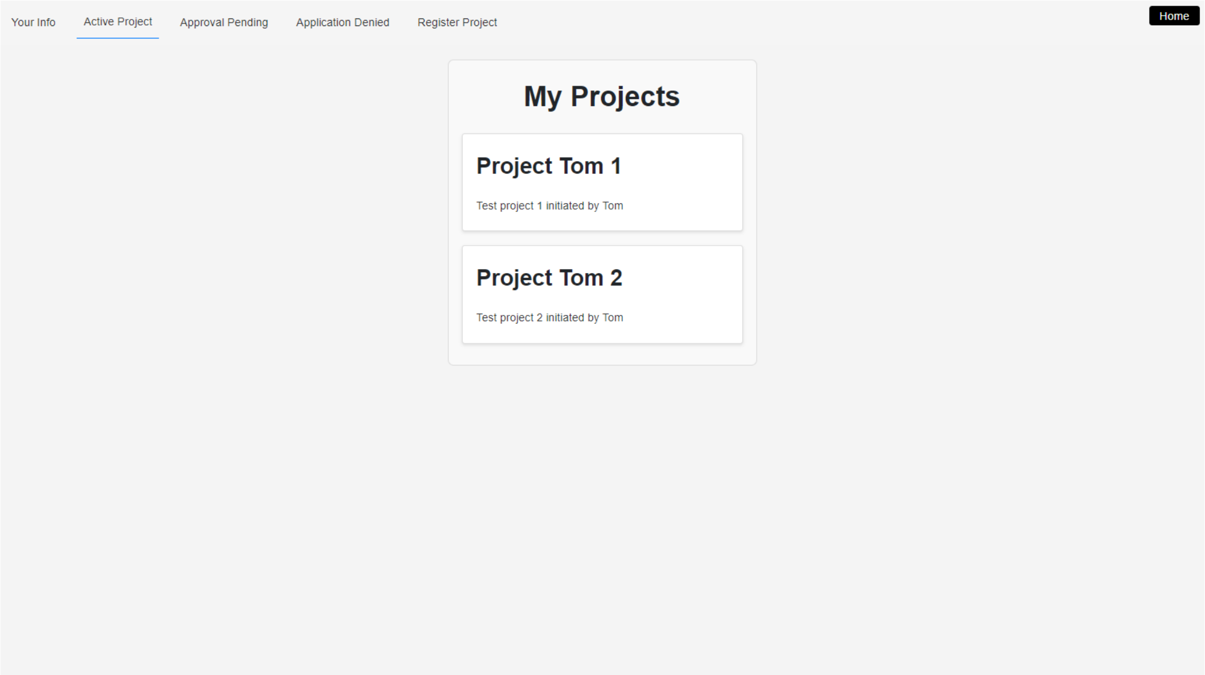
Figure 44 – Approval Pending tab for designers. This tab shows the projects the designers registered but yet to be approved by the project owner. The project card can be clicked to show project information.



No rejected projects found

Please check back later for updates.

Figure 45 – Application Denied tab for designers. This tab shows the projects that the designers registered, but unfortunately was not selected by the project owner.



My Projects

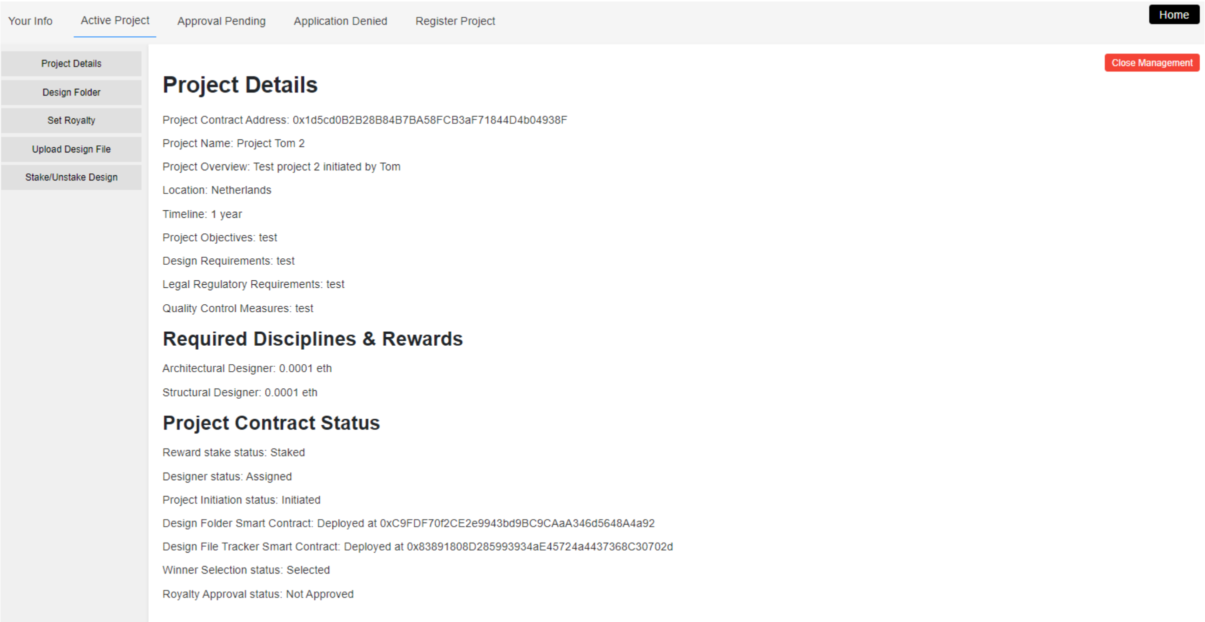
Project Tom 1

Test project 1 initiated by Tom

Project Tom 2

Test project 2 initiated by Tom

Figure 46 – Active Project tab for designers. This tab shows the projects that the designers registered and got chosen by the project owners. Clicking on the project card will direct the designers to the project management tab that allows them to perform various project-related tasks.



Project Details

Project Contract Address: 0x1d5cd0B2B28B84B7BA58FCB3aF71844D4b04938F

Project Name: Project Tom 2

Project Overview: Test project 2 initiated by Tom

Location: Netherlands

Timeline: 1 year

Project Objectives: test

Design Requirements: test

Legal Regulatory Requirements: test

Quality Control Measures: test

Required Disciplines & Rewards

Architectural Designer: 0.0001 eth

Structural Designer: 0.0001 eth

Project Contract Status

Reward stake status: Staked

Designer status: Assigned

Project Initiation status: Initiated

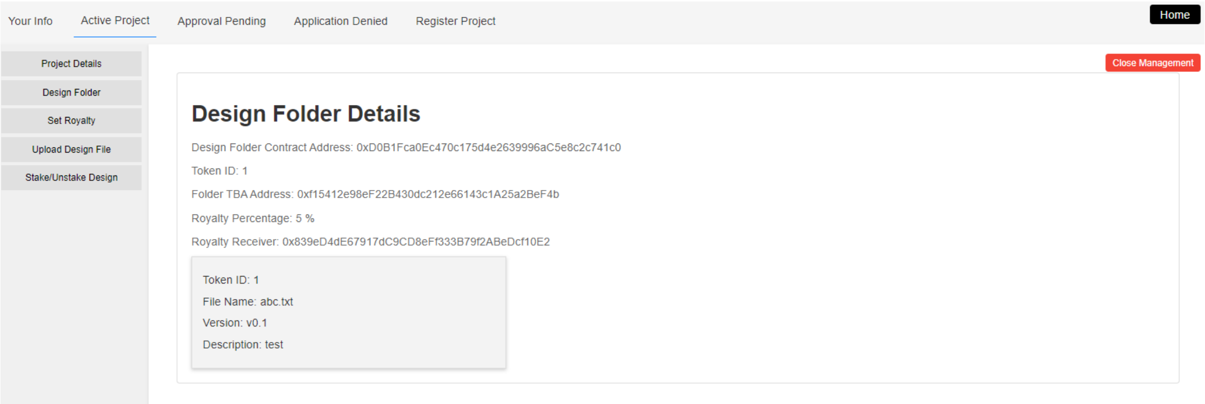
Design Folder Smart Contract: Deployed at 0xC9FDF70f2CE2e9943bd9BC9CAaA346d5648A4a92

Design File Tracker Smart Contract: Deployed at 0x83891808D285993934aE45724a4437368C30702d

Winner Selection status: Selected

Royalty Approval status: Not Approved

Figure 47 – Project Details tab for designers. This is the main page of project management tab. All the project details are summarised and displayed on this page. The designer can check the project information and project status. This UI is dynamically updated as the project progresses, showing the most updated information of the project.



Design Folder Details

Design Folder Contract Address: 0xD0B1Fca0Ec470c175d4e2639996aC5e8c2c741c0

Token ID: 1

Folder TBA Address: 0xf15412e98eF22B430dc212e66143c1A25a2BeF4b

Royalty Percentage: 5 %

Royalty Receiver: 0x839eD4dE67917dC9CD8eFf333B79f2ABeDcf10E2

Token ID: 1
File Name: abc.txt
Version: v0.1
Description: test

Figure 48 – Design Folder tab for designers. This tab only works after design folders are distributed by the project owner. The information about the design folder, as well as data of tokenized design files contained in the design folder, are shown in this tab. Clicking on the design files allows the designers to download the design files from IPFS.

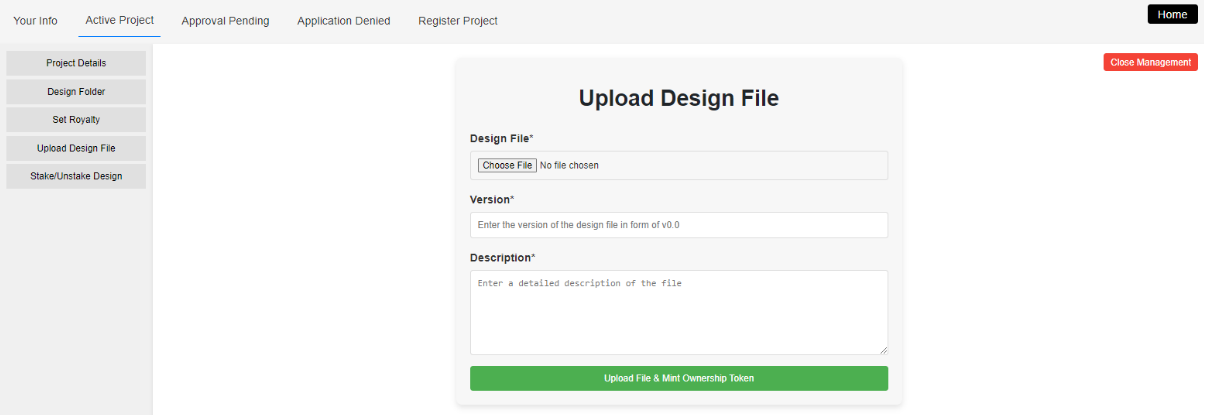


Figure 49 – Upload Design File tab for designers. This tab only works after design file tracker contract is deployed by the project owner. This designer can use this tab to upload their design files to IPFS, retrieve the IPFS hash, mint the design file token with IPFS hash attached. The whole process of design file tokenization is triggered by the "Upload File & Mint Ownership Token" button and conducted on the backend, allowing people with no blockchain knowledge to easily tokenize their design files.

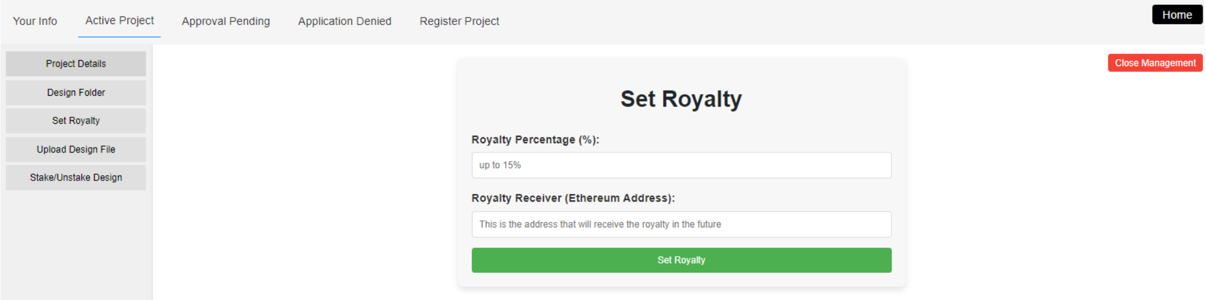
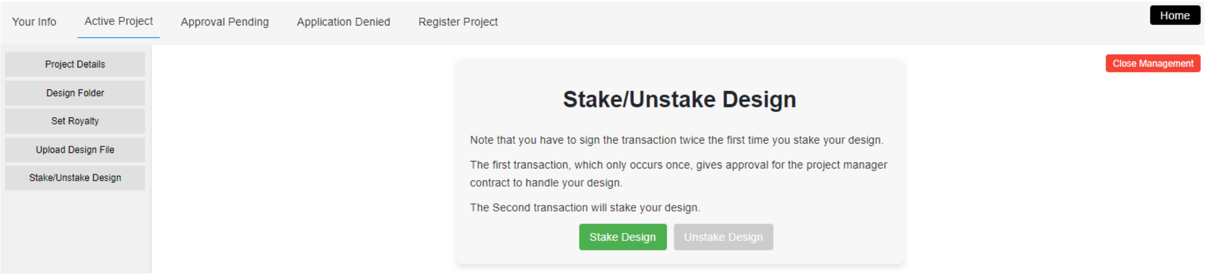


Figure 50 – Set Royalty tab for designers. This tab allows the designers to set royalties on their design folder tokens. The designers, no matter winner or not, are allowed to set royalties and the address that will receive royalties in the future. This is because the design that lost the competition can still be sold or traded on the platform's marketplace, so this is a crucial step to ensure that the designers will be compensated for possible future design reuse.



Stake/Unstake Design

Note that you have to sign the transaction twice the first time you stake your design.

The first transaction, which only occurs once, gives approval for the project manager contract to handle your design.

The Second transaction will stake your design.

Figure 51 – Stake/Unstake Design tab for designers. This tab only works if the designers are selected as the winner. The designers are asked to stake their design to the project manager contract before the final design handover stage. After successful design stake, the designers will wait for the project owner to initiate design handover process and get their reward.